



FREEDM

SYSTEMS CENTER

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Future Renewable Electric Energy Delivery and Management (FREEDM)
Systems Center – Generation 3 Engineering Research Center

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List of ERC Projects

List of ERC Core Projects by Thrust

System Demonstration

- Y8.GEH1.1: Distributed Renewable Energy Resources Integration into GEH
- Y8.GEH1.2: Green Energy Hub Testbed: IEM, IPM and IFM Demonstration of the FREEDM System
- Y8.GEH1.3: DGI Integration into GEH Testbed
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- Y8.GEH1.5: Demonstration and Integration of Multiple LV-SSTs with Islanding and Black-Start in GEH
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- Y8.GEH2.2: Detailed FREEDM System Cost Benefit Analysis under Different Deployment Scenarios
- Y8.GEH2.3: FREEDM Cost Benefit Analysis based on Detailed Utility Circuit Models
- Y8.GEH2.4: System Level Cost-Benefit Analysis
- Y8.GEH2.5: Evaluation of Codes, Standards, and Regulatory Documents relative to the FREEDM System
- Y8.GEH2.6: Cost Estimation Model
- Y8.GEH2.7: Voice of Customer Analysis and Commercialization Path
- Y8.HIL.1: Hardware in the Loop Testbed
- Y8.HIL.2: Reliable and Secure Communication Development in Support of the HIL Testbed and FREEDM Systems Center
- Y8.HIL3: Volt-Var Control on FREEDM System
- Y8.HIL.4: Multi-SST Cooperative Distributed Energy Scheduling
- Y8.LSSS.1: Validation of 100% PV Penetration in the LSSS-Inverterless PV
- Y8.LSSS.2: Islanded operation of LSSS
- Y8.LSSS.3: Development Pilot Directional Differential Protection Interaction with the FREEDM Loop

Enabling Technology

- Y8.ET1.1: DGI Integration with GEH & HIL & LSSS and Application Support
- Y8.ET1.2: Secure System-Level Invariant Derivation and Validation
- Y8.ET1.3: Resilient Energy Management Operation in FREEDM Systems
- Y8.ET1.4: Design of distributed Resilient Sensing Systems
- Y8.ET2.1: FAWG System Level Architecture and Metrics
- Y8.ET2.2: Plug and Play and Power Systems Enhancements to FREEDM Architecture
- Y8.ET3.1: Design and Development of Generation III SST
- Y8.ET3.2: Controller Hardware-in-the-Loop(CHIL) Development and Demonstration with Plug & Play Features
- Y8.ET3.3: Enhanced Integration of DESDs to SST

- Y8.ET4.1: Gen III Hybrid FID Development – Piezoelectric Actuated Fast Mechanical Disconnect Switch (PA-FMS)
- Y8.ET4.2: Fault Isolation Device (FID) Development – Power Electronics
- Y8.ET4.3: Innovative Means of Resolution of Issues with the Basic Impulse Level (BIL) and Other High Voltage Requirements in the FREEDM Distribution System
- Y8.ET5.1: Distributed Energy Storage Device (DESD)
- Y8.ET5.2: Safety Testing of Li-ion Batteries
- Y8.ET5.3: Battery Degradation Model for Real-Time Levelized Cost Calculation

Fundamental Science

- Y8.FS1.1: SiC Power Devices for SST and FID Applications
- Y8.FS1.2: GaN Low Voltage Power Device Development
- Y8.FS1.3: Packaging Research and Demonstration
- Y8.FS2.1: Distributed Control Methods for Intelligent Power Management with Moving Equilibria
- Y8.FS2.2: Modeling and Controller Design for SST with Plug and Play Features under High DG Penetration
- Y8.FS2.3: Distributed Model Predictive Control based for Intelligent Energy Management of the FREEDM System
- Y8.FS2.4: Real-Time Stability Analysis for the FREEDM System Utilizing Nonlinear Time-Series Analysis and Embedding Phase-Space Techniques
- Y8.FS2.5: Modeling, Analysis and Control of Distribution Networks Based on Solid-State Transformers
- Y8.FS2.6: Dynamic Phasor-based Controller Design for Solid State Transformer

List of Associated Projects by Thrust

System Demonstration

- Ocean Energy: Assessment of Energy Storage Aspects Including Control and Grid Connection off the North Carolina Coast
- Design and Analysis of Switched Reluctance and Flux Switching Permanent Magnet (FSPM) Machines for Industrial Applications
- Development of a Mobile Energy Generator for Use in Microgrids in the Dominican Republic
- Electricity Operations Model
- Olney Town Center Microgrid Project
- Permanent Magnet Transverse Flux Electric Machine with Flux Focusing Technique for Direct Drive Applications
- Power America™ SiC Inverter for Electric Vehicle Traction Drive
- Switched Reluctance Machine and Controller Development for Power Steering
- The Solar Endowment – Demonstrating University Leadership in the Solar Development
- Analysis of Practical Microgrid Stability in the Presence of Random Events

Enabling Technology

- Development and Characterization of Li-ion Capacitor Electrodes and Cells
- Enabling High Penetration of Distributed PV through the Optimization of Transmission Voltage Regulation
- Fabrication of Lithium-Sulfur Pouch Cell Batteries
- Investigation of Pre-Lithiated Anodes for Li-Ion batteries and Li-ion capacitors
- Li-ion Battery and Li-ion Capacitor Hybrid Energy Storage Devices
- Monolithic Li-ion Battery and Li-ion Capacitor Hybrid Cells for Brigade, Soldier and Small Unit Power
- Solar Electric Home Energy Management Program
- Determining Security Threats through Information Flow Analysis
- Missouri Advanced Security Training Education and Research
- Resilient Information Architecture Platform for the Smart Grid
- CPS:Synergy: Collaborative Research: Diagnostics and Prognostics Using Temporal Casual Models for Cyber Physical Systems – A Case of Smart Electric Grid
- Fast Electromechanical Disconnect Switching Chamber with Integrated Drive Mechanism
- Testing, Characterization and Design Optimization of High Voltage SiC Gate Turn-Off (GTO) Thyristors
- Development and Testing of Silicon Carbide Gate Turn-Off Thyristor Based High Solid State Circuit Breaker (SSCB) for DC Power Distribution System
- Development of Medium Voltage Fast Charger

- Development of SiC/GaN Based High Performance PV String Inverters and Micro Inverters
- Resilient Multi-terminal HVDC Using High Voltage Frequency Electronics Capability
- SiC Power Devices and DC Power Distribution System

Fundamental Science

- Power America: Medium Voltage Gate Drive with 10 KHz, 10kV SiC Mosfet for 2.3 kV Motor Drives
- Collaborative Research: Computational Methods for Stability Assessment of Power Systems with High Penetration of Clean Renewal Energy
- CPS: Breakthrough: Collaborative Research: Securing Smart Grid by Understanding Communications Infrastructure Dependencies
- CPS: TTP Option: Synergy: Collaboration Research: Hardening Network Infrastructure for Fast, Resilient and Cost-Optimal Wide Area Control of Power Systems
- Design of High Performance, Low Cost, Non-rare Earth Electric Machines Meeting IE4/IE5 Efficiency Requirements
- Load Regulation with PV-Storage and Electric Vehicle with Dynamic Programming
- The MidAmerica Regional Microgrid Education and Training (MARMET) Consortium
- Solar Electric Home Management Program
- US Ignite: Track 1: Collaborative Research: DISTINCT: A Distributed Multi-Loop Networked System for Wide-Area Control of Large Power Grids

List of Education Projects

- Engineering Guides of NC
- Kenan Fellow for the FREEDM Systems Center

Core Projects

System Demonstration

Y8.GEH1.1: Distributed Renewable Energy Resources Integration into GEH

Team Members

Project Leader:	Dr. David Lubkeman
Faculty:	Dr. Iqbal Husain (NCSU), Dr. Romeo Ortega (Centrale-Supelec)
Students:	Rui Gao, Rafael Montoya

1. Project Goals

- Design and build a 10 hp wind turbine emulation prototype for lab research and education.
- Develop and implement wind turbine characteristic emulation algorithm.
- Integrate wind energy as Distributed Renewable Energy Resource (DRER) into Green Energy Hub (GEH).
- Research and implement wind turbine system level advanced controls and power management strategy.

2. Role in Support of Strategic Plan

The wind turbine emulator testbed provides rotational renewable energy for the FREEDM system as a distributed renewable energy resource (DRER). It is a feasible method to study wind renewable system inside laboratory environment. Various wind turbine characteristics can be simulated. From GEH strategic level, the wind DRER project has served as the critical part of GEH for system function demonstration. System level power management strategy has been performed with SST, other DRER, and distributed energy storage devices (DESD). Wind DRER is capable of functioning as a plug-n-play renewable for the system. As a node, SCADA communication has also been implemented with current hardware setup for monitoring and communications.

3. Fundamental Research, Technological Barriers and Methodologies

a. Wind turbine characteristics study and emulation strategy implementation with lab prototype

The mechanical power that a wind turbine extracts from wind could be calculated as follows:

$$P_m = \frac{\pi}{2} \rho R^2 V_w^3 C_p(\lambda, \beta)$$

where ρ is air density (Kg/m^3); R is turbine blade radius (m), V_w is wind speed (m/s), C_p is power coefficient of wind turbine, which is a function of both tip-speed ratio (TSR) λ and the turbine blade pitch angle β . The mathematical representation of C_p is given as

$$C_p(\lambda, \beta) = c_1(c_2 - c_3\beta - c_4\beta^2 - c_5)e^{-c_6}$$

$c_1=0.5$, $c_2=116/\lambda_i$, $c_3=0.4$, $c_4=0$, $c_5=5$, $c_6=21/\lambda_i$, and λ_i is defined as

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

where $\lambda = R\omega/V_w$. ω is turbine rotor rotational speed (rad/s).

b. Solid-State Transformer (SST) interfaced wind energy system controls, system application and power management strategy

The system and controller diagrams for the SST interface wind energy system is shown in Figs. 1 and 2. The control strategy in the first implementation is based on PI controllers.



Figure 1. PMSG Wind System PCC Integration Configuration

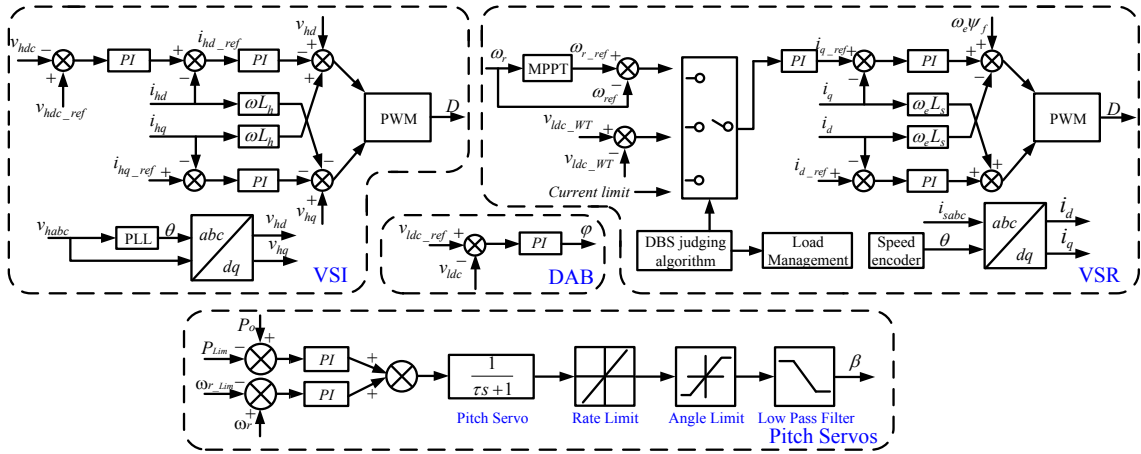


Figure 2. PMSG wind system control block diagram

c. Passivity based control (PBC) strategy proposal, verification, and implementation for wind energy conversion system

A passivity based control strategy for the SST interface wind DRER has been developed in Year 8. The wind turbine, PM synchronous generator (PMSG), and SST rectifier models are given as following:

$$\begin{aligned}
 L \frac{di_d}{dt} &= -Ri_d + \frac{P}{2} Li_q \omega_m - d_1 v_c \\
 L \frac{di_q}{dt} &= -Ri_q - \frac{P}{2} Li_d \omega_m + \frac{P}{2} \phi \omega_m - d_2 v_c \\
 J \frac{d\omega_m}{dt} &= -f \omega_m + \frac{1}{2} \rho A r v_w^3 \frac{1}{\omega_m} C_p \left(\frac{v_w \omega_m}{r} \right) - \frac{3P}{2} \phi i_q \\
 C \frac{dv_c}{dt} &= -R_e v_c + \frac{V_s}{R_s} + i_d d_1 + i_q d_2.
 \end{aligned}$$

Introducing the following definitions

$$\phi_1 := \frac{\phi^P}{2}, \gamma := \frac{P}{2}, J_1 := \frac{2}{3}J, f_1 := \frac{2}{3}f$$

$$x = \text{col}(Li_d, Li_q, J_1\omega_m, Cv_c), u = \text{col}(d_1, d_2),$$

The system can be rewritten as

$$\begin{aligned}\dot{x}_1 &= -\frac{R}{L}x_1 + \frac{\gamma}{J_1}x_2x_3 - \frac{x_4}{C}u_1 \\ \dot{x}_2 &= -\frac{\gamma}{J_1}x_1x_3 - \frac{R}{L}x_2 + \frac{\phi_1}{J_1}x_3 - \frac{x_4}{C}u_2 \\ \dot{x}_3 &= -f_1x_3 + \Phi(x_3) - \frac{\phi_1}{L}x_2 \\ \dot{x}_4 &= -\frac{R_e}{C}x_4 + \frac{x_1}{L}u_1 + \frac{x_2}{L}u_2 + \frac{V_s}{R_s}\end{aligned}$$

The system allows the Port-Hamiltonian representation as follows:

$$\dot{x} = (J_0(x_3) - \mathcal{R} + J_1u_1 + J_2u_2) \nabla H + E_0(x_3)$$

The final control in the original reference can be designed as

$$y = \begin{bmatrix} i_{d*}\tilde{v}_C - \tilde{i}_d v_{C*} \\ i_{q*}\tilde{v}_C - \tilde{i}_q v_{C*} \end{bmatrix}.$$

The control block diagram is shown in Fig. 3.

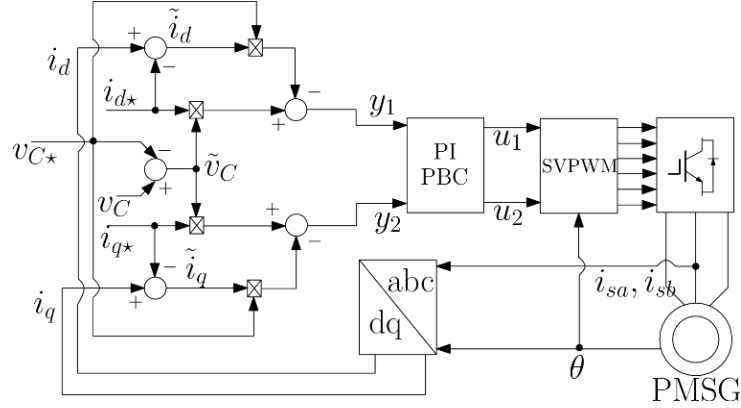


Fig. 3. Block diagram of the control implementation.

4. Achievements

- The 10 hp wind turbine emulation prototype for lab research has been built. The wind turbine emulator consists of an induction motor and programmable drive, and the permanent magnet synchronous motor (PMSG) is used as generator. A back-to-back full power converter and its controls based on DSP28335 are built. The wind turbine prototype communication with FREEDM SCADA system through PC104 implemented with FPGA is also realized. A montage of the hardware is shown in Fig. 4.
- Solid-State Transformer (SST) integrated hardware demonstration has been accomplished during previous NSF site visit review.

- Wind turbine mathematical modeling analysis has been completed and hardware implementation under various wind speeds is currently underway. The emulator performance under various wind speeds, static and dynamic response test results are expected. The emulation control algorithm is implemented in Microcontroller dsPIC24F. The interface board is designed to accommodate voltage level conditioning and isolation. The hardware set-up is shown in Fig. 5(a). The wind turbine characteristics are given in Fig. 5(b).
- The passivity-based PI control for the wind DRER system is currently under development. The simulation and controller design has been completed, and the hardware work is in progress.



Fig. 4. Wind DRER hardware prototype.

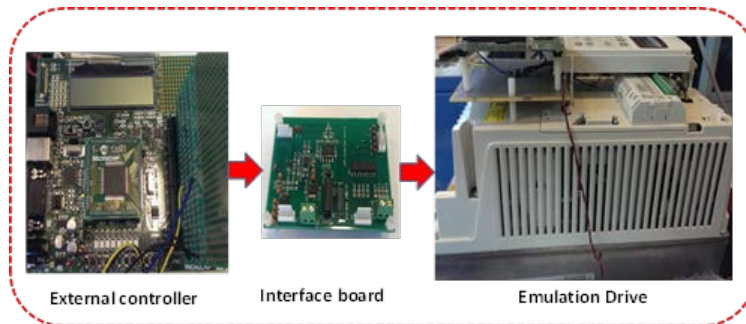


Fig. 5(a) Wind turbine emulator setup.

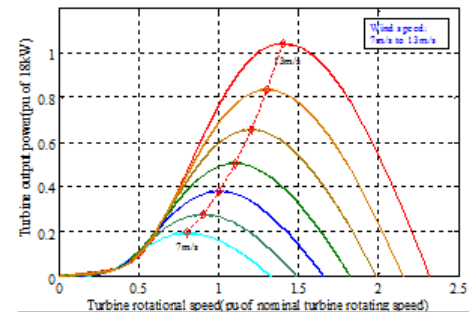


Fig. 5(b) Turbine characteristics.

5. Milestones and Deliverables

- The 10 hp wind turbine emulation prototype for lab research has been built.
- Power management capability investigation of SST interfaced wind turbine system simulation study has been carried out under grid-connected mode, islanding mode, and also mode transition without any energy storage devices.
- Wind turbine output characteristics have been studied and simulated. Hardware implementation is achieved in the microcontroller. Dynamic and static operation experimental results are expected in the coming month. Various programmed wind profiles will also be delivered.
- Advanced robust passivity-based control is expected to be implemented in hardware and evaluated in Summer 2016 to test and verify its feasibility. The advantages and comparisons with classical PI control will be illustrated. Discussion and study on this control's viability for FREEDM system multiple-converter structure are expected.

6. Plans for Next Five Years

- PMSG based wind generation system grid connection control, and research are expected. Extreme grid condition like grid voltage sag and grid support function shall be investigated.
- Functionalities of wind turbine as distributed energy resource under islanding mode will be investigated with and without energy storage devices under various loading situations.
- Additional advanced control methods could be evaluated on the wind turbine emulator testbed.

7. International Collaborations:

International collaboration has been established with Centrale-Supelec, France where they are working on passivity based controls for the FREEDM system and the wind DRER subsystem. Centrale-Supelec PhD student Rafael Montoya visited NCSU in summer 2015 to work on the theoretical development and simulation analysis passivity based controller developed for wind energy system jointly with NCSU PhD student Rui Gao. The PhD students are working on implementing and testing the algorithm in the GEH tested. One joint paper has been accepted at an International conference and another digest has been submitted for IEEE-ECCE 2016.

8. Related Publications

- [1] R. Cisneros, R. Gao, R. Ortega and I. Husain, A PI Passivity-Based Control for Maximum Power Extraction of a Wind Energy System with Guaranteed Stability Properties, *International Conference on Renewable Energy: Generation and Applications (ICREGA) (To appear)*, 2016.
- [2] R. Gao, I. Husain, F. Wang and A. Q. Huang, Solid-State Transformer Interfaced PMSG Wind Energy Conversion System. *Applied Power Electronics Conference and Exposition (APEC)*, pp. 1310 – 1317, 2015.
- [3] R. Gao, I. Husain, and A. Q. Huang, Autonomous Power Management of Solid-State Transformer Interfaced PMSG Wind Energy Conversion System. *Applied Power Electronics Conference and Exposition (APEC)*, (To appear), 2016.

Y8.GEH1.2: Green Energy Hub Testbed: IEM, IPM and IFM Demonstration of the FREEDM System

Team Members

Project Leader: Alex Q. Huang (NCSU)

Students: Sarah Hambridge (Ph.D.), Samyak Parakh (M.Sc), Yizhe Xu (Ph.D.),
Soumik Sen (Ph.D.)

Staff: Ruiyan Yu (postdoc), Dong Chen (postdoc)

1. Project Goals

The overall project goal of the GEH testbed is to test and demonstrate FREEDM developed enabling technology in a physical testbed closely resembling that of a real world implementation of the FREEDM concept. The specific objective of this project is demonstration of the FREEDM system's salient attributes, grouped in IFM, IPM, IEM and PnP.

2. Role in Support of Strategic Plan

The Green Energy Hub (GEH) physical testbed is a working model of a medium voltage (MV) distribution system configured to demonstrate FREEDM System concept. In previous years, we have integrated two generations of MV SST and two generations of FID into the GEH testbed and have demonstrated various PnP, IEM, IPM and IFM functionalities. This project continues to be critical for the Center to further demonstrate and validate the FREEDM System concept. The project is also critical in building up additional testbed capabilities for current and future research.

3. Fundamental Research, Technological Barriers and Methodologies

The greatest challenge continues to be the integration of Center-developed MV equipment into a MV grid and operate them simultaneously and safely. Each item developed by the Center can be operated as a stand-alone piece of equipment; integrating these individual components is far from straightforward.

In Year 7 and Year 8, one compromise solution was adopted which calls for the development of additional physical testbed capabilities at lower voltage levels. This will address the MV challenge and all functionalities can still be demonstrated.

4. Achievements

Previously, we have successfully integrated two generations of SSTs, FIDs and DESDs into the GEH testbed. Various IEM, IFM, IPM and PnP capabilities have been demonstrated. Table 1 below summarizes the major demonstrations that have been accomplished over the years.

	PnP	IFM	IPM	IEM
	- Arc-free DC plug (Actor: Plug and DC Energy Cell) - DC Energy Cell PnP Demonstration (Actor: Gen-I SST and DC Energy Cell including PV DRER)		Low voltage ride through (LVRT)(Actor: Gen-I SST)	
	DRER & DESD PnP integration (Actor: Gen-I SST, DESD, Wind DRER)		- Soft start-up (Actor: Gen-II SST) - Input Current Harmonic Compliance (Actor: Gen-II SST) - Input and Output harmonic Isolation (Actor: Gen-II SST) - Reverse power flow (Actor: Gen-II SST) - Voltage support via VAR injection (Actor: Gen-II SST)	Autonomous <i>Energy Cell</i> dispatch (Actor: Gen-I SST and DC Energy Cell)
		Short circuit current limiting and protection (actor: Gen-III SST)		Zero Energy Home Demonstration (Actor: LV SST and Energy Cell)
			Solid State Synchronous Machine (SSSM) (Actor: SST and Energy Cell)	Frequency based real-time pricing and energy dispatch (Actor: LV SST and Energy Cell)

Table 1: Summary of major salient features already demonstrated for the FREEDM System

In Year 8, the following three major achievements are being accomplished in this project.

Achievement 1: Development of low voltage FREEDM System testbeds

To address the grand challenge in conducting more flexible demonstrations on a medium voltage FREEDM system circuit with center developed equipment, we have initiated an activity to construct a low voltage testbed that is more suitable for IEM demonstration since IEM features is more or less independent of the FREEDM physical layer capability.

The low voltage FREEDM testbed involves a number of low voltage solid state transformers (LVSST), as well as various energy cell components such as the distributed energy storage system (DESD). All of these FREEDM devices are assembled and integrated into a single rack housing. Every FREEDM device is also designed to be an internet device. As shown in Fig. 1, the RS485 and MODBUS slave are implemented to the controller of all FREEDM devices. An ARM board/computer is serving as the master of the MODBUS to dispatch the FREEDM System as well as to archive collected data. The ARM board is also connected to Ethernet via TCP/IP. Online display of system condition is also achieved via a GUI.

In Year 8, two major demonstrations will be conducted using the testbed, one is the IEM demonstration focusing on frequency based real time pricing and energy dispatch by SST1. The other is the solid state synchronous machine (SSSM) demonstration. Both are discussed further below.

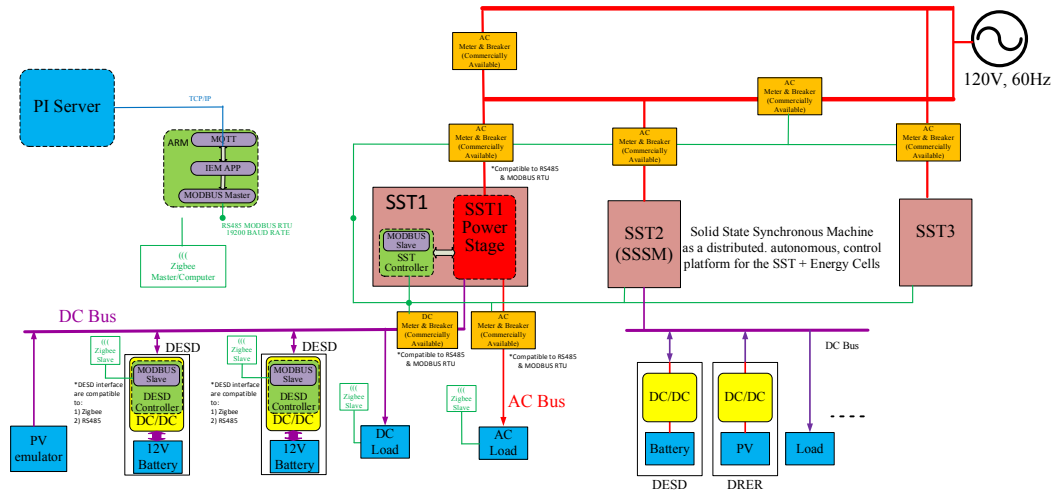


Figure 1: Low Voltage FREEDM System Testbed (SST1 and SST2) (SSSM) are in place. Additional SST and FID (breaker) will be added to the system in Y9 & Y10.

Achievement 2: From Solid State Transformer to Solid State Synchronous Machine (SSSM): Power Electronics Grid Interface to Support 100% Penetration of Distributed Energy Resources

As a spin-off research agenda from the SST subthrust, the new SSSM concept is developed based on Solid State Transformer and virtual synchronous generator concept. It is a fundamental contribution by the center to support 100% penetration of distributed energy resources (DER) such as photovoltaic, wind, wave, EV, storage, etc. Two major and fundamental issues under high penetration scenarios, i.e., voltage stability and frequency stability, are addressed with the SSSM through a distributed and autonomous power management strategy similar to today's synchronous generators that power the entire grid.

The proposed SSSM concept is shown in Fig. 2 as a new SST/universal grid interface for all DER devices (generations, storages and loads). It should be considered as an IPM functionality. By utilizing all of these devices in a unified manner similar to a synchronous machine, the SSSM will result in several major innovations:

First, the variability of the DER could be smoothed effectively, resulting in a more stable power generation from DERs regardless of the fluctuations from the weather or day type.

Second, the virtual stabling rotational inertia is embedded into SSSM for frequency regulation. The phase locked loop (PLL) commonly used in grid-connected inverter, is not necessary. Instead, SSSM self-synchronizes its own frequency and power angle, which mimics the behavior of a conventional synchronous generator with a lower rate of change of frequency (RoCoF) and smaller frequency deviation, hence improving the power system frequency stability with high DER penetration.

Third, up and down reserve could be provided by the SSSM according to AC frequency and DC bus voltage information. Via the energy storage and proposed dual droop control, all DERs and loads connected to the SSSM could output any power within the power rating at different grid frequencies.

Fourth, as a power electronics grid interface, the SSSM integrates power electronics components and controls into a single universal platform, significantly simplifying DER integration and can support plug-and-play of DERs. All available DERs (including load) are controlled by the SSSM collectively with no extra investment needed.

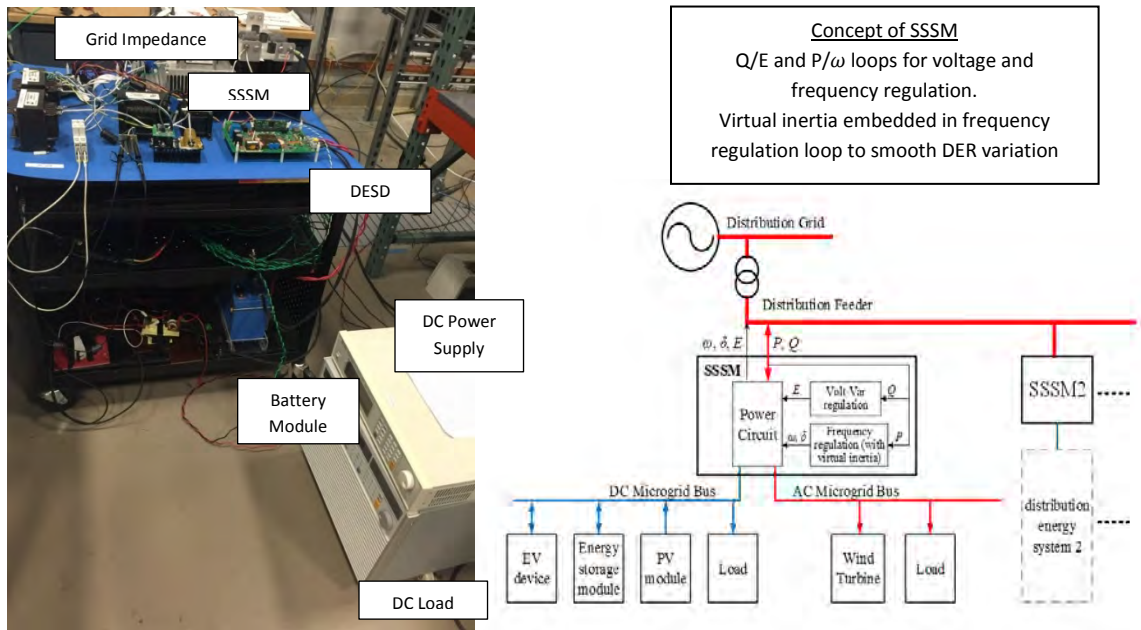


Figure 2: SSSM Concept and the SSSM testbed setup

In Year 8, the SSSM concept has been demonstrated by using the low voltage testbed discussed above (also shown in Fig.2). Figure 3 shows some of the significant testing results. SSSM work has been compiled and submitted to IEEE transaction for publications.

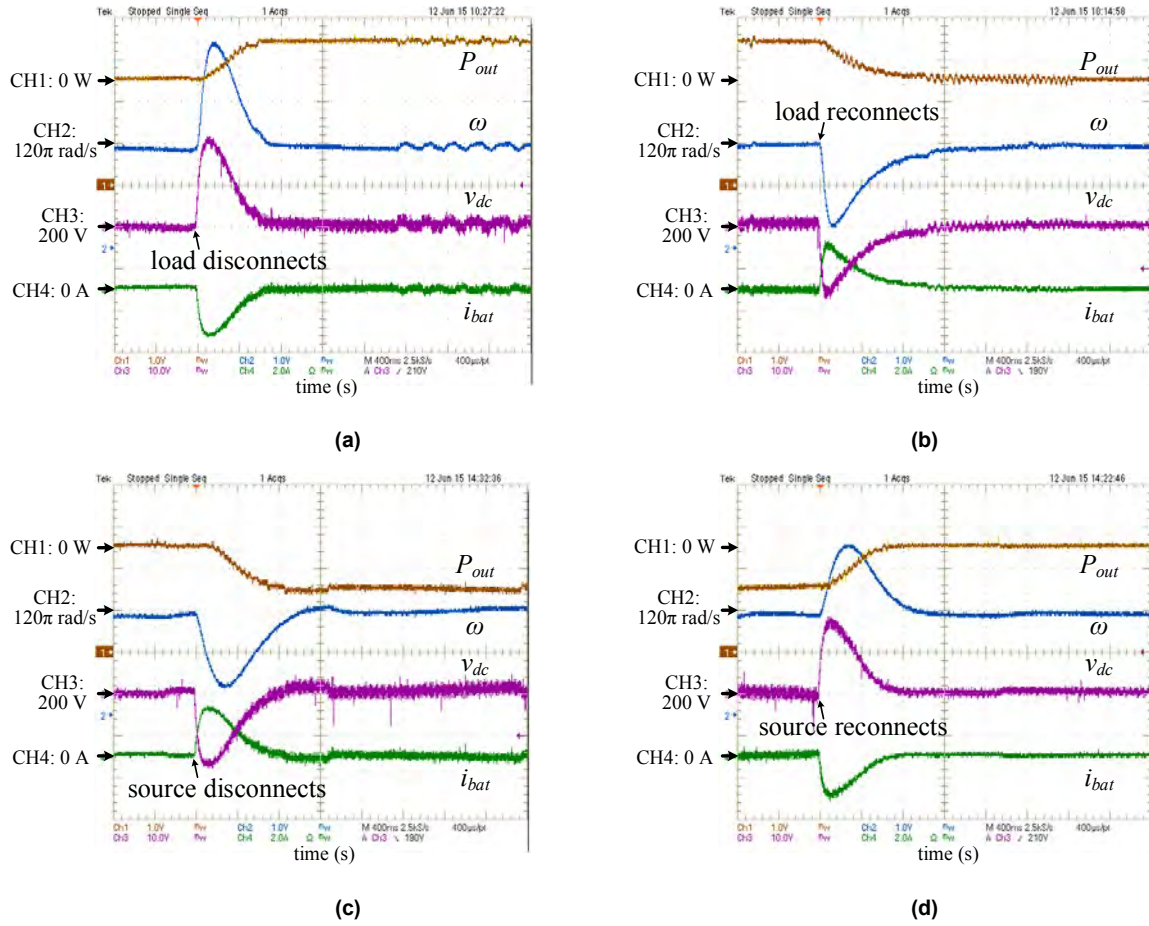


Figure 3: SSSM demonstration results. (a) and (b) shows the load change case while, (c) and (d) shows the DER generation change case. All cases demonstrate that the emulated rotating inertia slows down the power output change on the grid side, hence verified that improved frequency response, up reserve and down reserve supplied by SSSM.

Achievement 3: SST as an Energy Router: Frequency Based Real Time Pricing and Energy Dispatch

The long term goal of the FREEDM System is to support the **Energy Internet** in which energy cells can participate in the electricity market. To reach that goal, developing schemes to settle the energy transaction price is needed and our IEM research is moving towards energy dispatch optimization based on real time pricing rather than traditional Time-Of-Use (TOU) pricing scheme. One possible way of including real time pricing information is to use the *real time frequency* information which is an inherent capability of the SST Energy Router. The sampling rate of the frequency is very high and we can provide frequency information at 1s sampling rate. In Year 8, the SST Energy Router testbed has been set up and an advanced IEM algorithm is being developed to showcase the energy transactions between energy cells and grid based on real time pricing. Real-time power flow regulation (another SST Energy Router capability) is achieved using autonomous, distributed control that has already been demonstrated in the last few years. Currently, the IEM control is based on our work in Year 7, which optimized power flow (P_{grid}) according to the TOU prices determined by the utility and a solar and load forecast. The new algorithm improves the scheme by blending TOU prices with a real-time energy price. The basics of this proposed hybrid algorithm are shown in Fig. 4. In this scheme, the

SST measures the grid frequency, and then dispatches the Energy Cell to respond to the real-time frequency deviations, acting as an ancillary service. This capability promotes grid stability and frequency regulation in a future grid with high penetration of renewable generation and energy storage. Currently, utilities signal ancillary devices when their service is needed. This work proposes regulation in the form of an energy market. A real-time price is determined according to the measured frequency and the Energy Cell can optimize its response.

The hybrid algorithm shown will create a day-ahead schedule (according to TOU prices) and will update its response (Pgrid reference) in real-time, taking into account the actual solar generation, load, DESD State of Charge, and a frequency-based real-time price. This concept will be implemented as a Matlab code and demonstrated for one Energy Cell using the low voltage FREEDM testbed developed in this project. This work has also been accepted for publication at IEEE PES meeting in July 2016.

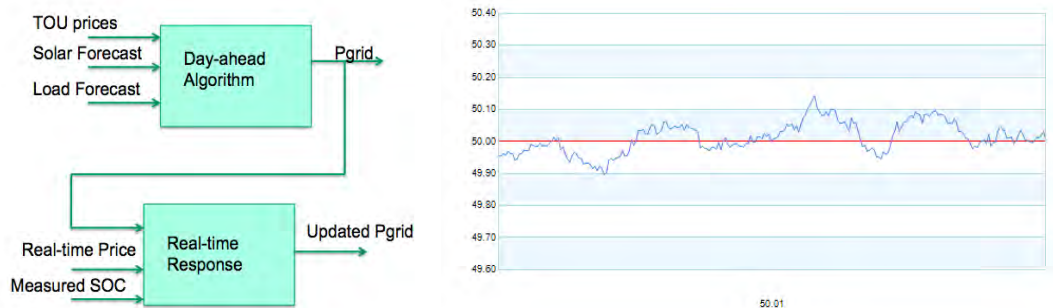


Fig. 4: Proposed Hybrid IEM Algorithm and Sample Grid Frequency Data

5. Other Relevant Work Being Conducted Within and Outside of the ERC

This project is part of a large GEH demonstration project.

6. Milestones and Deliverables

LV SST testbed will be finished which will provide at least two energy cell/SST demonstration capability with sufficient DESD.

7. Plans for Next Five Years

Gen-III SST will be integrated into GEH and additional IPM and IFM demonstration are expected. The LV testbed will be further matured to demonstrate IEM applications including Energy Internet concept demonstration: buying and selling energy from one energy cell to another energy cell.

8. Member Company Benefits

Testbed itself and testbed results are of great value to many of our member companies.

9. References

- [1] Hambridge, S.; Huang, A.Q.; Ruiyang Yu, "Solid State Transformer (SST) as an energy router: Economic dispatch based energy routing strategy," in Energy Conversion Congress and Exposition (ECCE), 2015 IEEE , vol., no., pp.2355-2360, 20-24 Sept. 2015.

[2] Rui Gao, Iqbal Husain, Alex. Q Huang, "An Autonomous Power Management Strategy Based on DC Bus Signaling for Solid-State Transformer Interfaced PMSG Wind Energy Conversion System", IEEE APEC 2016.

Y8.GEH1.3: DGI Integration into GEH Testbed

Team Members

Project Leader:	Dr. David Lubkeman
Faculty:	Salina Zabin
Students:	Pratheek Bramhasamudra Mallikarjuna

Project Goals:

FREEDM is developing a Distributed Grid Intelligence (DGI) software platform for hosting distribution management applications. These applications will be run in a distributed system that consists of multiple Solid-State Transformer (SST) and Fault Isolation Device (FID) nodes. The DGI operating platform has only been utilized in the GEH testbed on a limited basis for testing algorithms in past years.

This year's goal is to start integrating this platform into the GEH SSTs and enabling both power and energy management algorithms based on plug-and-play energy storage and distributed generation devices. More specifically these goals include:

- 1) Porting of DGI V2 into embedded system board for SST IEM applications.
- 2) Establish needed communication links:
 - a) Enterprise interface for DGI using DNP3.
 - b) FREEDM local device communications based on MQTT protocol.
 - c) Command and monitoring link to power electronics hardware components based on Modbus protocol.
- 3) Deploy DGI on multiple GEH low-voltage SSTs.
- 4) Develop basic monitoring and control capability based on DGI for GEH testbed SSTs.

1. Role in Support of Strategic Plan

The 1 MVA Green Energy Hub (GEH) physical testbed is a working model of a medium-voltage distribution system configured to demonstrate FREEDM System concepts. In previous years, the GEH was used as a power source for the individual FID and SST elemental components that form the FREEDM System. This year the individual parts are being connected together and operated as an energy management system to demonstrate technologies, hardware, and communications capabilities. The project continues to be critical for the Center in that it is the central physical demonstration platform that is being used to validate the FREEDM System concept.

2. Fundamental Research, Technological Barriers and Methodologies

The greatest challenge continues to be the integration of Center-developed equipment into a unified system supplied as a single source. Each item developed by the Center can be operated as a stand-alone piece of equipment or application software; but integrating these individual components is far from straightforward.

3. Achievements

The communications strategy supporting the GEH physical setup is illustrated in Figure 1. The communications between the energy cell devices (DESD, DRER, HEMS), SST DGI nodes and PI Server (for enterprise applications and viewing operation) was established in three steps in Year 7.

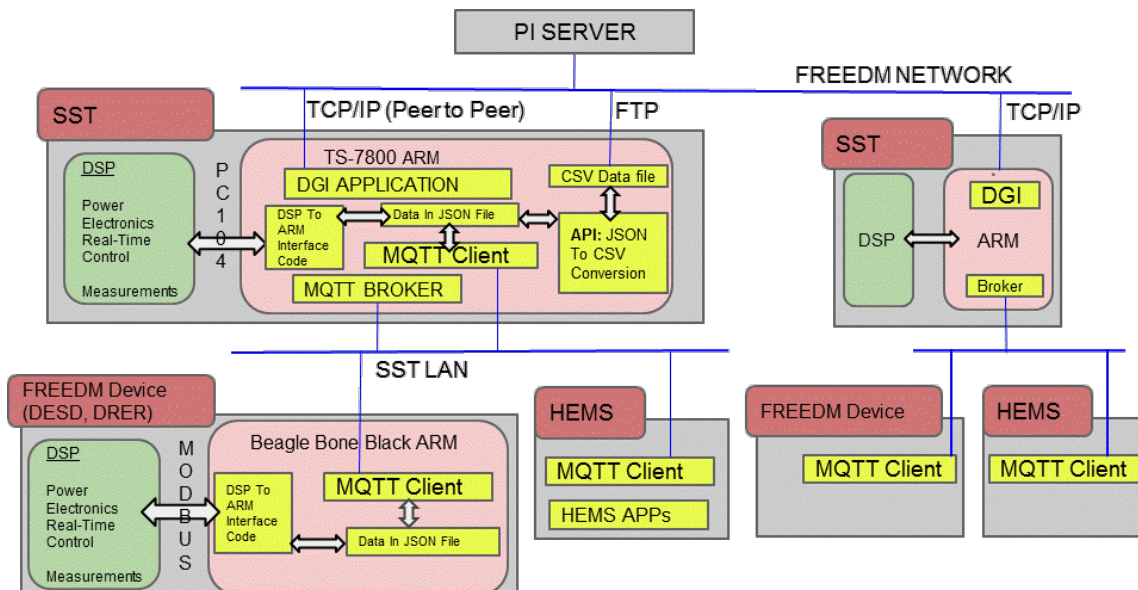


Figure 1: Year 7 GEH Data and Control Communications

First, the communication for data transfer between a FREEDM energy cell device and DGI node is established using MQTT (Message Queue Telemetry Transport) protocol. MQTT is a publish-subscribe lightweight messaging protocol developed for Internet of Things (IoT) applications. The SST DGI ARM board runs an MQTT broker which maintains the list of topics based on the device data points associated with each FREEDM SST. Every device in a single-SST cluster runs an MQTT client program that can publish/subscribe the needed data topics from the broker.

Each FREEDM device utilizes a DSP (digital signal processor) for control of the power electronics component, data acquisition and the execution of logic. Modbus protocol is used to transfer local data and commands between each FREEDM DSP end device and a FREEDM end device ARM board. The ARM board is used to support high-level applications and network communications. Each FREEDM device maintains its own device profile in an Excel-format file, which contains basic information describing the device, the device ratings and available data/command points. Then a JSON file which acts as a local device real-time database is generated from this Excel-format file using an interface program whose main purpose is to collect/send data/commands from/to the DSP using Modbus and write/read those information to/from the associated JSON file. If the FREEDM device is configured to publish any of its data set, then the associated MQTT client program communicates with the broker to broadcast these data to all other FREEDM devices which subscribe to the data.

The peer-to-peer communication between all DGI nodes utilized in the SSTs is established using TCP/IP protocol. A DGI MQTT broker also maintains all JSON files associated with all FREEDM devices or HEMSS connected to the associated SST. Data transfer from the DGI nodes to the PI

Server is supported by an application program that converts each JSON file to a CSV file and shares it with PI Server using FTP-based (WinSCP) file transfer.

The proposed Year 8 communications overview is shown in Figure 2. Last year MQTT based communication was a separate entity in each DGI node; in the current year, the MS&T team integrated the MQTT component within the DGI module. Therefore, when any application runs on the DGI platform, it will utilize data from inside the DGI code.

In regards to other improvements, an enterprise interface for DGI is being implemented. The main objective of this interface is to display and analyze the data in a SCADA system. Last year OSIsoft PI server was used to display data. An additional interface based on NI Labview is being planned as an alternative option. The NI labview has a module called datalogging and supervisory control (DSC) which extends graphical programming benefits to the development of the Supervisory Control and Data Acquisition (SCADA) or high channel count data logging application. Any Labview application is user friendly, and hence, would be a good choice in a testbed.

The main objective of GEH and DGI integration is to run the IPM or IEM applications in any SST node. Some of these applications will need the forecast data, while others may need the real time data; based on the requirement, a local database is needed to be established in each node. Since each SST will be run on an embedded system board, the database should be on that board as well. SQLite3 database is being utilized as the platform for supporting advanced IEM functionality installed in GEH embedded system applications.

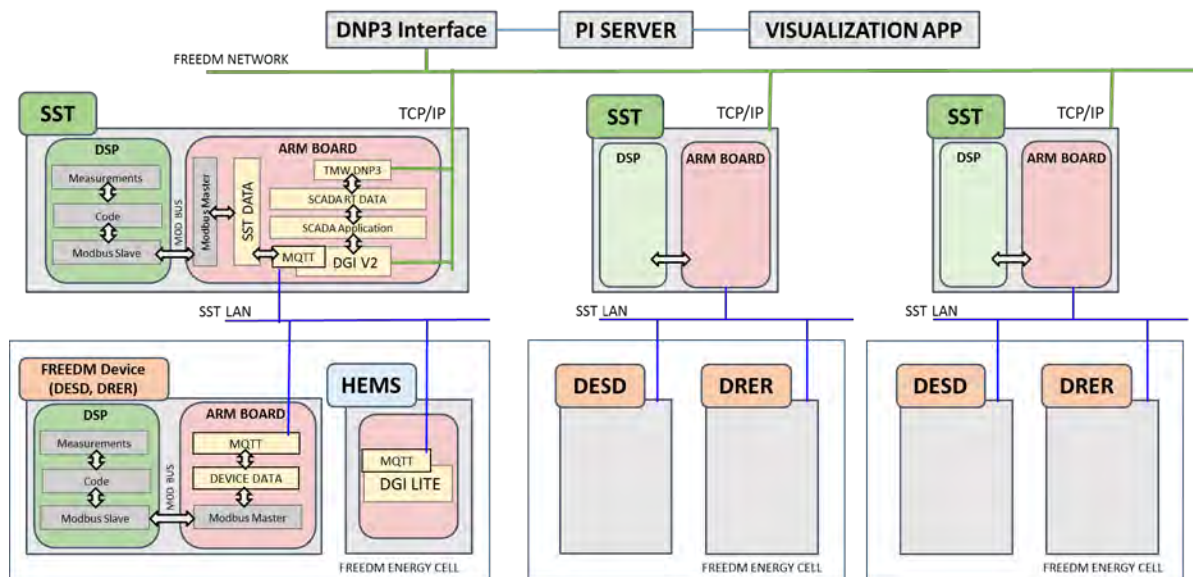


Figure 2: Year 8 GEH Data and Control Communications

4. Other Relevant Work Being Conducted Within and Outside of the ERC

Other associated projects within the ERC include:

- 1) Wind Turbine Distributed Renewable Energy Resources Integration – Husain, Gao (NCSU)
- 2) Multiple SSTs at MV with Islanding and Blackstart – Bhattacharya, De, Yan, Beddingfield (NCSU)
- 3) IEM, IPM and IFM Demonstration of the FREEDM System – Huang, Hambridge, Yu (NCSU)
- 4) Enhancement of GEH for Commercial HEM Projects – Lu, Yan (NCSU)

5. Milestones and Deliverables

Milestones:

- Q3 (9/2015) Unix and embedded-arm DGI implementation
- Q4 (12/2015) MQTT and Triangle Microworks Implementations
- Q1 (3/2016) Low-voltage SSTs enabled for DGI
- Q2 (4/2016) Test DGI with integrated MQTT protocol in Beagle Bone Black board
- Q2 (4/2016) Establish a local database to store real time and historical data
- Q2 (5/2016) Establish the communication between SCADA and the DGI
- Q2 (6/2016) Implementation of basic monitoring and control of LV SSTs based on DGI
- Q3 (8/2016) Set up a demonstration by integrating all the above steps together

Deliverables:

- Q2 (5/2016) Demonstration of the basic data handling and communications functionality designed for GEH testbed.
- Q3 (8/2016) Demonstration of DGI-MQTT implementation for a single node.

6. Plans for Next Five Years

- Single-SST demo of DGI supporting IPM and IEM for residential load.
- Multiple-SST demo of DGI supporting IPM and IEM for residential load.
- Compliance of MQTT interface with OpenFMB standard.
- Integration of DGI into FID device.
- Support for Intelligent Fault Management applications in GEH.

7. Member Company Benefits

FREEDM System Green Energy Hub DGI implementation will enable members to evaluate and test distributed algorithms for energy storage and renewable energy management.

8. References

- [1] <https://github.com/FREEDM-DGI>
- [2] <https://github.com/FREEDM-DGI/FREEDM/tree/MQTT>

Y8.GEH1.4: GEH Test Bed Enhancements for Commercial HEM Projects and GEH Industry

Team Members:

Project Leader:	David Lubkeman
Faculty:	Ning Lu
Students:	Jiahong Yan, Xiangqi Zhu, Jian Lu, Gonzague Henri, Lining Dong
Staff:	Hulgize Kassa

1. Project Goals

In this task, we will set up a GEH test bed for conducting commercial projects.

2. Role in Support of Strategic Plan

We envision that the application of the FREEDM system will have three transition stages. In stage 1, the FREEDM smart homes are supplied by regular distribution transformers via distributed grid intelligent. We will quantify cost and energy savings and the values for grid services such a system can provide, e.g., demand-side energy management, consume excess solar, and maintain power quality. In stage 2, regular transformers are replaced by solid state transformers (SST) to achieve better power management and routing capability to further improve the system efficiency, reliability, and power quality. In stage 3, the two kinds of FREEDM systems will spread out to the whole grid. Because the FREEDM system does not exist in field today, it is critically important that we can implement in hardware a 1-transformer/multi-smart home that can be used for conducting different tests and validate our control strategies and algorithms. This project will meet the following FREEDM goals: establish the system architecture relative to power system operation and establish the performance metrics and benchmark the performance of 1-node FREEDM system.

3. Fundamental Research, Technological Barriers and Methodologies

A flexible 1-node GEH test bed will represent the smallest building block of future FREEDM systems: a distribution transformer with 3 residential homes. The homes can be regular homes, smart homes controlled by home energy management systems, or a mixture of the two. The 1-node system can either be supplied by a solid state transformer (SST) or by a regular transformer. The users can control the 1-node test system via a graphical user interface. We will implement the sensors on devices and a communication platform for collecting the data and issuing commands. We will develop a transformer level energy management system to coordinate the operation of energy storage, solar PVs, electric vehicles, and controllable loads directly or through the home energy management system we have developed in Years 6 and 7. The results of the task can also be used for quantifying the performance, cost and benefit of a 1-node FREEDM system.

4. Achievements

- Built a 1- transformer (regular or SST) supplied FREEDM system.
- Built a graphical interface for transformer level energy management.
- Developed a common testing platform that is ready for conducting commercial projects.
- Developed the smart house as a thermal chamber for testing heating and cooling loads.
- Installed ECOBEE system for temperature and humidity control.
- Testing algorithms developed for time-of-use and peak energy pricing schemes.
- Published six conference papers [1-6], submitted 2 journal papers [7, 8] and graduated 1 master student.



Figure 1: A Matlab-based Graphical User Interface.

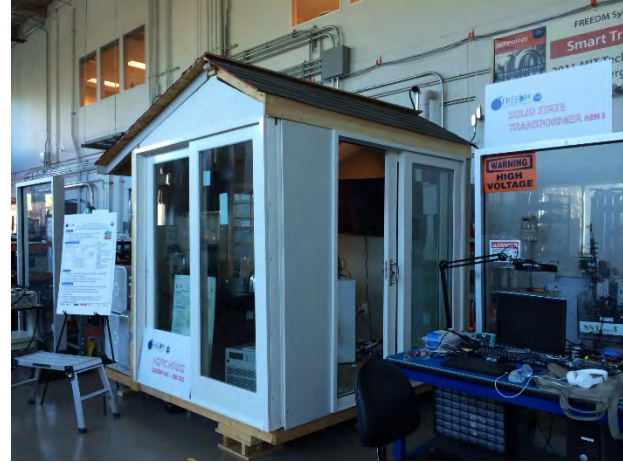


Figure 2: A hardware test bed that can serve as a thermal chamber.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

We are commercializing the algorithm developed with a company.

6. Milestones and Deliverables

- Built a hardware test system with single transformer (regular or SST) and up to 3 houses.
- Developed a common testing platform that is ready for conducting commercial projects.
- Developed the smart house as a thermal chamber for testing heating and cooling loads.
- Installed ECOBEE system for temperature and humidity sensing and control.

Deliverable – A fully functional 1-node FREEDM test platform.

7. Plans for Next Five Years

- a) Develop, test and deliver home and community energy management systems and commercialize them with our industry members.
- b) Standardize the testing platform and develop the hardware system into a state-of-the-art platform.

8. Member Company Benefits

We will provide the center and our industry members a combined software and hardware testing platform for innovation in the area of home and building energy management.

9. References

- [1] J. Yan, H. Zheng, N. Lu, "Temperature-Load Sensitivity Study for Adjusting MISO Day-ahead Load Forecast," accepted by Proc. of 2016 IEEE Power & Energy Society General Meeting, Boston, MA, 2016.
- [2] J. Lu, N. Lu, X. Wu, and J. He, "Short-term HVAC Load Forecasting Algorithms for Home Energy Management," accepted by Proc. of 2016 IEEE Power & Energy Society General Meeting, Boston, MA, 2016.

- [3] Xinda Ke, Anjie Jiang, and Ning Lu, "Load Profile Analysis and Short-term Building Load Forecast for a University Campus," under review on Proc. of 2016 IEEE Power & Energy Society General Meeting, Boston, MA, 2016.
- [4] Xiangqi Zhu, Jiahong Yan, Lining Dong, and Ning Lu, "A Matlab-Based Home Energy Management Algorithm Development Toolbox," accepted by Proc. of 2016 IEEE Power & Energy Society General Meeting, Boston, MA, 2016.
- [5] Xiangqi Zhu, Jiahong Yan, and Ning Lu, "A Probabilistic-based PV and Energy Storage Sizing Tool for Residential Loads," accepted by 2016 IEEE PES Transmission and Distribution Conference and Exposition, Dallas, TX, May, 2016.
- [6] Jiahong Yan, Xiangqi Zhu, and Ning Lu, "Smart Hybrid House Test Systems in a Solid-state Transformer Supplied Microgrid," *Proc. IEEE Power & Energy Society General Meeting*, Washington DC, July, 2015.
- [7] Xiangqi Zhu, Jiahong Yan, and Ning Lu, "Energy Storage Sizing Strategies for High Solar Penetration Residential Feeders," submitted to IEEE Trans. on Smart Grid, 2016.
- [8] Maziar Vanouni and Ning Lu, "A Resource Prioritization Based Framework for Participation of Thermostatically Controlled Loads in Regulation Services," submitted to IEEE Trans. on Smart Grid, 2016.

Y8.GEH1.5: Demonstration and Integration of Multiple LV-SSTs with Islanding and Black-Start in Green Energy Hub (GEH)

Team Members

Project Leader:	Subhashish Bhattacharya
Faculty:	Subhashish Bhattacharya, David Lubkeman
Students:	Yonghwan Cho (PhD), Richard Byron Beddingfield (PhD), Ankan De (PhD); Erin Fenton (ECE UG)

1. Project Goals

The overall objective of the Low-Voltage Solid State Transformer (LV-SST) testbed project is validation of three LV-SSTs tied to MV FREEDM lab GEH testbed with transformer, DRER (PV) and DESD (BESS – Battery ESS) to demonstrate DGI based IFM, IEM, and IPM functionalities and used cases, including islanding, and black start (Grid Forming) in an AC microgrid platform.

2. Role in Support of Strategic Plan

The GEH testbed is one of three primary testbeds along with the hardware-in-the-loop (HIL) and the Large Scale System Simulation (LSSS). The LV-SST testbed resides at the GEH testbed where a microgrid is formed with physical FREEDM components. The feasibility of the control algorithms for SST, DESD and DRER can be verified with the LV-SST testbed. The DGI based IFM, IEM, and IPM functionalities can also be developed and demonstrated in the testbed.

3. Fundamental Research, Technological Barriers and Methodologies

Research is focused basically on control strategies for the LV-SST testbed that guarantee reliable operation of LV-SSTs, DESDs, and DRERs. Moreover, control algorithms for the islanding and black start functionalities are being developed for seamless control mode changes with communication between LV-SST controller and DGIs. Technical challenges are to synchronize DSPs for the seamless black start operation and to operate IFM while the LV-SSTs are energized.

4. Achievements

4.1. LV-SST Testbed Construction

In Fig. 1, circuit diagram of the LV-SST testbed is shown. It consists of three LV-SSTs, two DESDs, and an IFM. Functionalities of SST such as bidirectional power flow, islanding, and black start can be developed and verified with the LV-SST testbed. The topology of the LV-SST has been changed to provide low cost, compact, and reliable testbed and to focus on control strategies for SST-based system. The high voltage grid side AC/DC stage (HV SST) consists of an LCL filter and an H-bridge. LCL filter is selected as an input filter to achieve black start functionality as well as to attenuate high frequency harmonics of the grid current. The topology of DC/DC stage is an isolated and bidirectional Dual Active Bridge (DAB) converter. For DESD, a simple bidirectional buck/boost converter is chosen. DRER can also be added to the low voltage DC bus by using this buck/boost converter. The final DC/AC stage is replaced with resistor load to simplify the testbed in this stage, and on developing the control strategies and the DGI based functionalities. The hardware structure of the LV-SST and the DESD is shown in Fig. 2. Three LV-SSTs are being built in the lab and they are integrated in a rack to form the microgrid as shown in Fig. 1.

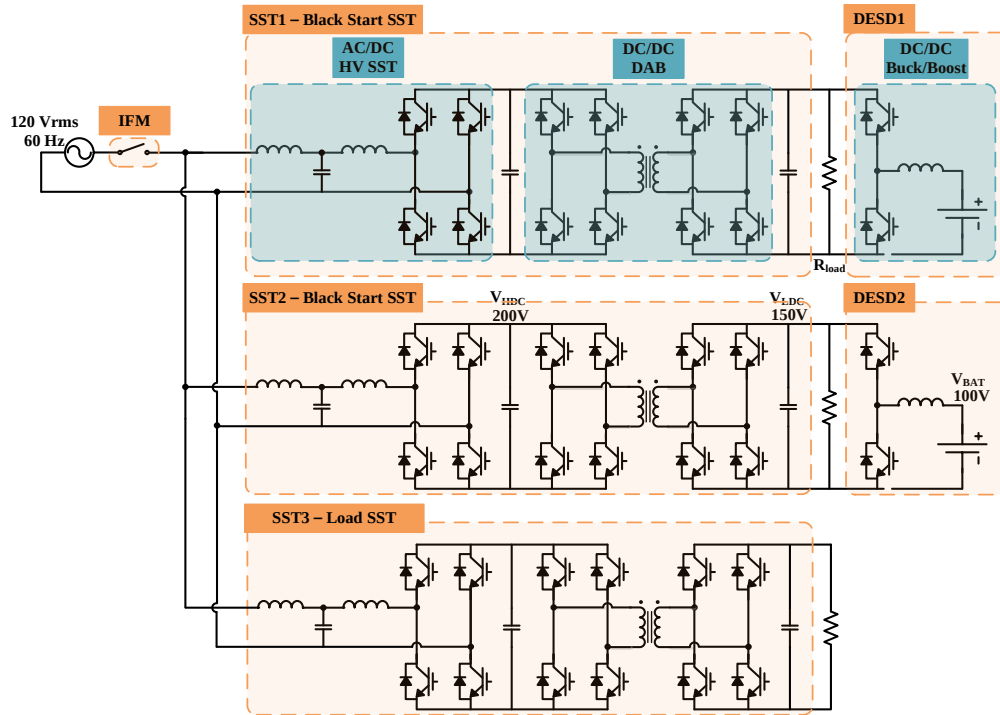


Fig. 1. Circuit Diagram of LVSST Testbed.

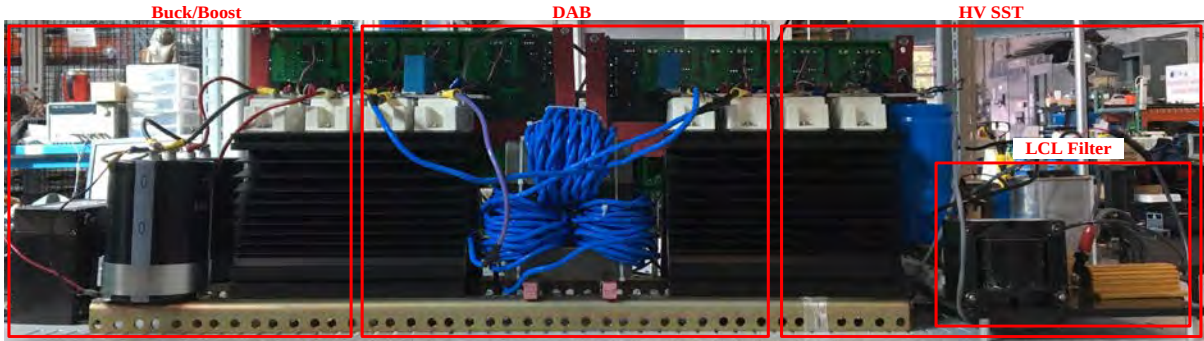


Fig. 2. Low-voltage scaled prototype of SST and DESD

4.2 Control Strategy Development

Control strategies for LV-SSTs and DESDs have been developed. In this year, LV-SSTs are differentiated as black start SST and load SST as depicted in Fig. 1. This enables seamless black start operation which means that the load SST can be provided power without any blanking time from the black start SST when the grid is disconnected due to power system fault. For the HV SST operation, the load SST uses typical grid current controller while droop method and capacitor voltage controller are applied for the black start SST. Controllers for bidirectional DAB converter and buck/boost converters have also been developed. The control strategies and the seamless black start operation are also verified by software simulations. Separate operations of the black start SST and the load SST is verified experimentally. The operation of the whole LV-SST testbed and functionalities of islanding and black start are being tested now.

Regarding control board configuration, one DSP controller board is assigned for each LV-SST and a DESD integrated at the low voltage side DC bus. Thus, totally three DSP controller boards are being

used for the LV-SST testbed. Each DSP controller board is equipped with Zigbee module to communicate with an ARM board where the DGI algorithms are implemented.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

DGI/RSC team is working on a new DGI platform. Communication protocol between ARM and DSP is being developed by an IEM team. Outcomes of those team can be integrated to LV-SST testbed so that it integrates all the components needed to form a LV-SST based microgrid.

6. Milestones and Deliverables

- GEH testbed operation with DGI control and operation of the LV-SSTs with DRERs and DESDs and demonstration of IEM used cases in the FREEDM lab.
- The islanding and black start operation of the LV-SST testbed.
- Demonstration of DGI functionality with ARM and DSP in the GEH testbed.

7. Plans for Next Five Years

- Construction of the LV-SST testbed and demonstration of bidirectional power flow.
- The validation of experimental test results from the GEH LV-SST testbed will be used to validate the SST models and control operations in the LSSS and HIL testbed.
- The developed GEH testbed will then become a platform for control performance and stability validation for the LSSS and HIL project team.
- The outcomes of this LV-SST testbed will be integrated in the GEH testbed and system demonstrations for industry.
- The success of this project will be to provide a SST enabled microgrid testbed to validate DGI enabled FREEDM architecture in the GEH testbed and also to provide a platform to quantify cost/benefit analysis for FREEDM system.
- Based on this GEH testbed experimental validation, inputs will be provided to FAWG in 2016-2018.

8. Member Company Benefits

The PI has been working closely with ABB, Eaton, Duke Energy, Enphase; which will continue during this project, and other industry members will also be asked to join.

9. References

- [1] T. Zhao, J. Zhang, S. Bhattacharya, M. E. Baran, and A. Q. Huang, "An Average Model of Solid State Transformer for Dynamic System," *Power & Energy Society General Meeting*, July 2009.
- [2] N. Parks, S. Dutta, V. Ramachandram, K. Hatua, S. Bhattacharya, "Black Start Control of a Solid State Transformer for Emergency Power Restoration," *IEEE Trans. on IEEE Energ. Conv. Cong. And Exp.*, 15-20 Sept. 2012, pp.188-195.
- [3] S. Dutta, V. Ramachandaran, and S. Bhattacharya, "Black Start Operation for the Solid State Transformer created micro-grid islanding with storage," *Proc. IEEE Energ. Conv. Cong. And Exp.*, 14-18 Sept. 2014, pp.3934-3941.
- [4] J. W. Feltes and C. Grande-Moran, "Black Start Studies for System Restoration," in *Proc. Power and Energy Soc. General Meeting - Conversion and Delivery Elect. Energy 21st Century*, Pittsburgh, PA, USA, Jul. 2008.

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- [6] Y. W. Li and C. N. Kao, "An Accurate Power Control Strategy for Power-Electronics-Interfaced Distributed Generation Units Operating in a Low-Voltage Multibus Microgrid," *IEEE Trans. on Power Electron.*, vol. 24, no. 12, pp. 2977-2988, Dec. 2009.

Y8.GEH2.1: Refinement of a Cost / Benefit Analysis for the FREEDM System

Team Members

Project Leader:	G. T. Heydt
Faculty:	G. T. Heydt, M. Baran, L. White
Students:	Abhishek Dinakar, Apurva Rahman

1. Project Goals

The project goals and objectives relate to electric power quality with regard to voltage regulation, power factor regulation, and the impact of frequency spectral components in FREEDM distribution systems. The objectives are:

- To evaluate the cost to benefit of maintaining voltage regulation in the FREEDM system under all loading and operating conditions including the impact on distribution and subtransmission system losses.
- To evaluate the cost to benefit of maintaining unity power factor in the FREEDM system under all loading and operating conditions.
- To evaluate the cost to benefit of energy storage in the FREEDM distribution system. The emphasis will be on battery energy storage in the 5 kWh residential site range.
- To accommodate various levels of storage energy and power ratings in the aforementioned multiobjective optimization.
- To examine the tradeoff between the use of fault interruption devices versus circuit breakers, and to examine the tradeoff of various circuit configurations for the FREEDM system.
- To interface with other cost / benefit calculations for the FREEDM system, and to provide timely results to be integrated into a full cost / benefit analysis.

2. Role in Support of Strategic Plan

Because cost is a key element in any engineering technology and design, the cost of the FREEDM system, as a new paradigm, is especially important. The role of this project and related elements of the larger cost / benefit analysis project is to identify the strengths and weaknesses of the FREEDM system design from a cost analysis point of view. The tradeoffs of certain advantages (e.g., reliability) are evaluated as well.

3. Fundamental Research, Technological Barriers and Methodologies

Most of cost / benefit analysis is relatively simple calculations of cost figures, value of equipment, monetary evaluations, evaluation of benefits of given technologies, and other calculation oriented procedures. In the sense of engineering research, this is not really fundamental research except to say that the assumptions made must agree with realities of the design and implementation. In this project there are some elements of fundamental research in the evaluation of cost / benefit sensitivity in terms of probabilistic formulations. This probabilistic formulation entails the calculation of such parameters as the expected payback period, the expected reduction of losses, the expected improvement of reliability and similar parameters in terms of basic equipment costs. The fundamental research is the formulation of these parameters as a multivariate probabilistic model in terms of 'input' assumptions such as the cost of solid state transformer components, the cost of both demand and energy in the future, and the failure rates of FREEDM system components. This is a classical calculation of the statistics of 'output' parameters in terms of 'input' parameters, or the calculation of the statistics of one multivariate vector in terms of another.

4. Achievements

The main achievements made in this project are:

- The preparation of a full scale study of the cost / benefit analysis of the FREEDM system in terms of a Masters thesis [1].
- The calculation of the tradeoff between the number of fault interruption devices (FIDs) versus the benefits attainable through the improvement of system reliability.
- An analysis of the role of energy storage in the FREEDM SST to alleviate requirements on the use of FIDs.
- Formulation of the costs and benefits in terms of a probabilistic model and the calculation of expected benefits, payback, reduction of losses, and similar parameters.

Tradeoff between alternative FREEDM feeder configurations

The cost of a FREEDM distribution system is primarily dependent on the cost of the fault interruption devices. The cost of an FID is predicted to be high and determination of the optimal number of FIDs becomes an important task for the cost to benefit analysis. This can be done by considering an individual topology and understanding the variation of cost and benefit with the fault interruption devices and predicting the optimal number from the result. This task was performed by using MATLAB software. The program calculates the percentage of net energy served by the feeder to the load, percentage of energy not served by the feeder by assuming a fault at the system, optimal value of fault interruption devices and plots of the variation of cost and benefits versus number of fault interruption devices for a particular cost of fault interruption devices, circuit breaker and benefit factor. Fig. 1 shows a representative result with assumptions [see 2, 3, 4] to obtain the model. The hourly load data was taken from the Electric Reliability Council of Texas (ERCOT) [5]. Reference [6] discusses some of the configurations used.

Alternative configurations were studied for the FREEDM feeder. The simple single circuit energized at both ends (a 'loop' circuit) is a base technology used in the FREEDM LSSS. Two other similar technologies were studied and these are basically parallel FREEDM primary conductors. The three configurations are shown in Fig. 2. The optimal number of FIDs in each configuration was studied and results are shown in Table 1. In Table 1, B_o is the annual benefit in dollars obtained by avoiding unserved energy in the FREEDM system, and C_f is the annualized cost of the FIDs.

Table 1 Expression for optimal value of FIDs (denoted as N_x)

Topology	Optimal number of FIDs, N_x
Topology 1 Loop circuit – one distribution primary energized at both ends	$N_x = \frac{B_o}{C_f} - 1$
Topology 2 Two parallel distribution primaries energized at both ends	$N_x = \frac{0.5B_o - 2C_f + \sqrt{4C_f^2 + 0.25B_o^2}}{2C_f}$
Topology 3 Three distribution primaries energized at both ends	$N_x = \frac{0.25B_o - 4C_f + \sqrt{16C_f^2 + 0.0625B_o^2 + C_fB_o}}{2C_f}$

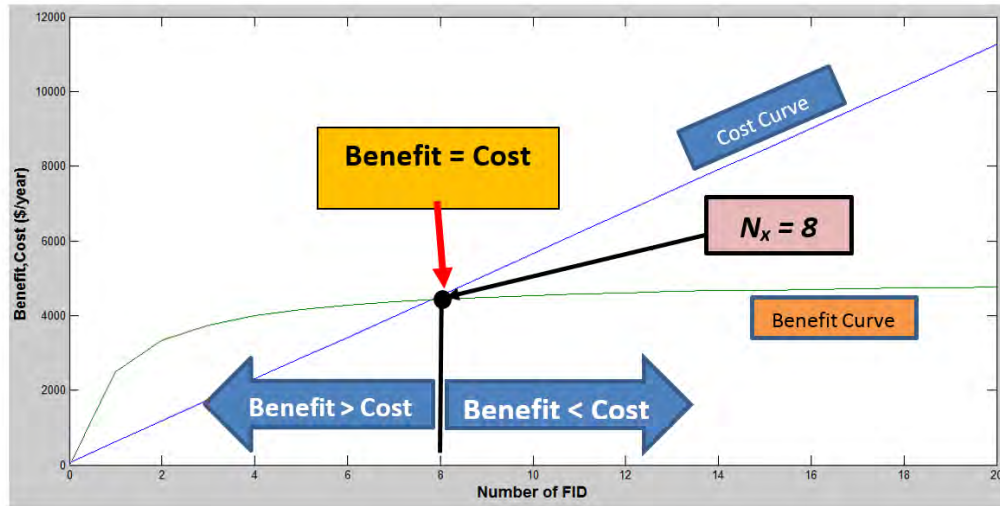


Fig. 1: The cost / benefit characteristics of a 1000 kVA distribution feeder with distributed 25 kVA SSTs. The number of FIDs are varied and benefits of the use of a loop circuit (the LSSS configuration) to obtain high reliability are modeled. The optimal number of FIDs is denoted as N_x in the figure.

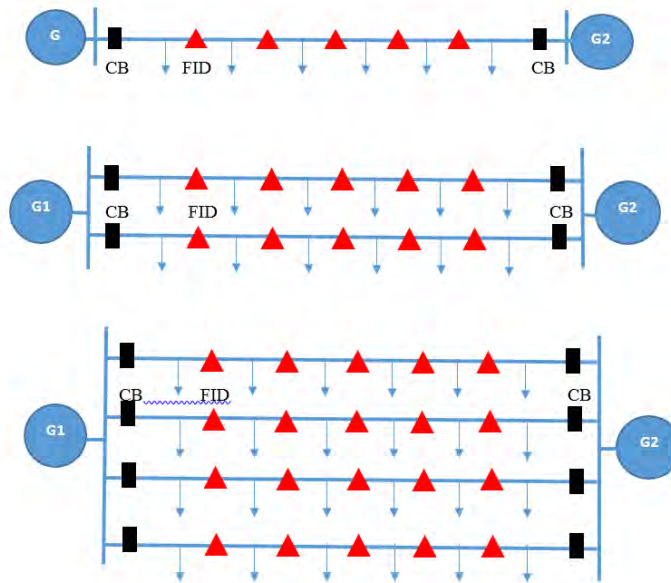


Fig. 2 Three different FREEDM topologies: configuration 1 is at the top (simple looped circuit); and configurations 2 and 3 are below with additional parallel feeders.

Loop versus radial configurations

The configurations discussed above are looped. This configuration gives high reliability as compared to a radial circuit. A simple radial distribution feeder can be refitted with connections between the feeders in order to reconfigure the circuits during fault conditions. This reconfiguration results in a circuit that is equivalent to topologies 2 and 3 described above and shown in Fig. 2.

Reformulation of the cost – benefit analysis as a probabilistic problem

As indicated above, the actual cost / benefit analysis is complicated by the fact that costs and benefits are not calculable exactly. There is a range for each of the elements of the FREEDM equipment costs, and the sum of those costs may be denoted as C . The parameter C is a random variable whose range is estimable. Using estimated costs in related technologies (e.g., machine drive manufacture, static var compensators), it is possible to estimate the statistics of C . As a quick example, the probability density of C may be taken as $f_C(C)$ and an example of $f_C(C)$ is a triangular density with a lower range C_{low} and an upper range C_{high} . The benefits of the FREEDM system are multivariate and similarly summed to form a single random variable B which is the annual dollar benefit. The probability density of B is $f_B(B)$. The number of years for payback is N ,

$$N = \frac{C}{B} - 1$$

$$N = g(C, B).$$

Then the probabilistic formulation is the calculation of the probability density $F_N(N)$ in terms of $F_{CB}(C,B)$ and B and C . This is the problem of one function of two random variables.

The probabilistic calculation as indicated is underway using two methods: Monte Carlo simulation, and calculation of the probability density of one random variable using a system theoretic formulation of function of two random variables. Example results are shown in Fig. 3 and Table 2. The system theoretic method entails adding a new function, $h(C, B)$ to the foregoing and then formulating a bivariate vector as follows,

$$N = g(C, B)$$

$$M = h(C, B) = C.$$

Then the bivariate probability density of vector $[N, M]^T$ is found from,

$$\begin{bmatrix} N \\ M \end{bmatrix} = [\det(J(C, B))]^{-1} f_{CB}(C, B)$$

Where J is the jacobian of the transformation,

$$J = \begin{bmatrix} \frac{\partial g}{\partial C} & \frac{\partial g}{\partial B} \\ \frac{\partial h}{\partial C} & \frac{\partial h}{\partial B} \end{bmatrix}.$$

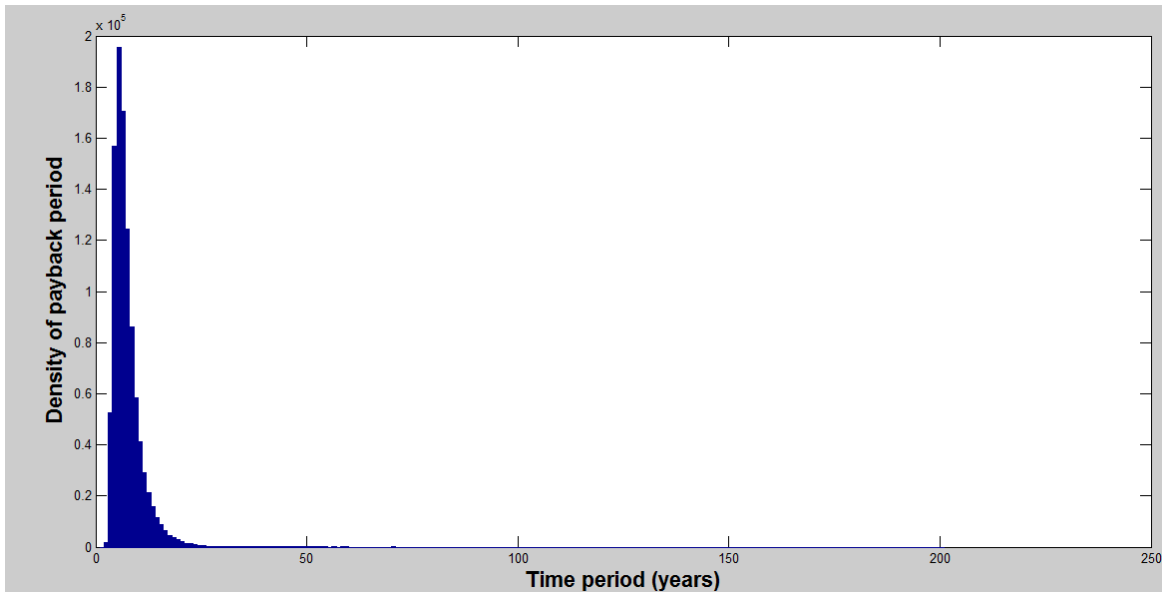


Fig. 3 The probability density of payback period for FREEDM topology 3: a representative study result

Topology	Mean	Standard deviation
1	20.5 years	16.2 years
2	10.5 years	7.2 years
3	7.35 years	3.27 years

Table 2 Simulation results: payback period statistics for a given set of assumptions for the FREEDM system

5. Other Relevant Work Being Conducted Within and Outside of the ERC

This cost to benefit analysis is related to most of the other FREEDM tasks because those tasks are specifying the FREEDM components, and the cost of the FREEDM components is determined by these specifications. Also, the benefits accrue from the capabilities of the FREEDM components, and this nexus is modeled in this project.

6. Milestones and Deliverables

The project milestones are:

Q3/2015 – Report alternative FID configurations

Q4/2015 – Report alternative SST sizing studies

Q1/2016 – Completion of tasks on integrating results into the cost / benefit analysis

Q2/2016 – A final report in the form of a MSEE thesis on all results of the analysis.

At the time of writing, these milestones are on schedule.

The project deliverables are:

- Deliverable for SV (04/2016): A report summarizing all results, for the 2016 NSF SV.

- Final Deliverable (08/2016): A final report in the form of a MSEE thesis on all results of the analysis.

7. Plans for Next Five Years

The immediate plans for the project are to complete the milestones and deliverables as indicated. It is planned to enhance the project results and research quality by expanding the concept of a probabilistic cost – benefit analysis. As the project progresses, it is expected that the granularity of the modeling shall improve and capture all of the salient costs and benefits of FREEDM.

8. Member Company Benefits

A favorable cost / benefit ratio is central to the success of the FREEDM project. This cost / benefit analysis should accurately capture the numerous benefits afforded by FREEDM including certain elements that are difficult to evaluate such as the enhancement of renewable generation use, reduction of CO₂, and other factors.

9. References

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Y8.GEH.2.2: Detailed FREEDM System Cost Benefit Analysis under Different Deployment Scenarios

Team Members

Project Leader:	M. Baran
Faculty:	M. Baran, David Lubkeman
Students:	Shashwat Singh, Fanjing Guo

1. Project Goals

We propose to address the main issues raised by the NSF Site Visit Team regarding the cost-benefit analysis:

- a. A more detailed cost-benefit analysis.
- b. Investigation of partial deployment scenarios for the early adopters.
- c. Investigating different energy storage adoption scenarios.

2. Role in Support of Strategic Plan

This Task is part of a cost-benefit analysis project, which is a cross-cutting activity. The project is undertaken by three main groups: engineering analysis group which focuses on the system analysis to determine system benefits, economic analysis group which aims to monetize the benefits and thus make an economics assessment of the system, and the market analysis group which identifies the likely adopters of the technology and market potential for the proposed technology.

3. Fundamental Research, Technological Barriers and Methodologies

The main challenges associated with this project are estimation of costs for the new FREEDM components, and economic evaluation of benefits. To address these challenges, we plan to (i) solicit help from industry members by establishing a working group, (ii) work with the diverse project team collaboratively on the various components of the project.

4. Achievements

This is the second year of this project, and this year the work has focused on the two main sub-tasks that have been identified based on the feedback from NSF SVT. These tasks build on the main accomplishments made during the first year. Since we have a large team on this project, in this task we focused on the benefits part of the analysis and considered also the FREEDM partial deployment scenarios. Main accomplishments made this year include the following:

4.1 FREEDM System Features-Benefits

The first step in the cost-benefit analysis involves identifying the new functions/features the FREEDM system offers over the base system. Based on the feedback obtained from Scientific Advisory Board members, the feature-benefit matrix developed last year has been revised. The revised matrix is given in Table I and shows the FREEDM system not only offers a comprehensive set of functions that facilitate high penetration of DERs, it also offers other sets of smart grid features including high reliability, advanced real-time monitoring and control which enables customer participation, and others listed in the table.

There is also one main addition on the benefits side that has been identified this year. This is related to the benefits of accommodating DERs by mitigating the variability effect of PV systems.

As current experience in California and Europe indicates, variability of DER impacts utility scale generation plants even at moderately low DER penetration levels [1-4]. Finally, it was recognized that accommodating DER provides benefits to other users as well, such as the owner of the DER, and thus all the main beneficiaries has also been considered: utility, customer, or environmental.

4.2 FREEDM System Deployment Scenarios

In the first year of the project, the scenario considered was the deployment of FREEDM system on a new feeder with 80% PV penetration, i.e., peak power from PVs is 80% of the peak load. We refer to this case as high penetration scenario. This year the focus has been on different deployment scenarios, especially for the early adoption cases. Three different deployment scenarios have been considered:

Case 1: Full FREEDM deployment for systems with High PV penetration

This is the same case as considered last year, but this year a more detailed analysis has been done to further identify the benefits for this case.

	Benefit	Type			
FREEDM System Features/Functions		Economics	Reliability & PQ	Society	Security
Accommodate High Penetration - Effective Volt/Var Control - Plug & Play - ES + DGI	- Reduced peak demand and energy demand - Mitigate voltage issues - Reduce power loss - Simplify DER integration - Mitigate variability of power	•		•	•
High Reliability & PQ - Looped Primary - Fault Locating, Isolation, Service Restoration - Fast Protection with FID - Regulated Service voltage	- Very high reliability - Minimize fault impact on system - Very high PQ		•		
Real Time Mon & Control - Enhanced DEMS - CVR	- Reduced O&M - Optimal capacity use - Load management: peak demand and energy reduction	•			
Resiliency - Microgrid at Node, Feeder Section, Whole Feeder	- High resiliency		•	•	
Customer Participation - DGI- Price Signals DLMP	- Customer DSM - Peak Dem. reduction - Economic efficiency	•			
Motivate New Business - Enhanced DEMS	- Transactive Energy	•	•	•	

Table I: FREEDM Features-Benefits Matrix

Case 2: Partial FREEDM deployment for systems with moderate PV penetration

Case 3: Partial FREEDM deployment for systems with commercial PV

In partial deployment scenarios, as it will be done in practice, a system study is first done on the system to determine: (i) if the impact of DERs on the system is severe enough to warrant some system upgrade, (ii) where to deploy SSTs that can provide the desired mitigation. Also, our studies on the prototype system confirms that at low DER penetration levels DER impacts on the

system are usually not severe enough to warrant system upgrades. Results based on the simulations performed on the prototype LSSS test system are summarized below.

5. Quantifying the Benefits of FREEDM System Deployment

Benefits of each of the FREEDM deployment scenarios considered above are quantified with respect to the base case. The base case corresponds to the system before any mitigation measure is implemented. Hence, for each case, it corresponds to the conventional system with different DER penetration considered for that case.

The system considered in this task is the LSSS test system, which is based on the IEEE 34 node feeder and represents a long residential feeder. Real feeder load and PV profile with a 15 min resolution is used for the study. Four weeks representative of each season were selected to study the impacts of PV penetration on the system. For FREEDM deployment, one of the voltage regulators (at node 852) and all three capacitor banks were removed, as FREEDM provides effective Volt/Var control through SSTs. For each case, time-series based power flow simulations have been conducted for each week selected, for both the base system and the FREEDM deployed for the case.

As listed in Table I, the main benefits quantified through simulations are the following:

- **Voltage Violation:** Utilities are required to maintain voltages at the customer supply point – secondary voltage- within certain limits, usually $\pm 5\%$ of the rated voltage. For residential feeders, the rated voltage is 120 V. Since, DERs inject power into the system, they affect conventional Volt-Var schemes and may cause over/under voltages. Hence, when such conditions occur, some mitigation is needed. To quantify how severe the voltage violation is on a feeder, we adopted a voltage violation index which measures the total number of voltage violation events seen on the feeder.
- **Peak Demand and Energy Reduction:** DERs on a feeder reduce the total demand and energy on the system. Hence, these quantities are directly measured and quantified.
- **Power and Energy Loss Reduction:** The advanced Volt/VAR scheme of the FREEDM System also reduces energy losses. Hence, these benefits are quantified using simulation results.
- **System Reliability:** FREEDM system is designed to offer high reliability. To quantify this benefit, the reliability indices used in practice has been adopted, SAIFI and SAIDI, and simulations have been performed to estimate these values.
- **Power Quality:** DERs may degrade power quality by introducing more voltage variation at the service nodes and worsen the voltage unbalance. Indices have been adopted to quantify these quantities. In this report, they are not included, as we could not find good data on the cost associated with these PQ improvements.
- **DER Variability:** As indicated above, intermittency of DERs – the PV systems in our case- impacts the utility generation. The main impact is on the high ramp rates imposed by variability of DERs. Energy storage is an effective mitigation option [5]. Hence, in this study this option is considered. Simulations have been done to determine the amount of energy storage needed to limit the ramp rates. An index has been adopted to quantify the amount of reduction in ramp rates a storage option provides.

Another main benefit considered in this task is the Customer Participation. Since the FREEDM system enables the utility to send real-time prices to the customers, customers can adopt emerging demand side management (DSM) options, especially by adopting DSM methods that integrate HEMS, DER and energy storage. Dr. Ning Lu has done extensive research in this area, and we have adopted the results from her research to: (i) identify the energy storage level a customer may adopt,

(ii) estimate the total peak demand and energy reductions a customer with DER and storage may achieve. This study is ongoing and done in parallel to the system studies undertaken in this task.

Results obtained from the simulations for the three cases are summarized below.

Case 1: Full FREEDM deployment for systems with High PV penetration

In this case, a high PV penetration on the prototype system is simulated by assuming that each load node has PV with peak power output which is 80% of the peak demand at the node. Hence, this case corresponds to 80% PV penetration. Since actual load and PV profile is not known, it was assumed that, all the loads and PVs are conforming, i.e., they all have the same profile. From the four weeks simulations, the benefits have been obtained for both the base case and for the FREEDM system. In this case FREEDM system is full deployment – i.e. all the loads are served through SSTs, and feeders are looped using FIDs as the main interruption devices. The main benefits quantified are the following:

- **Voltage Violation:** There were no voltage violations on the base system for this case. FREEDM system also did not have any voltage violation. This is mainly due to the fact that when PVs are distributed evenly across the feeder, the impact on the feeder voltage profile is mostly positive.
- **Peak Demand and Energy Reduction:** PVs on the system reduces the 15 minute peak demand and total energy demand on the base system by 7.3% and 30.37%, respectively. The same reductions will occur on the FREEDM system when no storage is used.
- **Power and Energy Loss:** A default Volt/VAR scheme is adopted in the simulations for the FREEDM system and this resulted in reduction of power loss on the primary circuit of the feeder. The average kW loss was 6.06% and 3.4% of the load for the base case and the FREEDM system, respectively. This power loss resulted in total energy saving of 186.69 MWh with FREEDM over the base case.
- **System Reliability:** Simulations on both the base case and the FREEDM system have been repeated this year to assess the reliability improvement FREEDM system offers [6]. Guidelines obtained from Duke Energy on number of customers served from a transformer has been used for the customer data. The results are given in Figure 1.

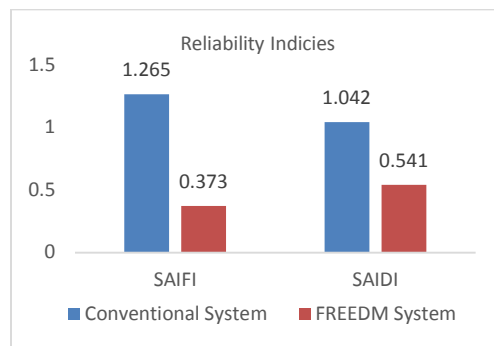


Figure 1: Reliability improvement with FREEDM system

- **Variability of Power from DERs:** To assess how the variability of power changes with PV integration, ramp rates for the total power measured at the substation end have been monitored. Figure 2.a compares the ramp rates before and after PV integration on the LSSS system. As the figure shows ramp rates increase considerably. In the FREEDM system, to reduce the ramp rates, an energy storage system at the substation has been considered. Simulations have been done to determine the storage capacity needed to bring the ramp rates to that of the original

system levels, i.e. before the PVs are integrated. Figure 2.b shows new ramp rates obtained with a storage of 600V, 780A, 1800Ah.

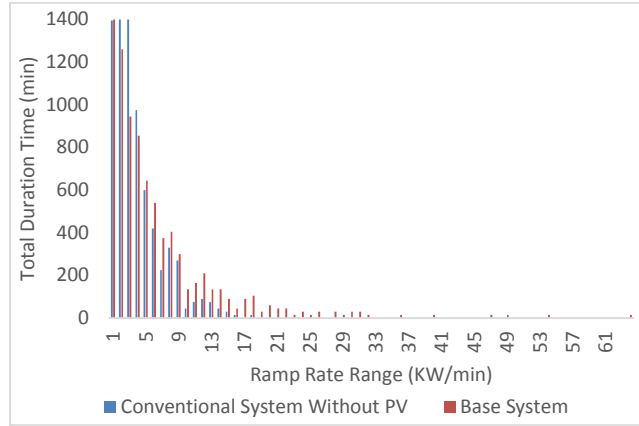


Figure 2a: Impact of PV on Ramp Rates

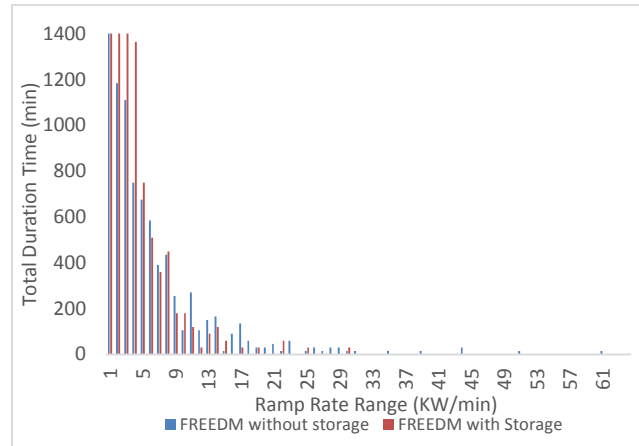


Figure 2b: Improving Ramp Rates with Storage

Case 2: Partial FREEDM deployment for systems with moderate PV penetration

In this case moderate level PV penetration on the prototype system is simulated by assuming that about 50% loads has PV with peak power output being equal to the peak demand at the node. To simulate a worst case in terms of impact of PVs on the system, all the PVs are assumed to be located towards the end of the feeder (nodes 860, 840, 844, 848, 830, 890, 806, 810, 822, 836, 846). This case yielded the following results:

- **Voltage Violation:** In this case, PVs cause voltage violation on the base system. Figure 3 shows the frequency of voltage violations observed at the feeder nodes. The annual voltage violation index for the system in this case is 997.75 (which corresponds to 3991 incidences of voltage violations lasted 15 minute annually). As shown in the figure, FREEDM mitigates these voltage violations even at the primary level. Note that voltages are regulated at secondary side of an SST, hence no voltage violations occur on nodes which have SST.

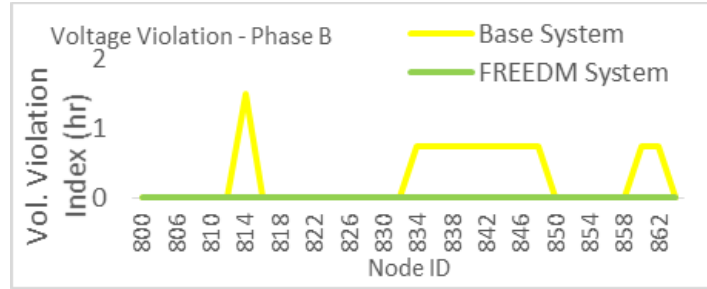


Figure 3: Voltage Violations in Case 2

- **Peak Demand and Energy Reduction:** PVs on the system reduces the 15 minute peak demand and total energy demand on the base system by 2.1% and 33.98%, respectively. The same reductions will occur on the FREEDM system if no storage is used.
- **Power and Energy Loss:** In partial deployment, the simulations show that using available SSTs will be enough for Volt/Var control on the FREEDM system to mitigate the voltage violations. This scheme helped reduce the average KW power loss on the FREEDM system to 3.3%, and the energy loss by 192.45MWh as compared to the base case.
- **System Reliability:** In this case, it is also assumed that FREEDM system does not have the full DGI to facilitate better fault management on the system than that of the base case. Hence, in this case FREEDM system does not necessarily improve the reliability of the system.
- **Variability of Power from DERs:** Ramp rates increase considerably in this case too and they are similar to that of the high penetration case. An energy storage option is again considered for the FREEDM system to reduce the ramp rates, like in previous case. Simulations indicate that a storage of 580 A, 1380 Ah is needed to bring the ramp rates to the levels before the PV system is introduced.

Case 3: Partial FREEDM deployment for systems with commercial PV

In this case a commercial scale PV system is assumed to be integrated into the system towards the end of the feeder (at node 840) with a capacity equal to the 80% of the peak load. As expected this case causes severe voltage violations as shown in Fig. 4. To mitigate this, again partial FREEDM deployment is considered, and only a few transformers at the nodes where big loads are served are replaced with SSTs to mitigate the voltage violations. This case yielded the following results:

- **Voltage Violation:** In this case, the commercial PV causes severe voltage violation on the base system. Figure 4.a shows the frequency of voltage violations observed at the feeder nodes. The annual voltage violation index for the system in this case is 13533 (which corresponds to 54,132 incidences of voltage violations lasted 15 minute annually). As shown in the figure (for 4 weeks), FREEDM mitigates these voltage violations. Note that these values are on the primary side and there will be no violations on the secondary side as it is regulated in FREEDM system.

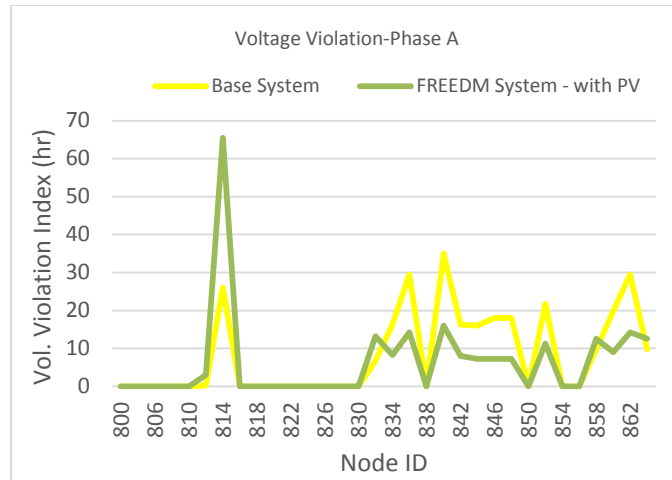


Figure 4a: Voltage Violations Case 3

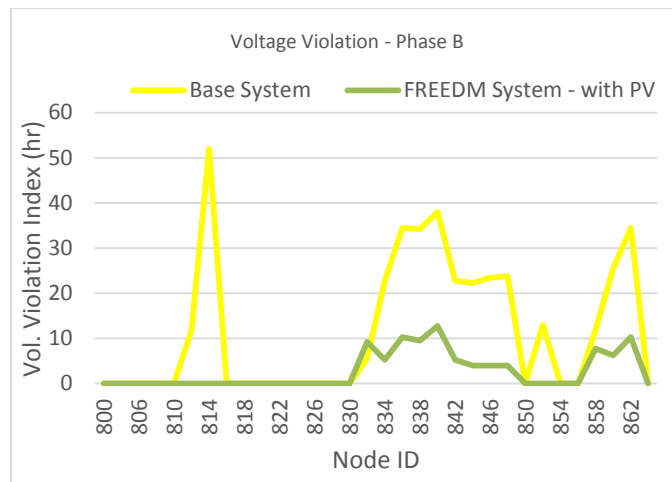


Figure 4b: Reducing Voltage violations with FREEDM

- **Peak Demand and Energy Reduction:** PVs on the system reduces the 15 minute peak demand and total energy demand on the base system by 2.5% (56.3 kW), and 38.4%, respectively. The same reductions will occur on the FREEDM system if no storage is used.
- **Power and Energy Loss:** In this case, the SSTs used resulted also reduction on the power and energy loss on the system: average KW power loss is almost same around 6.6% and the energy loss is increased by 83.2 MWh as compared to the base case.
- **System Reliability:** In partial deployment, it is assumed that FREEDM system has only SSTs, and thus does not have the full DGI to facilitate better fault management on the system than that of the base case. Hence, in this case FREEDM system does not necessarily improve the reliability of the system.
- **Variability of Power from DERs:** Figure 5, compares the ramp rates for this case before and after PV integration on the system. As the figure shows ramp rates increase considerably in this case. An energy storage option is again considered for the FREEDM system to reduce the ramp rates, like in previous case. Simulations are being conducted to determine the storage capacity needed to bring the ramp rates to that of the original system levels. The battery system needed is 600V, 870A, 2000 Ah.

6. Other Relevant Work Being Conducted Within and Outside of the ERC

Quantifying the benefits of DERs and storage is currently an active research area.

7. Milestones and Deliverables

A final report.

8. Plans for Next Five Years

Efforts will focus on quantifying the value storage brings to FREEDM system.

9. Member Company Benefits

Cost benefit analysis provides valuable feedback to Industry Members about the economic feasibility of the FREEDM system and its components.

10. References

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Y8.GEH2.3: FREEDM Cost Benefit Analysis based on Detailed Utility Circuit Models

Team Members

Project Leader:	Dr. David Lubkeman
Faculty:	Dr. David Lubkeman, Dr. Mesut Baran
Students:	Daixi Li, Lisha Sun, Ayesha Bari

1. Project Goals

The project goal is the establishment of testbed models for cost benefit analysis of FREEDM application scenarios. The testbed models are based on real distribution circuits provided by an electric utility. Modeling will be performed in OpenDSS and used to provide technical cost and benefit input into a comprehensive cost/benefit spreadsheet developed in a parallel project.

2. Role in Support of Strategic Plan

The project is critical for the Center since the cost benefit analysis will be used to direct future FREEDM effort with respect to device specifications and applications development.

3. Fundamental Research, Technological Barriers and Methodologies

The challenge lies in running the complicated detailed circuits that contains hundreds of nodes and modeling the Solid State Transformer for economic analysis in OpenDSS. Once the circuit is ready, different scenarios need to be set up for both steady state and time series analysis.

The approach addresses the challenges by developing the model in stages, testing and verifying each phase with the overall goal of minimizing re-design or re-work in later phases. To make sure our analysis is based on reasonable assumptions, we are seeking inputs from different domain experts and industry.

4. Achievements (*Including Previous Years, but with an Emphasis on the Current Year*)

4.1 Acquisition of test circuits from electric utility:

Detailed feeder models for three 12.47 kV circuits have been obtained from an electric utility. These circuits have voltage levels that correspond to the Green Energy Hub high voltage supply.

4.2 Selection of Cost and Benefit Metrics:

Cost and benefit metrics that will be tracked in the analysis has been determined. This a mix involving peak demand and energy reduction, voltage power quality, circuit efficiency, customer reliability and greenhouse gas emission with costs and benefits tracked by utility, customer and society categories.

4.3 Circuit Characterization:

The three test circuits were characterized with a summary of the results shown in Table 1.

Circuit Name	Circuit A	Circuit B	Circuit C
System Voltage	12.47 kV	12.47 kV	12.47 kV
Feeder Length (Backbone)	3 miles	4.3 miles	3.8 miles
Source kW	6200	5000	4800
Efficiency	99%	99%	98%
Number of Voltage Regulators	0	0	2
Number of Capacitors	4	4	4
Number of Transformers (Total)	309	297	456
Number of Dist. Transformers	309	269	444
- Less than 25 kVA	139	159	293
- Between 25 kVA and 50 kVA	139	55	114
- Between 25 kVA and 50 kVA	19	45	27
- Larger than 100 kVA	12	38	22
Number of Customers	1240	1511	1448

Table 1: Characteristics of Three Utility Test Circuits

4.4 CYME to OpenDSS conversion:

OpenDSS is an open source script driven electric power Distribution System Simulator (DSS) [1]. It's a comprehensive electrical system simulation tool for utility distribution systems. Unlike CYME, it can run not only steady state analysis, but also quasi-static time series (QSTS) analysis over certain time frames like one day or a year. OpenDSS also has many features to support distributed generation modeling. The original utility circuits have been converted from CYME to OpenDSS models to better analyze distribution feeders from a cost benefit analysis standpoint.

For the conversion process, the equipment, network, and load database have been exported from CYME using Excel VBA scripting. Given the difference in CYME settings, the VBA script was adapted for these three circuits based on the structure of the exported CYME files.

4.5 Validation of the OpenDSS Model:

To validate the conversion of the OpenDSS model, comparisons were made on feeder real power and reactive power flows, system losses and voltage profile. Figure 1 shows the topology of Circuit A. It can be seen from Table 2 that our conversion has accurately translated the circuit from CYME to OpenDSS. Since CYME can only do steady state analysis, the comparison is based on snapshot run results.

	CYME	DSS	%Difference
Sources (kW)	6,164	6,160	-0.06%
Sources (kVAR)	-341	-342	0.33%
Total Losses (kW)	47	43	-9.27%
Var Losses (kVAR)	93	90	-2.81%

Table 2: CYME and OpenDSS Model Comparison (Circuit A)

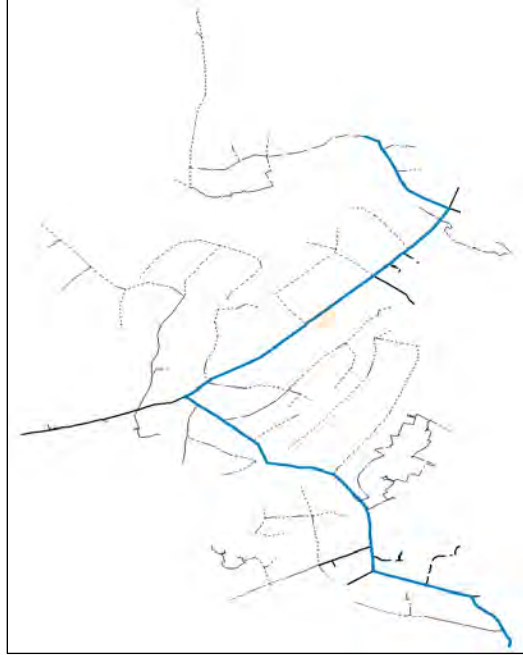


Figure 1: Circuit A Topology

4.6 Quasi-Static Time Series Simulation:

Besides the circuits' model information, the top of the feeder measurements for real power and reactive power with 15 minute interval resolution were also provided by the utility. With that piece of information, the time series analysis of the circuits during a certain duration can be accomplished.

To successfully run the model in time series, the top of the feeder power needs to be allocated to every single load in the model and then if there are capacitors in the circuit, a capacitor control needs to be modeled. The following graphs in Figure 2 show the comparison between OpenDSS simulation results and real measurements for the summer peak day on Circuit A.

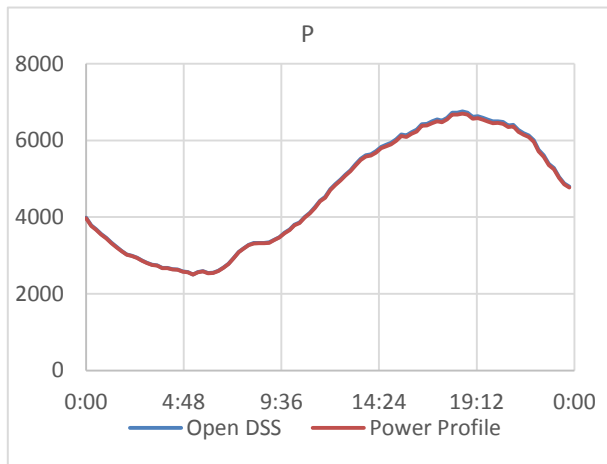


Figure 2a: Peak Day Top of the Feeder Real Power

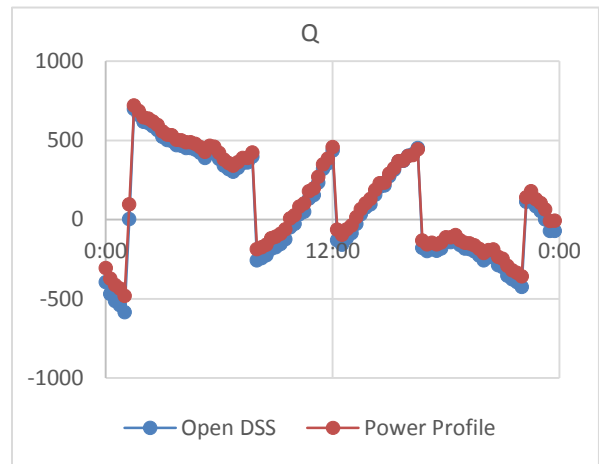


Figure 2b: Peak Day Top of the Feeder Reactive Power

4.7 Solid State Transformer (SST) and Transformer Modeling:

The circuits provided by the utility did not include any distribution transformer impedance. In order to better characterize the loss of the circuits, distribution transformers are modeled so as to include secondary side voltage drop and losses. In the base case, only distribution transformers are modeled. While in FREEDM case, the SST model is substituted for the traditional distribution transformers. The conventional transformer is modeled using typical parameters of distribution transformers, as provided in reference [2].

In the simulation of the FREEDM System for economic analysis, the SST is modeled using a step-down single phase transformer with a Unity Power Factor Controller (UPFC). The step-down distribution transformer converts the primary voltage to a residential voltage level. The UPFC has two main functions: regulating voltage on residential side, compensating power factor (PF) on the grid side. By setting a target PF and voltage in UPFC, the SST model provides regulated voltage to customers and maintains a desired PF at the same time, which emulates the main functions of the SST. Figure 3 shows a basic diagram of the SST model.

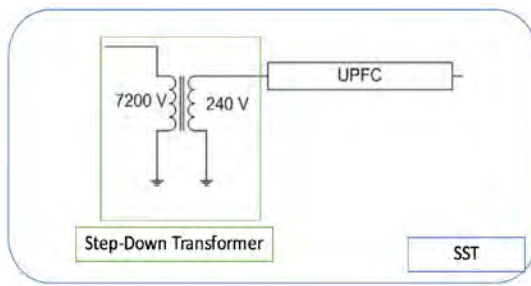


Figure 3: SST model

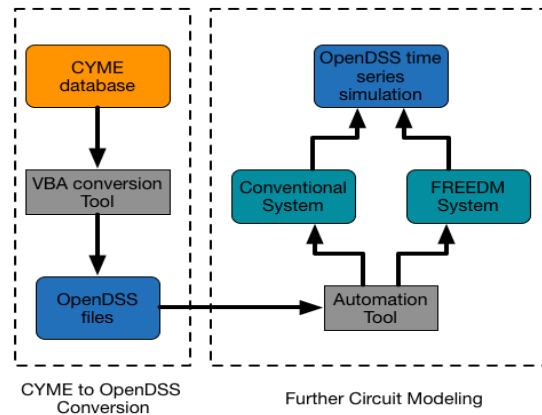


Figure 4: Flow chart of the simulation process

4.8 Circuit Analysis Automation:

A Python script has been written for automation of adding transformer/SST into circuits. The flow chart of the overall simulation process is shown in Figure 4.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Other associated projects inside the ERC include:

- Refinement of a Cost / Benefit Analysis for the FREEDM System, Heydt/ASU*
- Detailed FREEDM system Cost Benefit Analysis under Different deployment scenarios, Baran/NCSU*
- System-Level Benefit-Cost Analysis, DeCarolis/NCSU*
- Evaluation of Codes, Standards, and Regulatory Documents relative to the FREEDM System, White/NCSU*

6. Milestones and Deliverables

Milestones:

- Q3 (09/2015) – Selection of initial test circuits.
- Q4 (10/2015) – Circuit characterization of the initial test circuits.
- Q4 (11/2015) – Conversion of circuits in CYME to OpenDSS.

- Q1 (01/2016) – Validation of CYME to OpenDSS conversion.
- Q1 (02/2016) – Establishment of SST model in OpenDSS.
- Q1 (02/2016) – Automation script tool.
- Q1 (02/2016) – Set up base case of time series running in OpenDSS.
- Q1 (03/2016) – Analysis of circuits at 20-100% penetration with mix of residential and megawatt scale DER systems as a baseline.
- Q1 (03/2016) – Look at costs and benefits associated with following FREEDM application options: (i) Use of AC energy cell control using only storage, (ii) Use of LV SST with DC energy cell, (iii) Use of HV SST with and without storage.
- Q2 (04/2016) – Retrofit scenario involving FREEDM devices deployed at 5-10% of loads to solve localized voltage regulation and reliability issues.
- Q2 (04/2016) – Cost benefit analysis complete.
- Q2 (06/2016) – Cost benefit results linked to comprehensive spreadsheet model.

Deliverables:

- Deliverable for SV (04/2016): Cost benefit analysis metrics based on sample utility circuits.
- Final Deliverable (08/2016): Integration of cost benefit analysis with comprehensive FREEDM spreadsheet model.

7. Plans for Next Year

- Analysis on circuits at voltage levels other than 12.47 kV.
- More accurate modeling of impact of distributed energy management on FREEDM benefits.
- Other FREEDM deployment scenarios not included in Year 8 analysis.

8. Member Company Benefits

FREEDM system cost benefit analysis will enable the member companies to evaluate the FREEDM technology. The Member companies will benefit from utilizing the CBA tool which provide decision support and include the features of defining ownership, existing and future market regulation, future energy and environmental policy, and sensitivity analysis for the value proposition.

9. References

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Y8.GEH.2.4: System Level Cost-Benefit Analysis

Team Members

Project Leader:	Joe DeCarolis
Faculty:	Joe DeCarolis, Mesut Baran, David Lubkeman
Students:	Jeffery Thomas

1. Project Goals

Goal is to do a more comprehensive cost-benefit analysis for the FREEDM system, by working collaboratively with the benefit team and the cost team.

2. Role in Support of Strategic Plan

This Task is part of a cost-benefit analysis project, which is a cross-cutting activity.

3. Fundamental Research, Technological Barriers and Methodologies

The main challenge associated with this project is the economic evaluation of benefits the FREEDM system offers.

4. Achievements

A cost benefit analysis (CBA) was performed to estimate the potential benefits and costs accrued to electricity distribution companies (DISCOs) who make investments in the FREEDM system. In order to carry out this analysis, the best available estimates for costs and benefits are used to calculate the net present value (NPV) and the internal rate of return (IRR) associated with adapting a traditional feeder system to utilize FREEDM components. This study primarily considers the costs and benefits from both the DISCO and consumer perspective.

Table 1 presents a list of specific benefits offered by the FREEDM system, and categorizes them into four broad classes: economic (direct financial benefits), reliability, societal (accruing to society as a whole), and grid security. This work attempts to monetize each benefit category utilizing a variety of methods, including literature review, industry surveys, and power flow simulations.

Methodology

This analysis quantifies the benefits from each of the categories represented in Table 1 and assigns ownership to each cost and benefit. The following sections explore each benefit category in turn, and the Results & Discussion section presents the NPV and IRR for two different ownership scenarios. This analysis considers benefits and costs that accrue over 25 years, the predicted lifetime of the FREEDM components. This work assumes that there is negligible growth of electricity demand in each feeder.

In addition, this analysis reviews two potential FREEDM deployment scenarios – full deployment and partial deployment. Full deployment represents a feeder where all iron transformers have been replaced with FREEDM solid-state transformers (SST) and all traditional circuit breakers have been replaced with fast interrupt devices (FID). Partial deployment represents a feeder where SSTs have been installed only at 50% of node locations, and no FIDs are used. The partial deployment scenario represents a phased approach which is more likely to be the adoption strategy for early adopters.

FREEDM System Features/Functions		Specific Benefits	Benefit Category			
			Economic	Reliability	Societal	Security
Accommodate High PV Penetration						
	Value of Solar	Net benefit of PV above 20%				
	Plug & Play	Simplify DER integration				
	Effective Volt/Var Control	Reduction in power loss				
		Mitigate voltage issues				
	Energy Storage + DGI	Mitigate variability of power				
High Reliability & PQ						
	Looped Primary	High reliability				
	Fault Locating, Isolation					
	Service Restoration	Minimize fault impact on components				
	Fast Protection with FID					
	Regulate Service voltage	High power quality				
Real Time Monitoring & Control (M&C)						
	Enhanced System M&C	Reduced O&M				
		Optimal capacity use				
	CVR	Load management: peak demand and energy reduction				
System Resiliency						
	Enabling micro-grid tech	Micro-grid increases resiliency				
Customer Participation						
	DGI- Price Signals DLMP	Customer DSM				
		Peak demand reduction				
		Economic efficiency				
Motivating New Business						
	Enhanced DSM	Transactive Energy				

Table 1: FREEDM System Benefits

Unless otherwise stated, all energy and demand reductions are monetized using market prices from the PJM market. Analysis of 2015 data resulted in the prices shown in Table 2.

Type	Peak	Off-Peak
Energy (\$/MWh)	51	33
Demand (\$/MW)	100	34

Table 2: Pricing Data (PJM, 2015)

Accommodate High PV Penetration

High levels of PV penetration can cause problems such as voltage violations, reverse power flow, and reduced power quality (Denholm, 2007). There is some agreement in the literature that a PV level beyond 20% will require grid upgrades before additional capacity can be added (Hung, 2014; Denholm, 2007; Patsalides, 2012). Both FREEDM system deployment scenarios enable higher levels of PV penetration by addressing operational issues at the distribution level (Task GEH2.2, Vol II). Thus, for the purposes of this analysis, we assume that the economic benefits of increasing PV above the 20% threshold can be attributed to an investment in FREEDM components.

Existing literature has attempted to quantify the marginal economic value of PV as a function of increasing penetration levels (Hirth, 2014; EEE, 2014; Arizona Public Service, 2013; Mills, 2012). Figure 1 presents a summary of these findings from Arizona, California, and Hawaii. We applied an exponential trend line to these reported marginal values, which produced an R^2 value of 0.977. For simplicity, we assume that the area under the curve between solar PV penetration rates of 20% and 30% represents additional economic benefit that can be attributed to FREEDM in this analysis (in green).

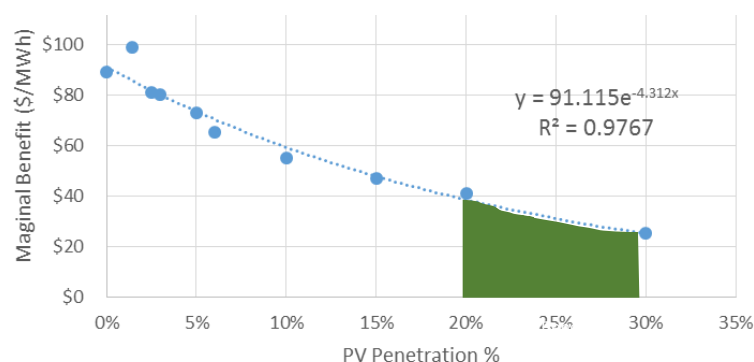


Figure 1: Marginal Benefit of PV [3, 5, 6]

In this analysis, the LSSS system load profile is used, which has total energy consumption of 5,000 MWh per year. Thus, integrating the curve in Figure 1 from 20% (1,000 MWh) to 30% PV penetration (1500 MWh) yields a per-feeder benefit of \$15.5k per year.

The FREEDM system SST also provides enhanced control in system voltage levels and reactive power consumption (volt/var control), which helps to reduce system losses (Task GEH2.2). The results show that FREEDM system in the LSSS feeder offers a 1.4% reduction of energy losses. This energy loss reduction represents an annual savings of \$3,482 utilizing average electricity prices of \$50/MWh and a day-ahead capacity price of \$100/MW.

Further benefits from this category include enhanced plug-and-play ability for DC devices to directly connect to the SST DC bus and energy storage with distributed grid intelligence. So far, these benefits have not been monetized due to lack of available data, but future work will attempt to assess these FREEDM-related benefits to DISCOs, customers, and society.

High Reliability and Power Quality

A primary feature of the FREEDM system is the looped primary circuit and fast fault protection at locations with FIDs. These aspects of FREEDM have been demonstrated to greatly improve the reliability of a feeder (Task GEH2.2). Table 3 summarizes these findings, presenting the improvements in reliability indices SAIFI and SAIDI as a percentage reduction from baseline (i.e., the existent system configuration without FREEDM). Outage costs to the customer and to the DISCO were used to monetize the reliability improvements (Short, 2004). For the partial deployment scenario, no reliability improvements were recognized because no FIDs are installed.

System	SAIFI Improvement	SAIDI Improvement	Annual Benefit to Customers	Annual Benefit to the DISCO
LSSS	36%	43%	\$762	\$1,283

Table 3: Reliability Improvements from FREEDM

The additional benefits in this category include an increase in power quality and minimized fault impact on system components. However, at this time no reliable data is available to monetize these benefits, and as such they are not included in the CBA. Future work will explore these topics.

Real Time Monitoring and Control

When a utility has system monitoring and control capability, it can deploy conservation voltage reduction (CVR) by lowering the voltage on the system during peak demand hours. Because FREEDM enables tight voltage regulation, it provides more effective CVR in both energy reduction and peak demand reductions. Duke Energy has implemented CVR and they estimate peak demand reduction of 1.0% for 4 hours a day in the summer months, and 0.5-0.6% over 2 hours a day in the winter months. These figures can be equated with an average CVR factor of 0.6%. Without FREEDM, DISCOs can utilize a voltage drop of 2 V over a feeder without voltage violations. With FREEDM, this voltage drop can be increased to 6 V. To calculate energy and demand reduction, the CVR factor is multiplied by the change in voltage drop, representing a 4.2% peak demand reduction and energy savings. For the LSSS system, these energy savings are \$6,900 per year (135 MWh/year) while peak demand reductions are 0.034 MW, resulting in a reduction of peak-time tariffs paid of \$200/year. These CVR savings are realized in both full and partial deployment scenarios. Volt-Var control with SSTs also reduces the need for voltage regulators in the system. For the LSSS system, one voltage regulator can be eliminated when FREEDM system is deployed. This yields a one-time cost reduction of approximately \$13k per feeder based on voltage regulator list costs obtained from General Electric and Siemens. Other benefits from the enhanced monitoring and control systems are not quantified in this report.

System Resiliency

Natural disasters, most notably the recent events of Hurricane Sandy and the tsunami that caused the Fukushima nuclear disaster, have illustrated that the power grid is vulnerable to large-scale sustained outages. Annual estimates of outage costs range from \$18-33 billion (DOE, 2013) and many municipalities have begun investigating micro-grids as a potential solution to large-scale outages in the centralized grid network. The FREEDM system can enable micro-grids on feeders. At this time, no direct monetary benefits have been calculated for system resiliency benefits. However, future work will attempt to quantify these benefits.

Customer Participation

FREEDM system enables utilities to send real-time price signals to consumers. When electricity customers are given the option to shift demand from peak demand to off-peak demand via a subsidy payment or tiered rate system, an overall reduction in peak demand and energy consumed during peak demand is expected. Estimates of the impact FREEDM can have on peak demand has been obtained (Gorria, 2013). The study provides estimates of 20-30% peak demand reduction when a 5 cent/kWh incentive is offered to customers. These benefits are able to accrue to the DISCO in the form of reduced use of thermal power and reduced capacity reserve requirements during peak demand hours, when capacity is most expensive. Based on the analysis with the LSSS feeder, utilizing peak and off-peak prices from the PJM market, savings accruing to the customer as energy

usage reduction is \$500/year and savings accruing to the DISCO as peak demand reductions is \$30/year.

Transactive Energy

Advanced DGI on the FREEDM system offers the adopters of the system to explore the transactive energy market. Transactive energy enables market participation by renewable generators, enabling those sources to buy and sell electricity directly to the market without passing through the DISCO. The concept of an electricity “prosumer” – a consumer who produces and sells into the market – is attractive not only in making market transactions more efficient, but also creating so-called “hardened nodes”. These nodes can act as mini-micro-grids, generating enough electricity independent from centralized sources to supply energy to other grid loads in the event of an outage. This concept is very new to the electricity grid, and as such no quantified benefits are calculated here.

Costs

The costs of the FREEDM system pertain to the SSTs and FIDs, which replace a traditional feeder’s iron transformers and circuit breakers. Detailed cost breakdowns are examined in other sections of the FREEDM annual report (Task GEH2.6). For this CBA, the costs to the DISCO are assumed to be the 15-year list prices for a high deployment scenario. This assumption is made because there is no large-scale adoption of FREEDM expected in the next 5-10 years due to ongoing research, development, and commercialization. The costs used for both FREEDM components and the traditional grid counterparts are given in Table 4. It is expected that implementation of FREEDM will displace traditional grid components, which can be used elsewhere in the DISCO system.

Component	15-year High Deployment Cost	Source
25 kVA SST	\$3,103	FREEDM cost study
25 kVA iron transformer	\$1,192	GE & Siemens 2015 List Price
50 kVA SST	\$4,653	FREEDM cost study
50 kVA iron transformer	\$2,385	GE & Siemens 2015 List Price
3 phase FID	\$16,225	FREEDM cost study
Vacuum circuit breaker	\$20,000	GE & Siemens 2015 List Price
Residential Energy Storage	\$3000 / 7 kWh	Tesla Powerwall, 2015
DISCO Energy Storage	\$240 / kWh	California Energy Commission, 2015

Table 4: Component Costs

Results & Discussion

A spreadsheet tool was developed to evaluate these annualized benefits and costs in order to calculate the NPV and IRR of a FREEDM system. Total annual savings from FREEDM were calculated between \$22,700 and \$25,700, depending on the feeder used in power flow analysis. Table 4 below presents these calculations based on two ownership scenarios. The first scenario represents residents with PV investing in energy storage. In the second scenario, the DISCO invests in community energy storage at the feeder level. The discount rate used was 10%, which was the weighted average cost of capital (WACC) used by DISCOs surveyed (Task GEH2.7). Annual cash flows were assumed constant over the lifetime of the FREEDM devices, currently estimated at 25 years.

From the DISCO perspective, it is clear that the full deployment scenario, with a negative NPV and an IRR below the average DISCO WACC, the FREEDM system with storage needs additional study before it can be considered a profitable investment. Similarly, for the customers to adopt storage additional incentives are required. The partial deployment scenario is an attractive investment for first adopters. This work has enumerated numerous benefit categories that have not yet been monetized, and these benefits will guide future work that will expand the scope of benefits.

Metric	Full Deployment		Partial Deployment	
	Customer Owns Storage	DISCO Owns Energy Storage	Customer Owns Storage	DISCO Owns Energy Storage
NPV	\$ - 48,000	\$ - 372,000	\$ 47,700	\$ - 276,200
IRR	15.0 %	2.5 %	32.2 %	5.0 %

Table 5: Results

In addition, we explored the sensitivity of key model parameters. Figure 2 presents a tornado diagram, which ranks ten key parameters based on their impact to NPV. For each parameter, the base value (indicated in parenthesis) was varied by +/- 25% while all other parameters were held constant. The change in NPV from each of these proportional changes indicates which individual parameters most influence the CBA outcome. It is interesting to note that discount rate, feeder size (in MW), and the value of solar are three of the most influential variables. It is not surprising that discount rate exerts a strong influence on the NPV. The feeder size is significant because it affects all energy and peak demand savings that were calculated as a percentage. The greater influence of electricity price compared to capacity price reflects the fact that the FREEDM system does more to reduce energy losses than reduce peak demand. Future work will attempt to limit the range associated with the most sensitive parameters in order to increase confidence in the CBA results.

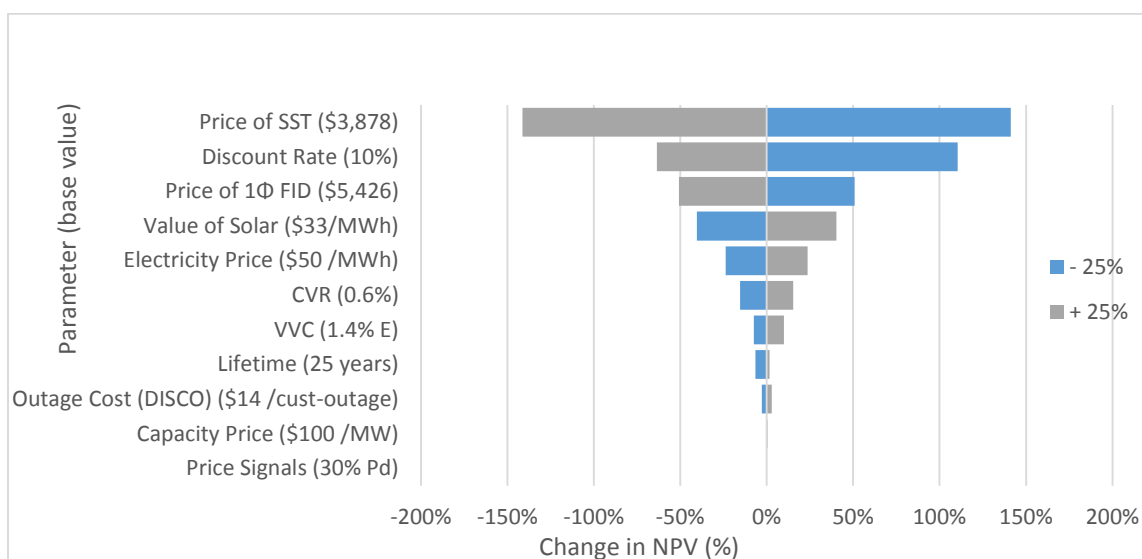


Figure 2: Sensitivity analysis of key parameters

We also note that the FREEDM system is likely to be deployed in niche markets where a combination of economics and policy require it. For example, the marginal value of solar PV estimated from Figure 1 does not reflect the best potential markets. For example, Hawaii had the highest average residential electricity price of \$370/MWh in 2014, which is 200% higher than the national average of \$125/MWh. Given Hawaii's remote location, electricity generation is largely supplied by petroleum-fired power plants that operate on imported fuel. This analysis estimates the FREEDM break-even point of solar prices to be \$63/MWh, with higher prices resulting in a positive NPV under full deployment and DISCO-owned storage scenarios. In this case the marginal value of solar enabled through FREEDM system deployment will be much higher, and will substantially increase the associated benefits accruing to a DISCO that employs the FREEDM system. Furthermore, renewable portfolio standards and climate policies will drive higher deployments of renewables, which in turn will require enabling grid technologies to manage the distributed, variable output. Future work will explore the effects of policy on the economic benefits of the FREEDM system.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Cost-benefit analysis is commonly done by utilities and vendors.

6. Milestones and Deliverables

A final report.

7. Plans for Next Five Years

Quantify some of the benefits that could not be assessed this year.

8. Member Company Benefits

Cost benefit analysis provides valuable feedback to Industry Members about the economic feasibility of the FREEDM system and its components.

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Y8.GEH2.5: Evaluation of Codes, Standards, and Regulatory Documents relative to the FREEDM System

Team Members

Project Leader: Leonard W. White
Faculty: Leonard W. White

1. Project Goals

The overall objective is to review selected codes, standards, and regulatory documents that might contain compliance requirements that have a negative impact upon implementation of the FREEDM System. A secondary goal is to recommend modifications to selected documents to mitigate the negative effects of present wording where such is found to exist.

2. Role in Support of Strategic Plan

The role of this sub-task is to investigate the framework of standards and codes into which the FREEDM system will be integrated. The task itself is essentially non-technical but is important as the existing standards and code structure is based upon equipment and concepts that are entirely different from those embodied in the FREEDM matrix. The task is vital in that, generally, Codes reference Standards that must be met before equipment can be installed and operated in commercial and public electrical distribution systems. It is necessary to know, *a priori*, which standards present barriers to the implementation of FREEDM technologies.

3. Fundamental Research, Technological Barriers and Methodologies

N/A

4. Achievements

This is a new sub-task; no work had been directly performed on this task prior to the present year. At the end of the third quarter of Year 7 a listing of relevant standards had been generated. The standards list was consensus based with inputs being obtained from the other FREEDM partner institutions, from industry partners, and from utility stakeholders. Other standards were added to the list as the review work progressed.

The specific work of the subtask was defined as follows:

- a. Identify specific codes, standards, and regulatory documents for review.
- b. Obtain copies of most recent edition of documents selected for review.
- c. Divide documents into logical subsets and distribute to partner universities and appropriate IAB members.
- d. Review documents for specific application and content relevant to FREEDM concepts, proposed equipment, and overall functionality.
- e. Generate listing of adverse content. Devise alternate (proposed) wording to mitigate effect of adverse content.
- f. Submit proposed wording to appropriate code-making interties or organizations.
- g. Summarize work in a written report for distribution.

The codes and standards that were evaluated are presented below as Table 1. The initial listing of documents was somewhat shorter; additional documents were added during the evaluation process as they were either encountered in the review of earlier documents – it is very common for one standard to reference another standard – or as they were recommended for evaluation by other Team members. It is noted that the documents reviewed is by no means an exhaustive listing; there are

very many standards in existence, some of which have fallen into disuse or have been superseded by more recent publications. No efforts were made to track down obscure or out of date standards.

UL 1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
UL 1449	Surge Protective Devices
IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems
IEEE 1547.1	IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with electric Power Systems
NFPA 70	National Electrical Code
ANSI C62.41	IEEE Recommended Practice for Surge Voltage in Low-voltage AC Power Circuits
ANSI C62.45	IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits
IEEE 142	IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems
IEEE 519	IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
ANSI C57	Pad-Mounted Equipment— Enclosure Integrity for Coastal Environments
ANSI C37	IEEE Standard for Metal-Clad Switchgear
NFPA 780	Standard for the installation of lightning protection systems
IEEE 446	IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications
IEEE 1100	IEEE Recommended Practice for Powering and Grounding Electronic Equipment
IEEE 929	IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems
IEEE 1001	IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems
IEEE 1035	IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters
ANSI C2	National Electrical Safety Code
IEEE 519	IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Table 1: Listing of Codes and Standards

In the sequel, it developed that review of regulatory documents for the purpose of meeting the sub-task requirements is not practical. There are several reasons for this, among them the following:

- a. There are multiple levels of regulatory control of the electric distribution system, starting from the Federal level, down to the State level, and, in some cases, extending into the local level.

There are simply too many documents to review under the present project; the generation of a *listing* of relevant regulatory documents is a significant task.

- b. The regulatory documents that were obtained for review typically reference standards and codes with compliance mandates. A significant number of those codes are being reviewed as a part of the present sub-task.
- c. Regulatory documents are at a high level and are (generally) non-technical in that they deal with energy transactions at the gross level rather than at the technical level being addressed by the FREEDM concept.

Table 2 shows the reviewed codes and standards and the ranking of the standard with respect to impact on the FREEDM Concept and FREEDM Components.

Item	ID	Title	Impact Ranking
1	ANSI C37	IEEE Standard for Metal-Clad Switchgear	3
2	UL 1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources	3/4
3	UL 1449	Surge Protective Devices	1
4	IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems	4
5	NFPA 70	National Electrical Code	4/5
6	ANSI C62.41	IEEE Recommended Practice for Surge Voltage in Low-voltage AC Power Circuits	3/4
7	ANSI C62.45	IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits	3/4
8	IEEE 142	IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems	2
9	IEEE 519	IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems	3/4
10	ANSI C57	Pad-Mounted Equipment - Enclosure Integrity for Coastal Environments	2
11	NFPA 780	Standard for the installation of lightning protection systems	1/2
12	IEEE 446	IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications	2
13	IEEE 1100	IEEE Recommended Practice for Powering and Grounding Electronic Equipment	2/3
14	IEEE 929	IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems	2
15	IEEE 1001	IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems	3/4
16	IEEE 1035	IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters	3
17	ANSI C2	National Electrical Safety Code	2/3

Table 2: Listing of Codes and Standards Impact

The original goal of the present task was to secure modification of standards that contain requirements that might negatively affect the FREEDM System concepts. Toward that end, the reviewed standards were ranked in accordance with the following scheme:

1. Not relevant to the proposed FREEDM proposed physical equipment
2. Relevant to the FREEDM equipment but the requirements are incidental to the equipment and can be easily met.
3. Relevant to the FREEDM equipment but the requirements can be met with reasonable design efforts.
4. Relevant to the FREEDM equipment; the requirements can be met with significant design efforts.
5. Incompatible with the FREEDM equipment.

As can be seen from Table 2, the overall impact of the reviewed Codes and Standards on the FREEDM Concept is relatively benign. That said, there are several items that are worth mentioning:

Applicability: There are a number of the standards that are essentially low voltage (*i.e.*, < 600 V) documents. The FREEDM System concept is basically a Medium Voltage, utility side, system that, strictly speaking, is not impacted in any way by low voltage standards or codes. Even so, some of the features of those standards could be applied to the present work. It is for that reason that these standards were evaluated with other that were more directly applicable. No distinction has been made in the impact ranking between standards that are low voltage and those that are at medium voltage.

Incompatibility: Of all the reviewed documents only one, the National Electrical Code (NFPA 70), presented an absolute barrier to the FREEDM concept. Again, strictly speaking, the relevant system is at low voltage but the limitation presented by the Code is severe enough to justify separate mention: this impediment will severely limit the expansion of DC into buildings. The specific NEC article, Section 210.6, *Branch-Circuit Voltage Limitations*, specifies a maximum voltage that can be used. Briefly, the article limits the voltage in residential and similar occupancies to 120 Volts (RMS) between conductors for typical cord-and-plug connected loads. For specific loads the limits are raised to 277 Volts between conductors. The voltage limitations imposed by 210.6 effectively excludes the use of DC at efficient voltage levels from the majority of applications in this country. In other countries, Canada for example, there are similar restrictions from the *Canadian Electrical Code* (CSA C22.1).

It is obvious that wording to modify this section will be simple but it is noted that the NEC is on a three-year review cycle and, considering the justifications and safety inputs necessary to effect changes, rapid modification of this restriction is highly unlikely.

Challenges: The concept of Basic Impulse Level (BIL) and testing to determine BIL are important concepts which must be resolved before FREEDM-type equipment can become widely accepted into the grid. It is obvious that the testing methods that are presently used for iron-based legacy system components are not appropriate for solid-state equipment. As an example, the concept of energy-limited testing sources is not particularly important for normal BIL testing. When these same tests are applied to solid state equipment – where the internal components are protected by clamp-type devices that limit voltage – the matter of test energy dissipated inside the solid state equipment becomes critical. The insistence upon using inappropriate standards for technologically new equipment will result in equipment that will not function properly in the intended environment. At this writing, there is much conversation about this exact item as applied to Solid State Lighting, where

failure rates are high due to inappropriate transient suppression for LED drivers and similar internal components.

Recommendations: From the review efforts it is clear that modification of existing standards to 'patch' them for application to FREEDM Systems equipment is not the best solution. Aside from the fact that there are *many* standards, each with its associated committees and panels – making uniform and timely changes difficult - it has been previously noted that this approach has not been particularly successful with respect to SSL equipment. In our specific case the problem is even more complex since we are dealing with multiple types of equipment covered by multiple standards.

Conceptually, what is needed is a new standard that is specifically dedicated to FREEDM Systems equipment. The new standard could be appended to some existing standard, *e.g.*, UL 1741 or IEEE 1547, but it would probably be more effective if it were a completely independent document that covered only the physical equipment and the testing thereof. Other standards, perhaps existing, should be modified as needed to cover the details of connections, grounding, interface, safety aspects, and modes of operation.

5. Milestones and Deliverables

The following are originally proposed milestones:

15 Q3 (9/30/2015)	Identification of review items and distribution of review work among team members; possess most recent copies of review documents.
15 Q4 (12/31/2015)	Initial review of documents complete; possess initial comments.
16 Q1 (3/31/2016)	Proposed revisions complete; submittal process for all documents determined.
16 Q2 (6/30/2016)	Recommended changes submitted to relevant organizations.

The following are originally proposed deliverables:

4/2016	Summary report of specific codes reviewed and recommended modifications.
8/2016	Final report of task activities. Results of submitted change requests where same is available.

6. Plans for Next Five Years

No specific plans are in place for the next year. Should additional codes or standards become a concern these can be reviewed on an as-needed basis.

Y8.GEH2.6: Cost Estimation Model

Team Members

Project Leader: Leonard W. White
Contributor: Steve Watts, STEAM Ventures

1. Project Goals

Estimated costs of the Solid State Transformer and Fault Isolation Device are key components of the Cost Benefit Analysis. FREEDM hired STEAM Ventures to create a cost estimation model.

2. Role in Support of Strategic Plan

This task supports the overall Cost Benefit Analysis.

3. Fundamental Research, Technological Barriers and Methodologies

N/A

4. Achievements

The following system configurations of Solid State Transformer (SST) and Fault Isolation Device (FID) were used to model costs across suitable timescales and volumes of monthly production.

SST: 25 kVA, 50kVA, 75 kVA and 100 kVA (1 Phase)
112.5 kVA and 150 kVA (3 Phase)

FID: 15kV, 200A (3MVA, 1 Phase)
15kV, 200A (3MVA, 3 Phase)

A model was used based on the existing design, industry standard estimation and manufacturing methods and some parameters projected for specific technologies.

4.1 Existing Design Data and Configurations

Existing design data was analyzed for cost today in low volume; this was used as a starting point for the model. As existing prototypes did not perfectly fit the configurations above the first stage of the model projected costs from the available prototype models to the target configurations detailed above. As the designs for the SST and FID were modular in nature, all configurations listed above could be modelled via two methods; combining the subsystems present in the existing prototypes in different combinations or scaling power based on a multiplier. The multiplier was based on observed data from appropriate semiconductor devices that form a majority of the costs of the subsystems. This method managed the step from single to three phase systems for the SST and for the FID this step was dealt with via use of three single phase devices. Voltages were all set at 7.2kV phase to neutral and 12.47kV phase to phase across all systems configurations.

4.2 Deployment

The original design costs data did not include any component costs for enclosures or fixtures required in the deployment of such devices. Suitable NEMA4 enclosures from an established industry provider (Hoffman), pole or pad fixtures and miscellaneous control costs were added to

the cost for each system configuration based on currently available pricing. Results from this stage are shown below:

System	Width	Depth	Height	Volume	Product	Costs	Fixtures	Total	Notes
	inches	inches	inches	cubic inches					
SST									
25 kVA, 1Ø	48	15	18	12960	CSD483612	\$873.51	\$100.00	\$973.51	Same chassis for all selected
50 kVA, 1Ø	48	15	18	12960	CSD483612	\$873.51	\$100.00	\$973.51	Room for cooling, communications etc.
75 kVA, 1Ø	48	15	18	12960	CSD483612	\$873.51	\$100.00	\$973.51	
100 kVA, 1Ø	48	15	18	12960	CSD483612	\$873.51	\$100.00	\$973.51	
112.5 kVA, 3Ø				16848	CSD483612	\$873.51	\$100.00	\$973.51	No prototype, estimate at a 1.5 multiple
150 kVA, 3Ø				16848	CSD483612	\$873.51	\$100.00	\$973.51	
FID									
15kV, 200A (3MVA), 1Ø	10		26	2041	CSD302010	\$435.47	\$100.00	\$535.47	Cyclinder
15kV, 200A (3MVA), 3Ø				6123	CSD302010	\$1,306.41	\$300.00	\$1,606.41	Multiple of 3 but just use three enclosures?

4.3 Manufacturing

Manufacturing costs (parts procurement, sub-system outsourcing, system assembly, production test, final configuration, inventory management and delivery) were added into the costs model based on a review by local contract manufacturers, of system complexity and manufacturing rates for US on shore labor. These rates were scaled to be at suitable levels for the various configurations. The rate was set at \$35ph with a \$5 overhead to create a fully loaded rate of \$40ph.

Results from this stage are shown below:

System	Time	Rate on shore	Rate off shore	Production Test	On shore CM Charge	Off shore CM Charge	Notes
	hours	\$/hr	\$/hr		\$	\$	
SST							
25 kVA, 1Ø	6	\$40.00	\$18.00	\$150.00	\$390.00	\$258.00	
50 kVA, 1Ø	6	\$40.00	\$18.00	\$150.00	\$390.00	\$258.00	
75 kVA, 1Ø	6	\$40.00	\$18.00	\$150.00	\$390.00	\$258.00	
100 kVA, 1Ø	6	\$40.00	\$18.00	\$150.00	\$390.00	\$258.00	
112.5 kVA, 3Ø	8	\$40.00	\$18.00	\$150.00	\$470.00	\$294.00	No prototype, estimate at a 1.5 multiple
150 kVA, 3Ø	8	\$40.00	\$18.00	\$150.00	\$470.00	\$294.00	
FID							
15kV, 200A (3MVA), 1Ø	3	\$40.00	\$18.00	\$150.00	\$270.00	\$204.00	
15kV, 200A (3MVA), 3Ø	9	\$40.00	\$18.00	\$150.00	\$510.00	\$312.00	Multiple of 3

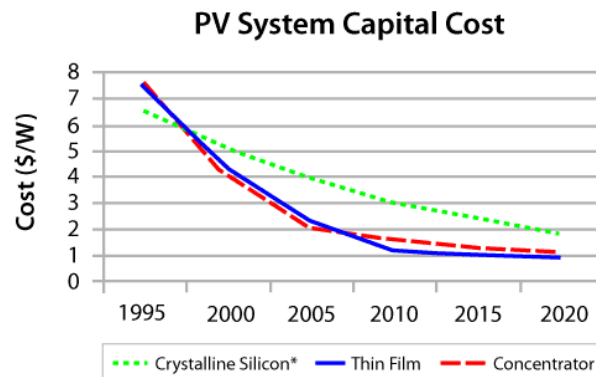
4.4 Maturity

At this point in the serial model a best estimate for a US manufactured and deployable product was available based on the system configurations targeted. Deployment of the SST and FID was considered to be an organic process across a timescale of several years due to the installed base and traditional market development. The timescales considered were: Present Day (R&D Cost to manufacture), 5 year (Utility trials), 10 years (Limited deployment) and 15 years (Full deployment).

This part of the model presented the most subjective parameter estimation. As a technology matures a natural decrease in costs will be seen based on free market forces including competition with newer competing solutions and technologies or currently installed solutions. Decreases in costs are also seen as manufacturing capabilities increase to meet the needs of the newer adopted technologies as well as new producers coming on line to profit from the growing need. These factors are taken into account in a one-time based cost function for estimation purposes based on similar technologies and markets from a historic perspective. The conservative factor used was 0.9 per year and this was supported by several methods including

correlation with the PV market, SiC introduction data from Cree and US government industry reports.

It is worth noting that a large proportion of the cost dependency in the SST is based in semiconductor technology. Although based on geometries, Moore's Law has some value here for comparison as it is dependent on semiconductor development timelines. In Moore's Law processing power is doubled about every two years. This, if used as a direct analogy would generate a maturity factor of around 0.7. The maturity of power electronics devices may also be compared to the PV market where a similar maturity curve has been witnessed over recent years. The graph below is from the US department of energy and displays an approximate maturity rate of 0.92; it is felt that the less optional nature of utility grid enhancements easily justify the 0.02 difference.



Results from this stage are shown below:

System	Current COGS	Maturity Factor	Timeline in years		
			5	10	15
SST					
25 kVA, 1Ø	\$17,331.41	0.9	\$10,234.02	\$6,043.09	\$3,568.38
50 kVA, 1Ø	\$25,990.61	0.9	\$15,347.20	\$9,062.37	\$5,351.24
75 kVA, 1Ø	\$43,736.85	0.9	\$25,826.17	\$15,250.10	\$9,005.03
100 kVA, 1Ø	\$88,214.74	0.9	\$52,089.92	\$30,758.58	\$18,162.63
112.5 kVA, 3Ø	\$39,717.21	0.9	\$23,452.62	\$13,848.53	\$8,177.42
150 kVA, 3Ø	\$61,018.41	0.9	\$36,030.76	\$21,275.80	\$12,563.15
FID					
15kV, 200A (3MVA), 1Ø	\$51,979.59	0.9	\$30,693.43	\$18,124.16	\$10,702.14
15kV, 200A (3MVA), 3Ø	\$155,638.77	0.9	\$91,903.14	\$54,267.88	\$32,044.64

4.5 Volume

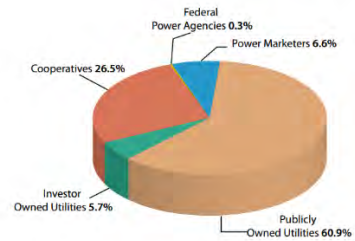
Manufactured goods naturally decrease in cost to manufacture as volume increases due to the discounted prices of goods, materials and labor at higher volumes provided by the free market system. With new technology this trend can sometimes fail or be delayed if the ability to produce in volume is not invested in due to an unclear market future. For the purposes of this investigation it will be assumed that the usual discounts seen for volume production in similar technologies will be experienced.

The volumes to be used in the estimation will be based on the useful and usual product life cycle for existing utility grade equipment used in the distribution grid and assume an appropriate adoption time. These deployed numbers will be used to estimate actual manufacturing volumes on a per month basis. Based on deployed units from field test to full deployments, monthly manufacturing volumes will be modeled in 100, 1000, 5000 and 10000 lots.

The choice of volume ranges is supported by the purchase volume data below provided by Duke Energy under NDA. For just Duke Energy the one year totals for standard distribution transformer purchases are shown below across the US taken from the Directory manufacturing volumes.

Number of Electricity Providers

		% of TOTAL
Publicly Owned Utilities.....	2,013	60.9%
Investor-Owned Utilities.....	189	5.7%
Cooperatives.....	877	26.5%
Federal Power Agencies.....	9	0.3%
Power Marketers.....	218	6.6%
TOTAL	3,306	100.0%



- 25kVA 19,328
- 50kVA 9,411
- 75kVA 852
- 100kVA 939
- **YEAR TOTAL 30,530**

4.6 Gross Margin

At this point a final Cost Of Goods Sold (COGS) figure was available. COGS are the direct costs attributable to the production of the goods sold by a company. Although distribution grid utility equipment is usually sold via bid, a list price was also generated as a reference based on a Gross Margin of 31% that is typical of the industry.

$$\text{Gross Margin} = (\text{List Price} - \text{COGS}) / (\text{List Price})$$

Results from this volume and gross margin stages are shown below. Three sets of results for a 5, 10 and 15 year horizon each show a base COGS for the set maturity and then are projected across all targeted volumes.

Volume COGS/LIST at 5 years													
System	Maturity	Prototype		Field Test		Limited Deployment		Low Deployment		Medium Deployment		High Deployment	
Vol per month	5	100		1000		5000		5000		10000		10000	
Vol discount		20.00%		30.00%		35.00%		35.00%		40.00%		40.00%	
		COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST
SST													
25 kVA, 1Ø		\$10,234.02	\$8,187.22	\$11,865.54	\$7,163.82	\$10,382.34	\$6,652.12	\$9,640.75	\$6,652.12	\$9,640.75	\$6,140.41	\$8,899.15	\$6,140.41
50 kVA, 1Ø		\$15,347.20	\$12,277.76	\$17,793.85	\$10,743.04	\$15,569.62	\$9,975.68	\$14,457.50	\$9,975.68	\$14,457.50	\$9,208.32	\$13,345.39	\$9,208.32
75 kVA, 1Ø		\$25,826.17	\$20,660.94	\$29,943.39	\$18,078.32	\$26,200.46	\$16,787.01	\$24,329.00	\$16,787.01	\$24,329.00	\$15,495.70	\$22,457.54	\$15,495.70
100 kVA, 1Ø		\$52,089.92	\$41,671.94	\$60,394.11	\$36,462.94	\$52,844.85	\$33,858.45	\$49,070.22	\$33,858.45	\$49,070.22	\$31,253.95	\$45,295.58	\$31,253.95
112.5 kVA, 3Ø		\$23,452.62	\$18,762.09	\$27,191.44	\$16,416.83	\$23,792.51	\$15,244.20	\$22,093.04	\$15,244.20	\$22,093.04	\$14,071.57	\$20,393.58	\$14,071.57
150 kVA, 3Ø		\$36,030.76	\$28,824.61	\$41,774.80	\$25,221.53	\$36,552.95	\$23,419.99	\$33,942.02	\$23,419.99	\$33,942.02	\$21,618.46	\$31,331.10	\$21,618.46
FID													
15kV, 200A (3MVA), 1Ø		\$17,897.01	\$14,317.61	\$20,750.15	\$12,527.91	\$18,156.38	\$11,633.06	\$16,859.50	\$11,633.06	\$16,859.50	\$10,738.20	\$15,562.62	\$10,738.20
15kV, 200A (3MVA), 3Ø		\$53,513.88	\$42,811.10	\$62,045.07	\$37,459.71	\$54,289.44	\$34,784.02	\$50,411.62	\$34,784.02	\$50,411.62	\$32,108.33	\$46,533.81	\$32,108.33
Volume COGS/LIST at 10 years													
System	Maturity	Prototype		Field Test		Limited Deployment		Low Deployment		Medium Deployment		High Deployment	
Vol per month	10	100		1000		5000		5000		10000		10000	
Vol discount		20.00%		30.00%		35.00%		35.00%		40.00%		40.00%	
		COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST
SST													
25 kVA, 1Ø		\$6,043.09	\$4,834.47	\$7,006.48	\$4,230.16	\$6,130.67	\$3,928.01	\$5,692.77	\$3,928.01	\$5,692.77	\$3,625.85	\$5,254.86	\$3,625.85
50 kVA, 1Ø		\$9,062.37	\$7,249.89	\$10,507.09	\$6,343.66	\$9,193.70	\$5,890.54	\$8,537.01	\$5,890.54	\$8,537.01	\$5,437.42	\$7,880.32	\$5,437.42
75 kVA, 1Ø		\$15,250.10	\$12,200.08	\$17,681.27	\$10,675.07	\$15,471.11	\$9,912.56	\$14,366.03	\$9,912.56	\$14,366.03	\$9,150.06	\$13,260.95	\$9,150.06
100 kVA, 1Ø		\$30,758.58	\$24,606.86	\$35,662.12	\$21,531.00	\$31,204.35	\$19,993.08	\$28,975.47	\$19,993.08	\$28,975.47	\$18,455.15	\$26,746.59	\$18,455.15
112.5 kVA, 3Ø		\$13,848.53	\$11,078.83	\$16,056.27	\$9,693.97	\$14,049.24	\$9,001.55	\$13,045.72	\$9,001.55	\$13,045.72	\$8,309.12	\$12,042.20	\$8,309.12
150 kVA, 3Ø		\$21,275.80	\$17,020.64	\$24,667.60	\$14,893.06	\$21,584.15	\$13,829.27	\$20,042.42	\$13,829.27	\$20,042.42	\$12,765.48	\$18,500.70	\$12,765.48
FID													
15kV, 200A (3MVA), 1Ø		\$10,568.00	\$8,454.40	\$12,252.76	\$7,397.60	\$10,721.16	\$6,869.20	\$9,955.37	\$6,869.20	\$9,955.37	\$6,340.80	\$9,189.57	\$6,340.80
15kV, 200A (3MVA), 3Ø		\$31,599.41	\$25,279.53	\$36,637.00	\$22,119.59	\$32,057.37	\$20,539.62	\$29,767.56	\$20,539.62	\$29,767.56	\$18,959.65	\$27,477.75	\$18,959.65
Volume COGS/LIST at 15 years													
System	Maturity	Prototype		Field Test		Limited Deployment		Low Deployment		Medium Deployment		High Deployment	
Vol per month	15	100		1000		5000		5000		10000		10000	
Vol discount		20.00%		30.00%		35.00%		35.00%		40.00%		40.00%	
		COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST	COGS	LIST
SST													
25 kVA, 1Ø		\$3,568.38	\$2,854.71	\$4,137.26	\$2,497.87	\$3,620.10	\$2,319.45	\$3,361.52	\$2,319.45	\$3,361.52	\$2,141.03	\$3,102.94	\$2,141.03
50 kVA, 1Ø		\$5,351.24	\$4,280.99	\$6,204.33	\$3,745.87	\$5,428.79	\$3,478.30	\$5,041.02	\$3,478.30	\$5,041.02	\$3,210.74	\$4,653.25	\$3,210.74
75 kVA, 1Ø		\$9,005.03	\$7,204.02	\$10,440.61	\$6,303.52	\$9,135.54	\$5,853.27	\$8,483.00	\$5,853.27	\$8,483.00	\$5,403.02	\$7,830.46	\$5,403.02
100 kVA, 1Ø		\$18,162.63	\$14,530.11	\$21,058.12	\$12,713.84	\$18,425.86	\$11,805.71	\$17,109.73	\$11,805.71	\$17,109.73	\$10,897.58	\$15,793.59	\$10,897.58
112.5 kVA, 3Ø		\$8,177.42	\$6,541.94	\$9,481.07	\$5,724.19	\$8,295.93	\$5,315.32	\$7,703.37	\$5,315.32	\$7,703.37	\$4,906.45	\$7,110.80	\$4,906.45
150 kVA, 3Ø		\$12,563.15	\$10,050.52	\$14,565.97	\$8,794.20	\$12,745.22	\$8,166.05	\$11,834.85	\$8,166.05	\$11,834.85	\$7,537.89	\$10,924.48	\$7,537.89
FID													
15kV, 200A (3MVA), 1Ø		\$6,240.30	\$4,992.24	\$7,235.13	\$4,368.21	\$6,330.74	\$4,056.20	\$5,878.54	\$4,056.20	\$5,878.54	\$3,744.18	\$5,426.35	\$3,744.18
15kV, 200A (3MVA), 3Ø		\$18,659.14	\$14,927.31	\$21,633.78	\$13,061.39	\$18,929.56	\$12,128.44	\$17,577.45	\$12,128.44	\$17,577.45	\$11,195.48	\$16,225.33	\$11,195.48

4.7 Summary

It is felt that the projected COGS and list prices are appropriately conservative with an acceptable error margin considering the timeline used. It is worth noting that with maturity and volume, both are driven by demand and so the introduction of the SST and FID into the utility distribution grid presents a “chicken and egg” situation when it comes to List Price. In many countries around the world it has been government action that has spurred step functions in an industry. For example we can look at the telecommunications revolution of the 1990’s and early 2000’s that was kicked off due to US government de-regulation of certain service providers use of the nation’s existing infrastructure and in Germany the use of fuel cells and associated innovation after the government banned idling engines in all its public land.

To a large extent, demand and hence price will be dependent on future government regulation with respect to distribution grid efficiency, safety and security. The estimates in this report have assumed that deployment is desirable to the energy companies. At the same time no account has been made for competition or acceleration due to legislation based deadlines or similar incentives.

Work continues in terms of correlating the model results above with analogous industries or technologies. Information from recent a US Governments Wide Bandgap Power Electronics Technology Assessment and data from Cree, Inc. on cost trends for SiC product families was used to model a general trend of cost reduction over time and generate a further maturity factor for consideration (maturity being the most subjective parameter used in the model). It was assumed that the majority of the costs under consideration are associated with switching semiconductor devices and that the cost reductions found in the data were present across all volumes under consideration. It was observed that since the introduction years for the 600V Schottky, 1200V Schottky and 1200V MOSFET, a significant cost reduction was seen with maturity factors of 0.928, 0.87 and 0.675 respectively for the first three years. This wide spread of values, explained perhaps, by the effect that advances in one technology benefit those following, does not provide a clear value for the timescales provided. However, the data projects forward from 2012 and the three technology devices follow a similar path of lesser cost reduction that if linear shows a modest yearly reduction leveling out at approximately 10% of introduction cost after 10 years.

If we apply this general model, assuming that the majority of the costs of our target systems is the new semiconductor devices and look at the 10 year time line we found that this comparison showed a final COGS of approximately half the value that was generated from our serial model. This difference may be seen as pointing to a conservative model as proposed.

Y8.GEH2.7: Voice of Customer Analysis and Commercialization Path

Team Members

Project Leader:	Mesut Baran
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Contributors:	Accelerating Commercialization of Technology (ACT) Team, NCSU Poole College of Management

1. Project Goals

The Cost Benefit Analysis should include an estimate of Total Available Market and Serviceable Available Market. To explore this and other commercialization aspects, FREEDM collaborated with an ACT Team from the NCSU Poole College of Management who completed a Voice of the Customer Analysis.

2. Role in Support of Strategic Plan

The FREEDM Systems Center commissioned a market analysis team from the Accelerating the Commercialization of Technology (ACT) program at North Carolina State University. This team was tasked with quantifying the total addressable market and total serviceable market, identifying commercialization opportunities, and assessing barriers to adoption of FREEDM technologies. A voice of the customer analysis was conducted to achieve these objectives. A total of 184 contacts were obtained by the team and 40 unique interviews were conducted. Electric utilities, smart grid companies, energy storage, renewable energy developers/installers, universities and research labs, policy makers, and commercial and residential energy consumers were identified as key stakeholders. FREEDM technologies have an addressable market of \$1.94 billion. The total serviceable market was not estimated because of the early stage technology development and significant uncertainty with regards to future policy changes. Industry adoption is expected to be incremental and system ownership and complementary products, such as energy storage will play a significant role. Scenario planning was used by the team to conceptualize current and future positioning of FREEDM technologies. The team was able to facilitate conversations between FREEDM, the NC Utilities Commission and the SAS Institute for future pilot projects and educational opportunities. A more in-depth commercialization plan will be needed for future business development.

3. Fundamental Research, Technological Barriers and Methodologies

N/A

4. Achievements

A voice of customer (VOC) analysis is conducted to uncover the need(s) and problem(s) of a particular market(s) to assess the commercialization potential of an idea and/or emerging technology. This analysis was done by reaching out to potential customers and key stakeholders. Both general and specific questions were asked to identify the pain points and market opportunities.

The market analysis team obtained 184 contacts as part of the voice of the customer analysis. These contacts included many key stakeholders, including; electric utilities, renewable energy developers/installers, universities and research institutions, policy makers, commercial developers, energy storage, and smart grid manufacturers. The team conducted 40 interviews (Figure 1).

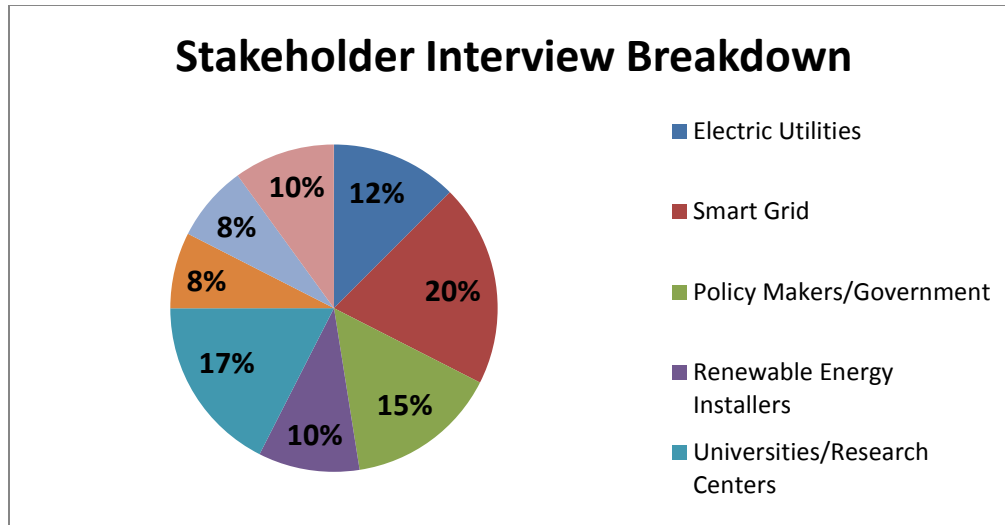


Figure 1: Stakeholder interview breakdown.

4.1 Key Market Segments

Electric Utilities

Electric utilities are expected to be early adopters and represent an addressable market of \$1.94 billion. This estimate included electric vehicle charging stations, transformer replacements, and residential solar rooftop installations. The market analysis team assumed the local electric utility would own the electric facilities in each of the different cases.

Electric utilities are allocating a significant amount of resources to modernize their grid and to lower their SAIFI (the average interruptions a customer would experience) and SAIDI (average outage duration for each customer served) scores by predicting faults and improving reliability. The increasing number of electric vehicles on the road presents a growing market opportunity for the SST. DC Fast Charge (DCFC) and Level II charging stations in particular will require transformer replacements due to their high load requirements. The adoption of the entire FREEDM System is eventually expected but wider industry acceptance and greater residential renewable energy penetration are needed. The lowest cost principle must be satisfied to gain industry acceptance. As a result, the commercialization value for the entire FREEDM System was not included in the addressable market estimate.

Smart Grid Companies

Smart grid companies view the FREEDM System as a way to modernize the electric grid. These companies are already investing in and developing products that can communicate with one another but these systems are typically on the transmission level. Companies, such as ABB, see the opportunity for grid modernization with the SST and FID by bringing the “smart” systems to the distribution level. Smart grid companies expect electric utilities to embrace these innovative technologies. These companies are a key stakeholder in development and deployment of the SST and FID component.

Energy Storage

Widespread PV adoption is contingent on advances in energy storage solutions. The grid currently acts as a battery for solar producers; the excess production is sent back to the grid. Net metering agreements (NEM), which reimburse solar producers at a retail rate for the energy sent back to the grid, help build the business case for solar. However, many utilities are scaling back NEMs by dropping reimbursement to a wholesale rate and adding fees to solar customers' utility bills. The payback period becomes too long and solar becomes impractical, especially for households who consume the majority of their power when the sun does not shine. NEMs would not be necessary with storage solutions and would allow customers to become far more independent from the central grid. Energy storage opens the possibility of price arbitrage, but many energy storage solutions are not economically feasible.

Renewable Energy Developers/Installers

Renewable energy developers and installers are critical for advancing PV adoption. These companies procure the technology, provide financing, and maintain solar systems. A solar power purchase agreement (PPA) is a financial agreement where a developer arranges for the design, permitting, financing and installation of a solar energy system on a customer's property at little to no cost. There are no major players in the solar installation industry and competition is high, especially in California and Hawaii. Solar bond markets have also emerged as a way for solar companies to finance their activities, thereby securing low cost financing for end users.

New business models and applications of solar PV panels will emerge in the future. PV shingles are coming down in price and are attractive for residential application. Solar canopies over parking lots protect cars from heat, supply nearby buildings with power, and enable electric car charging. Electric car adoption is growing and will continue to grow as storage improves. Businesses purchase charging stations and charge customers for usage; EV owners will install PV chargers in their homes.

Government and Policy Makers

Government and legislation at the federal, state, and local levels will continue to play an important role in distributed power adoption. It's unlikely that federal mandates will drive solar adoption; support at the federal level will continue in the form of incentives. States can require utilities to increase the amount of renewables on the grid, expanding the renewable energy portfolio. Municipalities can pass laws that prevent homeowner's associations from banning rooftop solar panels and speed up the approval process for solar installations.

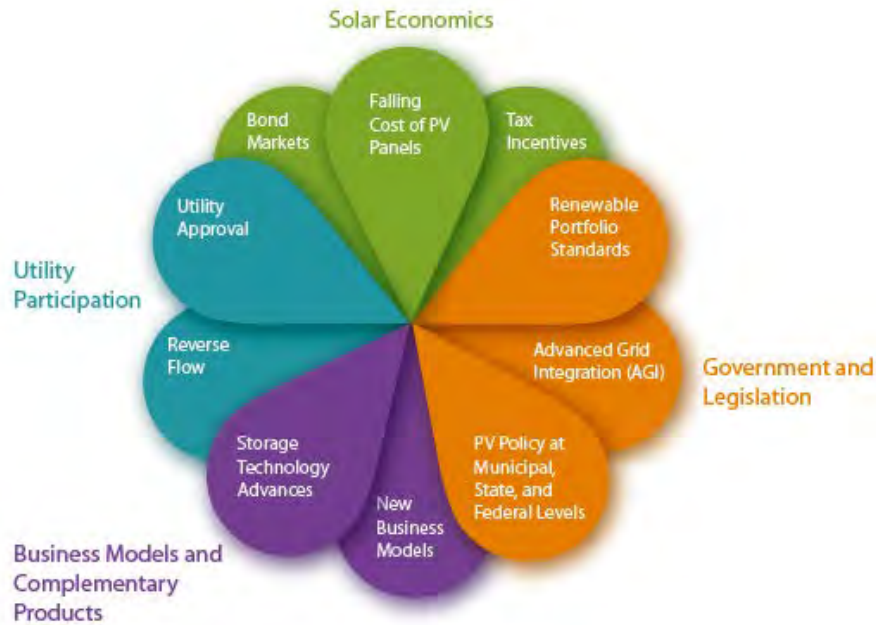


Figure 2: PV adoption is contingent on these forces coming together.

4.2 FREEDM System Value Proposition

To understand which customers would adopt the FREEDM System, it's important to understand the value that the FREEDM system can offer. After speaking with FREEDM System stakeholders, two potential value propositions were developed (Figure 3). Value propositions are constructed by considering the product capabilities and how these capabilities can solve a need. The model below is a tool for refining a value proposition for each target segment. Color cells vary by target customer segment; utilities are highlighted yellow and PV installers are highlighted in green in the example below. Each colored cell is linked to the adjacent cell to construct the value proposition.

Target Customer		Statement of the Need		Product Name	
For	Utilities	Who	Want to diversify their energy portfolio	the	FREEDM System
	Microgrid Installers		Want to accommodate more solar PV		SST
	PV Installers		Need to meet renewable mandates		FID
	EV Charger Installers		Want to reduce SAIFI scores by introducing better fault detection devices		
	Military Bases		Want to put the word smart in grid		
	Small Scale Commercial		Want to replace old technology and improve resiliency		
			Want to reduce operating costs by shaving peak demands		
			Want to explore new business models		
			Want to lower operating costs and improve reliability of their grid		

Product/service Category		Statement of Benefit	
Is a	Distribution system	That	Reduces risk by diversing electric portfolios
	Smart Grid		Allows easier government mandate compliances
	Intelligent power electronic device		Allows easy plug and play capabilities for distributed energy
	Behind the meter service		Enables predictive controls and real time market transactions
	Power Grid		Allows Energy Internet
			Allows demand side management
			Allows fault monitoring and predicting
			Reduces peak demands

Primary Competitive Alternative		Statement of Primary Differentiation		Economic Impact (Savings or Revenues)	
Unlike		Product Name	Reduces power loss in AC/DC conversion	Which leads to	20% reduction in demand at peak times
	Centralized Power Systems		Improves bi-directional power flow		Increased incentives from the government due to more renewable energy
	Current Transformers		Enables transformer level IT capabilities (real time monitoring, control, predictability)		Increased ROE due to increased SAIDI
	Current Transformers/Capacitor Banks		Price Arbitrage		Quicker DSDR (Distribution System Demand Response) for utilities.
					Better grid stability
					Greater revenue due to more efficient system operations.

Figure 3: FREEDM Value Proposition Template

Adoption Timeline

The FREEDM System was found to be the most beneficial to electric utilities when PV penetration exceeds 20%. Both governmental mandates and incentives coupled with technology advances in energy storage were identified as key drivers. Industry adoption is expected to be incremental and will take several years if not decades to change. Wider industry adoption of SSTs will enable companies to leverage data analytics to predict outages, better understand consumer demand, manage their energy system more efficiently, real-time energy pricing, and create the basis for future products. This network of these smart devices will create what is referred to as the “energy internet.”

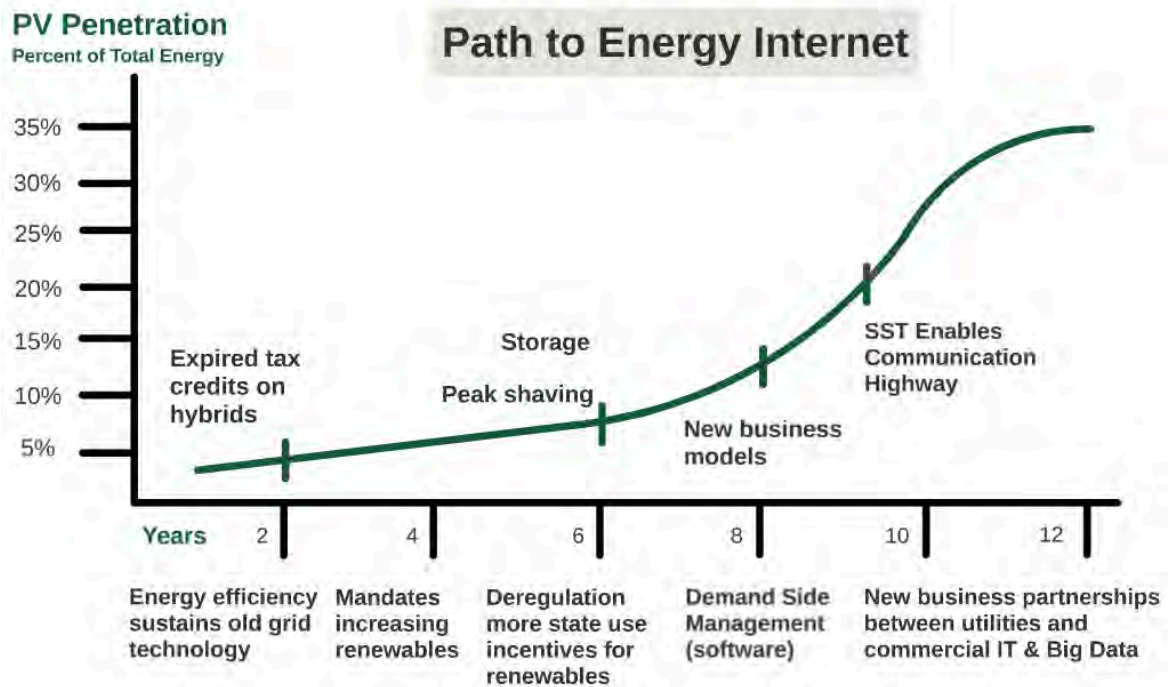


Figure 4: A possible commercialization path for FREEDM technologies adoption

Scenario Planning: A Positioning Model Understanding the Future of Distributed Energy

The scenario planning process identified two major driving forces that influence FREEDM adoption over the next decade. The vertical axis measures governmental mandates and incentives. The horizontal axis measures ownership of PV, storage and smart grid infrastructure by electric utilities and consumers (Figure 5.) These scenarios help position FREEDM technologies based on current market conditions and expected future changes.

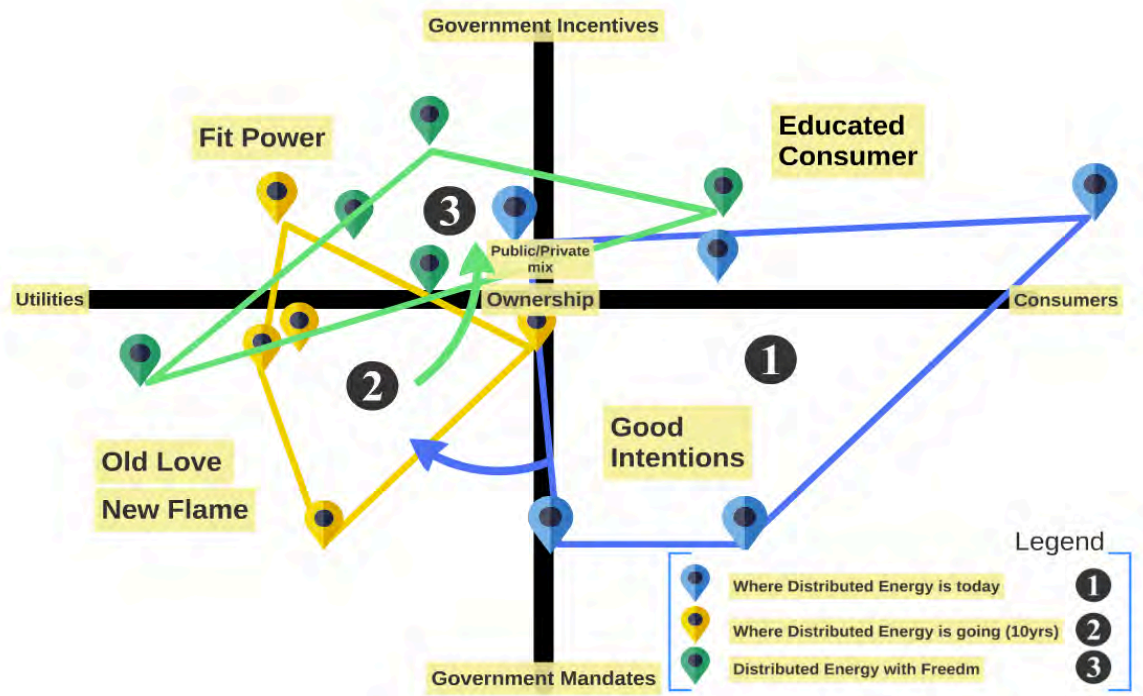


Figure 5: Scenario Planning for FREEDM Technology adoption.

Four Scenarios for FREEDM Adoption

Educated Consumer: Incentives and consumer ownership drive a piecemeal and incremental adaptation that varies by state. Neighborhoods, retailers and area developers are financing EV charging stations, PV and energy storage. Commercial big data companies are expected to play a significant role.

Good Intentions: Regulatory mandates force renewables and distributed power adoption by consumers that lead to less optimal market outcomes.

Old Love, New Flame: Regulatory mandates drive electric utilities to adopt innovative distributed power solutions. Some new business models with leasing PV and Demand Side Management are expected to emerge.

Fit Power: Incentives encourage electric utilities and smart grid companies to innovate towards a smart grid with new business models. These models are expected to integrate energy with data communication.

What does this mean for FREEDM commercialization?

FREEDM System Center's technology is well positioned to exploit the growing interest and need for distributed power and the "energy internet." Multiple issues that may hinder FREEDM System adoption include: technology deployment; government policy; cost and development of complementary products; and competing technologies. California, New York, and Hawaii were considered early adopters of distributed power due to high electricity costs, deregulation, and

favorable government policies. These markets should be targeted first by FREEDM to gain the strongest industry adoption.

In addition, the electric utilities are experiencing a shift from simple power delivery to incorporating data analytics to optimize operations and to provide the highest reliability and service to its customers. Data analytics are being used to predict and minimize outages; price electricity in real-time; help manage energy consumption and power generation; and to better understand customers' wants and needs. These techniques are creating a whole new industry for innovative products and services. The SST and data intelligence component of the FREEDM System are potentially good fits for this emerging market. SAS has expressed interest in collaborating on a pilot with the FREEDM Systems Center to explore this opportunity. In addition to real time energy data analysis, SAS envisions an SST to channel DC created by its onsite solar farm to support their 48 EV charging stations for 120 vehicles.

Despite the high future market potential of new product and services in distributed power, challenges exist for the adoption and deployment of new innovative technologies. Electric utilities are traditional tightly regulated and slow to innovative due to the severe consequences of service interruptions. Distributed power technologies are a paradigm shift compared to the centralized construction of the existing electric grid, which poses as an obstacle to early adoption. Therefore, the team foresees the adoption of the FREEDM System to be incremental and at least initially, as separate components instead of the entire system. As the technology is used and validated in the field, industry acceptance should grow over time.

Another vital component to technology deployment and industry acceptance is regulation and incentives. Electric utilities are regulated by federal agencies and state utility commissions. These governing bodies should enact financial mechanisms for utilities to recover their distributed power investments and also incentivize greater adoption. Currently, new policies are being drafted and implemented, which will shape the existing grid and what the grid will ultimately be in the near future. FREEDM Systems Center is closely monitoring new policy developments and regulations as they continue to unfold including the formation of a direct relationship with the North Carolina Utilities Commission.

The last implication identified by the market analysis team is the cost and development of complementary and competing products or technologies. Energy storage is an essential component to fully implement distributed power solutions. Currently, battery storage is not economically feasible in many situations. However, battery storage costs are expected to decline similar to solar panels over the next five years. Universities and smart grid companies are developing competing technologies. University of Central Florida and University of Southern California are developing energy solutions, such as distributed control, optimization, advance communications, smart grid, and renewable energy generation. MIT is working on dynamic pricing to exploit price arbitrage. FREEDM Systems Center should design and deploy their technology in markets with the greatest need and match their technology development to satisfy these needs better than their competition. This approach encourages greater industry adoption and commercialization potential of their innovative technologies.

Possible Next Steps

- Commit to partners to launch pilot projects, which include a dedicated team and resources to manage these projects (i.e. solar charging stations, solar to DC appliances, microgrids, etc.)

- Reach out to state utility commissions in target markets to start initial conversations (i.e. Hawaii, California, New York, etc.)
- Initiate an economic analysis and/or in-depth commercialization plan to identify technology-product-market linkages and quantify business values for multiple market segments

Y8.HIL.1: Hardware-in-the-Loop Testbed

Team Members

Project Leader:	Mischa Steurer (FSU)
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Students:	Li Feng, Stephen Jackson, Jonathan Ng, Thomas Roth, Yue Shi, Sindhuja Sundararajan, Zhenmin Tang, Qiushi Wang, Tong Yao, Selena Zabin, Yuan Zhang, Bokang Zhou
Staff:	Isaac Leonard, Harsha Ravindra, Mike Sloderbeck, Mark Stanovich

1. Project Goals

The overall objective of the hardware-in-the-loop (HIL) testbed (HIL-TB) project is to provide a flexible platform that facilitates the design, analysis, and demonstration of FREEDM concepts using both physical and simulated devices. The specific goals for this year are:

- Scientific: Develop a systematic method for comprehensive system performance evaluation of FREEDM functions on the HIL-TB
- Support deployment and testing of several system control algorithms coded in DGI as they become available
- Upgrade of the RTDS-DGI interface
- Complete implementation of HIL-TB model version control
- Improve speed and user-friendliness of remote access capability for other FREEDM users of HIL-TB
- Support CHIL and PHIL testing of protection devices and Gen-III SST and FID

2. Role in Support of Strategic Plan

The HIL-TB is one of three primary testbeds along with the Green Energy Hub (GEH) and the Large Scale System Simulation (LSSS). The GEH is primarily composed of physical FREEDM components, while the LSSS consists solely of off-line (non real-time) simulated components. The HIL-TB fills the gap between the other two testbeds by providing a platform to study physical and simulated devices together. When compared to a testbed that features only physical devices, this mixture of real and simulated hardware allows researchers to analyze cyber-physical systems in a safer and more controlled environment. Since the HIL-TB is accessible remotely from all partner schools yet it requires several disciplines to operate (e.g. DGI, RSC, and the power network simulation all have to be functional for any given use case scenario) it naturally fosters collaborations between team members.

3. Fundamental Research, Technological Barriers and Methodologies

Compared to fundamental science layer projects, this project resides at the FREEDM test bed layer. As such, we do not primarily address fundamental research challenges. However, we foster an environment (the testbed) and manage a highly interdisciplinary team to bring together all the relevant pieces of a functional system in a real-time HIL simulation based demonstration. The challenges

associated with such a project are primarily driven by the need to clearly define and establish the interfaces between all the sub-systems (SSTs, power distribution network, DGI nodes, protection algorithms, RSC network, etc.), such that a functional system of meaningful size can be established. Moreover, this project provides one of the key platforms for evaluating system designs. The central components to addressing these challenges are collaborative team work (i.e. bi-weekly phone calls, shared digital locations for files and work product, etc.) and allowing all team members access to the HIL testbed from their remote locations.

4. Achievements

This section outlines the progress made on the subtasks included in the Y8.HIL.1 project.

Performance Evaluation of FREEDM Functions Using the HIL-TB

The HIL-TB project team at FSU proposed to develop a systematic method for comprehensive system performance evaluation of FREEDM functions on the HIL-TB. This work will allow FREEDM researchers to systematically evaluate the performance of their control algorithms, components, and system concepts. Based on the principles outlined for design of experiments, this evaluation framework using the HIL-TB has been developed during this project year.

The generalized approach can be summarized as the following set of consecutive steps: determine the metrics / response quantities of interest for the specific evaluation that is to be performed, determine the experimental input parameters and their ranges, create a table of experiments, configure and run these experiments on the HIL-TB using script automation, calculate the metrics of interest, publish the test results. The HIL-TB is a diverse system of hardware and software components working together, principally the Real-Time Digital Simulator (RTDS), embedded controllers, and the OPNET network simulator. In order to coordinate these three systems for each experiment, an automated software framework was established to reduce user fatigue and bookkeeping error.

This testing framework serves to augment the experiment sample space, more easily compare control algorithms, and verify changes in a control application by observing response quantities. For each experiment, a specific run directory is created which contains all of the configuration and log files for each of the HIL-TB components. The calculated response quantities are updated in a consolidated results file after each experiment such that the user can interrupt the experiment at any time and modify the parameter space accordingly. This directory structure and methodology ensures repeatability of experiments. The framework also supports repeating the same experiment multiple times. This can be used to determine the confidence interval of the obtained response quantities.

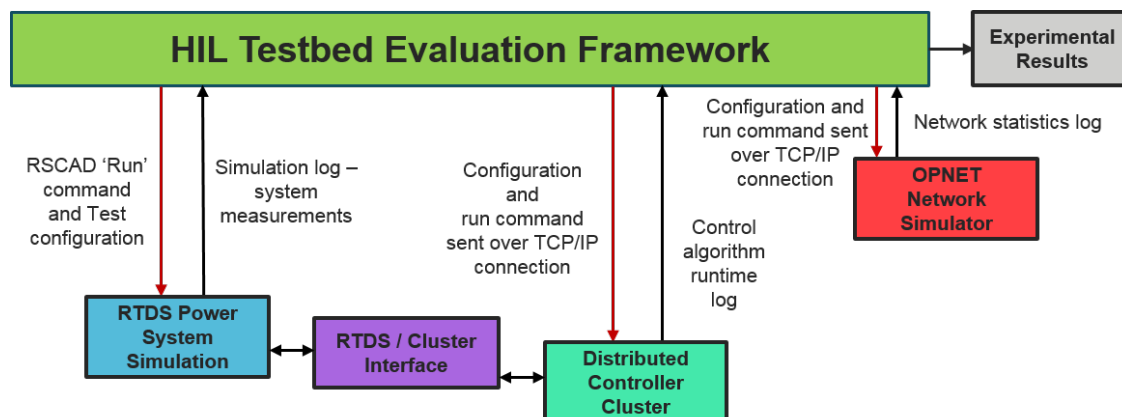


Figure 1 - HIL-TB Performance Evaluation Overview

Updated RTDS-DGI Communication Interface

To support Federated DGI research ongoing at MS&T, a new RTDS-DGI communication interface was developed to enable a larger number of signals to be passed from the real-time system simulation to the DGI processes. The previous interface was developed principally with high speed in mind, and therefore had a relatively low upper limit to the number of signals that could be communicated. The new interface uses the RTDS GTNET card, instead of an FPGA, and utilizes the GTNET-SKT protocol for message passing.

Several issues with this approach were resolved during development, however the final solution is capable of up to 240 signals (a factor of four increase), at an update rate of 200 Hz. While the previous interface was able to send out updates at the nominal simulation time step size of 50 μ s, most of our collaborating researchers reported that this level of performance was unnecessary for their control algorithms.

SST and DESD CHIL Testing Support

The SVT emphasized a focus on incorporating plug and play features in FREEDM components as well as stability demonstrations of the FREEDM system in high DG penetration scenarios. This task involves demonstrating these scenarios using CHIL experiments on the HIL-TB. DSP/FPGA control boards developed by NCSU and programmed by researchers at ASU are accessed by collaborating partners, remotely, to conduct CHIL experiments. During this year, the robust controller design developed at ASU for Gen-II SSTs was verified in CHIL on the HIL-TB. Additionally, non real-time simulations of smooth transitioning from grid-connected to grid-islanded mode for SSTs were confirmed in the real-time HIL testing environment. A Gen-III SST robust controller is currently under development using the CHIL setup on the HIL-TB. The year 8 demonstrations at the site visit will showcase new IPM developments from this project year.

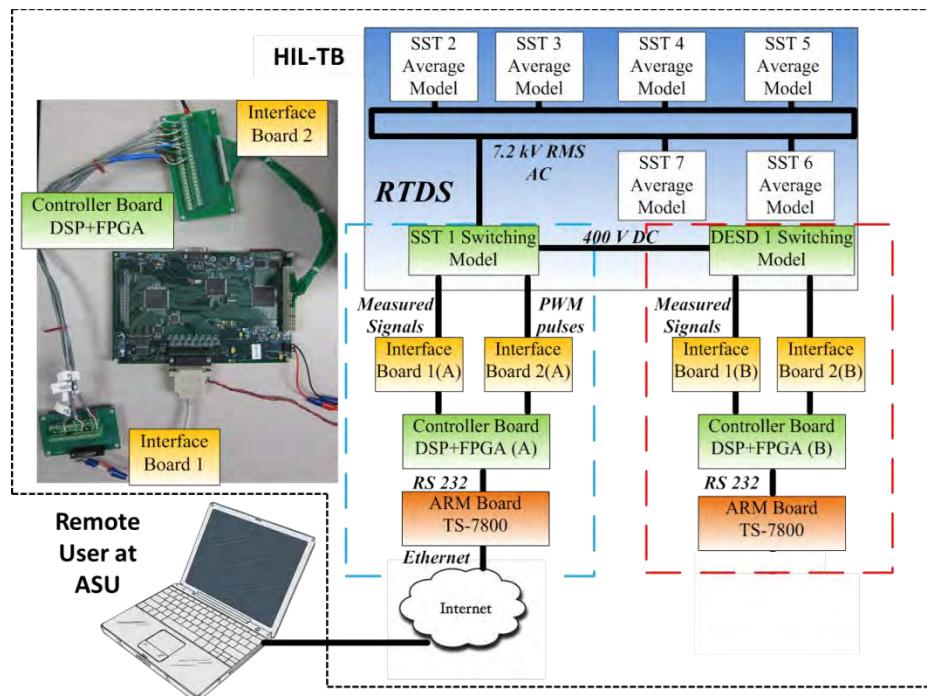


Figure 2 - SST and DESD CHIL Experimental Setups on the HIL-TB

CHIL Testing Support of Pilot Directional Differential Protection Hardware

ASU has developed a pilot directional differential protection system for FREEDM which uses two wirelessly interconnected Schweitzer digital relays. Pilot directional protection via wireless communication is designed to protect the distribution lines in the FREEDM system from faults occurring within any section of the loop. Because the magnitude of these fault currents differs very little in a looped system, it is very difficult to coordinate overcurrent protection for relays in such an environment. The ASU protection system was tested using CHIL techniques on the HIL-TB during year 8. Two SEL-351S directional protection relays were interfaced with the RTDS to detect a wide variety of simulated fault conditions. The inputs to the relays were low voltage signals representing secondary currents and voltages at different monitoring locations within the looped distribution system. The trip signals from each relay were sent back into the simulation to control simulated Fault Isolation Devices (FID).



Figure 3 - ASU Protection Hardware CHIL Setup on the HIL-TB

5. Other Relevant Work Being Conducted Within and Outside of the ERC

This project has no associated projects currently taking place within the FREEDM ERC.

6. Milestones and Deliverables

- Q3 (9.30.2015) – Completed implementation of HIL-TB model version control
- Q4 (12.31.2015) – Updated the RTDS-DGI communication interface
- Q1 (3.31.2016) – Upgrade of OPNET communication network functionalities
- Q2 (6.1.2016) – System demonstration with all components of a FREEDM system operational simultaneously
- Q2 (6.30.2016) – Systematic method for comprehensive system performance evaluation on the HIL-TB

7. Plans for Next Five Years

Overall, the HIL-TB is on a very good trajectory for graduation of the FREEDM System Center. Plans for the next few years include: continuing to increase the complexity of the system the HIL-TB can simulate and improve the framework for evaluating performance of system control deployed/tested on the HIL-TB. This requires continuing expansion of the number of SST and DGI nodes, as well as the number of local loads and energy sources connected to the LV side of the SSTs. As the Gen-III SST and FID matures the focus of the HIL-TB regarding PHIL testing will increase accordingly. The HIL-TB team will also spend a significant amount of effort in the next few years to develop and automate

benchmark use cases so that comparisons of different control and protection functions can be performed using the performance evaluation framework developed in year 8.

8. Member Company Benefits

No member companies are related to this project.

9. References

- [1] K. Schoder, Z. Cai, S. Sundararajan, M. Yu, M. Sloderbeck, I. Leonard, M. Steurer, "Real-Time Simulation of Communications and Power Systems for Testing Distributed Embedded Controls", Engineering & Technology Reference, 10.1049/etr.2015.0022, ISSN 2056-4007, www.ietdl.org
- [2] T. Yao, I. Leonard, R. Ayyanar, M. Steurer "Single-Phase Three-Stage SST Modeling using RTDS for Controller Hardware-in-the-Loop Application", in Proc. of the IEEE Energy Conversion Congress and Expo (ECCE), Sep 20-24, Montreal, Canada

Y8.HIL.2: Reliable and Secure Communication Development in Support of the HIL Testbed and FREEDM Systems Center

Team Members

Project Leader: Ming Yu

Students: Jonathan Ng

1. Project Goals

Since year five of this project our goals have been building a real-time network simulation environment that suits the needs of DGI's data communications, affiliating additional security and quality control functions to the environment, and comparing the performance impacts of different security levels on the communication network. For this year, our specific goals are:

- Maintain and extend the system-in-the-loop (SITL) module with ECN support demonstrated in year 7
- Measure the impact of security implementations on network performance; choose optimal security measures with appropriate encryption key lengths

2. Role in Support of Strategic Plan

The communications network is a distinctive building block of the complete system that operates outside of the Real-Time Digital Simulator (RTDS) on the HIL Testbed. Any communication traffic generated by DGI is routed through the simulated networks inside OPNET, which can simulate metrics such as latencies, network breakage and recovery, so that the DGIs can be preprogrammed to cope with unexpected situations affecting their command interactions. Traffic is converted into OPNET packets when it enters the simulated communications network by adding additional simulation information through packet encapsulation, then it is converted back to real TCP/IP packets before it leaves OPNET. In this way, the expensive cost of communication network hardware is saved for research purposes.

3. Fundamental Research, Technological Barriers and Methodologies

The network simulation development involves work in three stages: 1) Configuration of the simulation environment to integrate with the DGI platform; 2) Interaction between OPNET and OS tools to achieve desired goals for secure and reliable communication, which involves programming both inside OPNET and on the Linux OS; 3) Measure the impacts of the network simulation on the DGI communications.

With respect to the goals, there are two main challenges regarding the implementation and the performance of the system.

One challenge during the implementation is that the closed source code of OPNET makes it unrealizable to obtain the structure of the packets that are captured inside OPNET. This posts extra work on the ECN mechanism to reduce the effects of network congestion for improved communications quality. The final solution is combining code modifications in OPNET and other utility programs on Linux to realize the same functions as when ECN is enabled on the Linux OS.

Another challenge is the impact of encryption on the communication latency. First, encryption itself requires additional computation time; second, the Blowfish encryption algorithm also lengthens the transmitted data, which would cause longer transmission time. Although data compression (Zlib) can

theoretically reduce the amount of data transmitted, the real influence of the encryption on the responsiveness of the system needs further investigation.

4. Achievements

Encryption on the transport layer for DGI communications is implemented with Zebedee

We implemented encryption on the transport layer for the communications between the DGIs through the OPNET simulated network. The encryption is through an open source tool “Zebedee” on the Linux OS. The comparison of the data flowing between DGIs before and after the encryption process is inserted is illustrated as in Figure 1.

“Zebedee” uses Zlib compression, Blowfish encryption and Diffie-Hellman key agreement as the core algorithms. When a communications session is initiated, all traffic from the DGI (which uses a specific port) is mapped to another port on the initiating DGI host. The new port is connected by Zebedee to the same port on the destination host, where the port is mapped back to the original port that DGI reception would use. Thus, all traffic on the IP level is protected by the encryption of Zebedee, while no additional modifications are needed for the DGIs. On the other hand, the encryption incurs additional computation to the DGI host computers and may cause extra delays, in which case Zebedee allows for encryption of different strengths by adjusting key generation levels and key lengths to alleviate the impacts on the systems.

This mechanism is illustrated as follows in Figure 1:

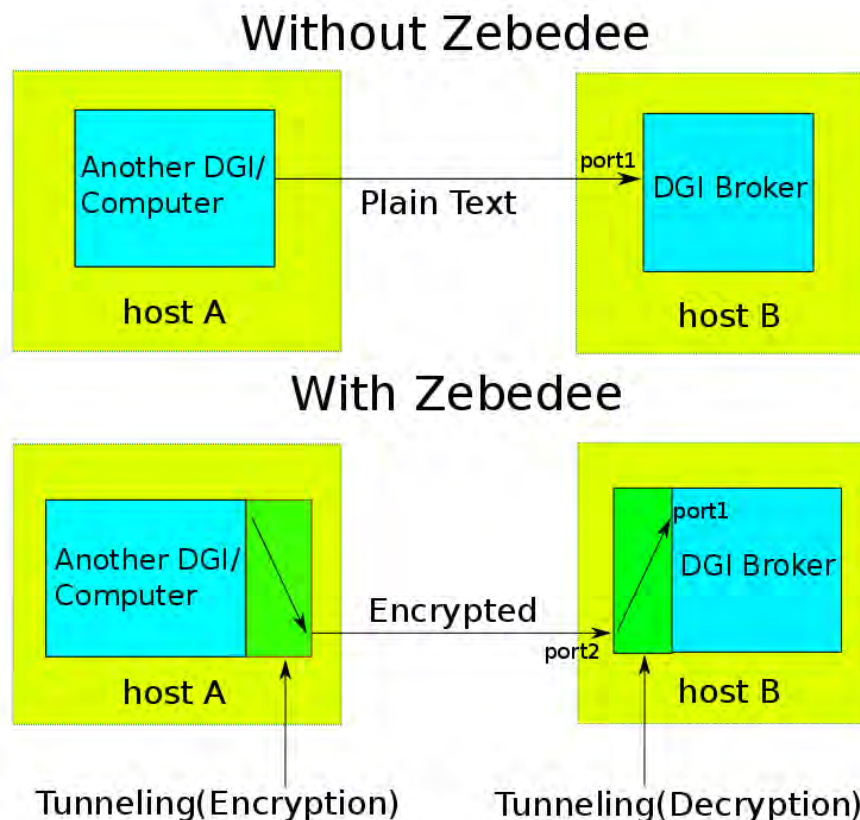


Figure 1 - Zebedee IP tunnel encryption for secure DGI communications

ECN network congestion control via client-server structure between OPNET and DGI

We implemented a similar mechanism for ECN congestion notification for the traffic through OPNET compared with the one that is available on the Linux OS.

According to RFC 3168, ECN uses the two least significant (right-most) bits in the IPv4 or IPv6 header originally for the DiffServ field to express the network congestion state. For ECN Capable Transport (ECT) packets, routers in between terminal nodes can set both bits to denote CE (Congestion Encountered) to inform the receiver of the network condition, instead of dropping the packets. The receiver then needs to echo back the sender the bits to signal it to adjust its transmission rate. Due to the closed source attribute of OPNET, directly modifying the ECN bits in the IPv4 header through analyzing the source code of OPNET is not realizable. Therefore, we take another approach to realize the same function by implementing a client-server structure between OPNET and the sender.

The implementation adds new code into OPNET and also makes use of tools that are already on Linux, namely, “tc”, which is a traffic control command for the kernel and can do shaping, scheduling, policing, and dropping of the packets.

When OPNET begins to drop packets that it receives, which means that the network is becoming congested so that all packets cannot be sent out from the buffer in time, OPNET, which runs as a client, will send out a message to the DGIs. A service in the DGIs runs as a server and receives the message, and will start an external program to regulate the traffic rate, which would decrease the data rate. Therefore, the congestion at the central OPNET node will be alleviated. When no congestion has been detected for some time, OPNET will send another message to the DGIs. After the service in the DGIs receives the message, it will slowly increase the data rate. Thus, a congestion control mechanism is implemented through a closed-loop control. Figure 2 below illustrates the control structure.

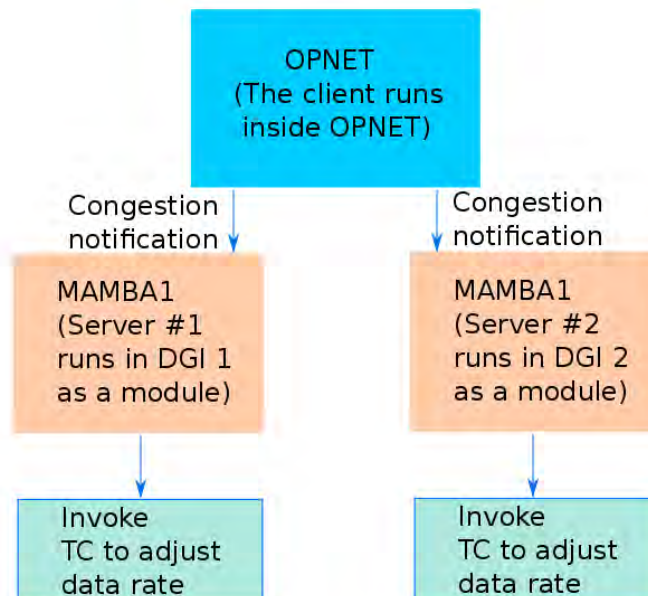


Figure 2 - Network congestion notification and control through a client-server structure

Experimental results on the impact of security on network performance

With the default key generation level (2) and the default key length (128), latencies on the transport layer from MAMBA1 to MAMBA2 with and without the Zebedee tunneling encryption are tested with NetPIPE (a latency test tool) using OPNET as the routing unit. The results are shown below in Figure 3.

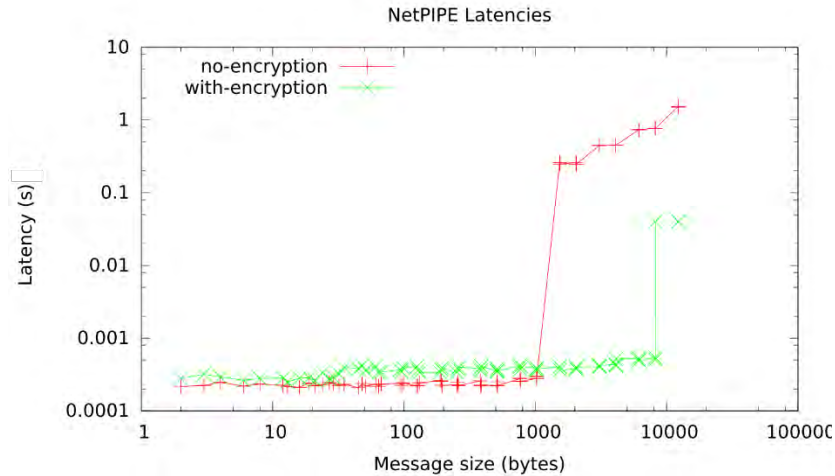


Figure 3 - Comparison of TCP latency on the transport layer from MAMBA1 to MAMBA2 with and without Zebedee tunneling encryption

From the results, it can be seen that when the message size is less than the MTU of Ethernet (1500 bytes), which means that a message can fit into one Ethernet frame, the performance without encryption is a little better than with encryption, with the latency of the latter being approximately 47% longer than that of the former. When the message size exceeds 1500 bytes, the performance with Zebedee encryption overwhelms the counterpart by a very large scale (over 30 times shorter latency). The gain can be attributed to the data compression by Zlib, which also means that when the data transmitted is not compressible (for example, the data is already compressed before transmission), the gain can fall back to the previously mentioned situation.

When the routing for MAMBAs is done through a switch (namely using the 192.168.200.xxx IP addresses of the MAMBAs) instead of OPNET, the results are slightly different:

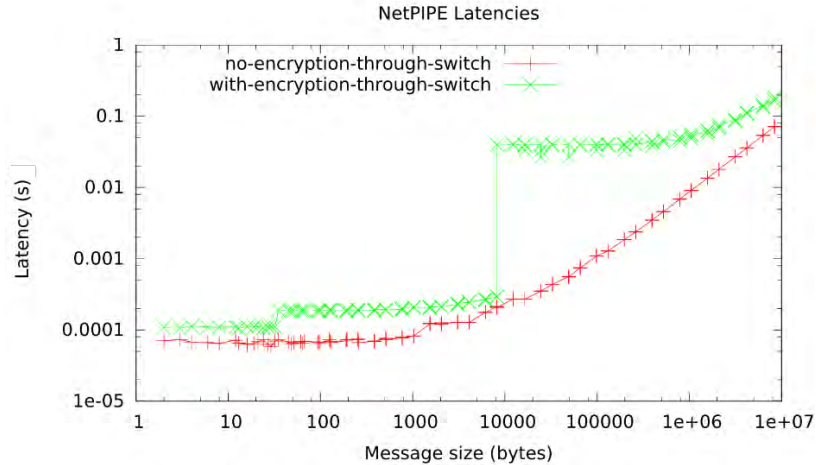


Figure 4 - Comparison of TCP latency on the transport layer from MAMBA1 to MAMBA2 with and without Zebedee tunneling encryption, while the traffic is through a switch

It can be seen that without IP tunneling, the latency is uniformly lower than it is with tunneling. The differences for small message sizes are approximately the same as in Figure 4, while the scenarios for larger message sizes differ by a large margin. This can be explained by the difference in performance between a switch and a network simulation device (OPNET) when processing a large amount of data.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

This project has no associated projects currently taking place within the FREEDM ERC.

6. Milestones and Deliverables

- Demonstration of transport layer encryption at the site visit
- Demonstration of ECN and DGI communication throttling at the site visit

7. Plans for Next Five Years

As the security features in the peer-peer communications develops we must also develop adequate means of testing their efficacy and their impact on system control performance. Moreover, the system level topic of “cyber security” of “cyber physical energy systems” should include not only methods to prevent cyber intrusions but also, and maybe more effectively so, methods to detect emerging adverse behavior of the energy system and a graceful degradation of performance to avoid catastrophic events. We plan to develop approaches for all of these needs in the context of this project in the future.

8. References

Z. Cai, M. Yu, M. Steurer, H. Li, Y. Dong, "Network Modeling for A Real-time Hardware-in-the-loop Prototype of Smart Grid Distributed System," Journal of Network and Computer Applications, Volume 59, January 2016, Pages 264-273, ISSN 1084-8045

Y8.HIL.3: Volt-Var Control on FREEDM System

Team Members

Project Leader: M. Baran

Students: Yue Shi

1. Project Goals

The goal of this task is to implement the decentralized volt/var control method which has been developed over the last two years for the FREEDM systems. Main effort will involve the following:

- 1.1. Port the code to the recent DGI platform and run it on the ARM boards.
- 1.2. Develop a test case and implement it on the HIL at FSU. This will allow us to demonstrate the performance of the proposed method.

2. Role in Support of Strategic Plan

Volt/Var is one of the main real-time system level control functions on the FREEDM systems.

3. Fundamental Research, Technological Barriers and Methodologies

Volt/Var is currently an active research area as it is the main application for smart distribution systems. The control function is not unique, but the proposed method is new and it makes use of the additional capability FREEDM provides.

4. Achievements

Volt-Var control (VVC) is one of the main real-time control functions on a distribution system. Within last two years the focus has been development of decentralized control schemes for VVC. Decentralized schemes make use of the DGI in order to facilitate actual implementation, and thus achieve the main benefits of a decentralized control.

This year's efforts on VVC has focused on two subtasks: (i) finalize the gradient based scheme developed last year and test the scheme on a PSCAD based platform, (ii) migrate the VVC to the HIL based platform, which is the final goal. The accomplishment made this year on these two tasks are summarized below.

4.1. Gradient based Decentralized Volt/Var Control Scheme

In this scheme, the updates for the controls – reactive power injection Q_{inj} settings for the SSTs – are updated using the gradient:

$$\nabla f = \frac{\partial P_{loss}}{\partial Q_{SST}} = - \left[\frac{\partial g}{\partial Q_{SST}} \right]^T \lambda$$
$$\text{where } \frac{\partial g}{\partial Q_{SST}} = \begin{bmatrix} \frac{\partial \Delta P}{\partial Q_{SST}} \\ \frac{\partial \Delta Q}{\partial Q_{SST}} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \lambda = - \left(\begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix}^T \right)^{-1} \begin{bmatrix} \frac{\partial P_{loss}}{\partial \theta} \\ \frac{\partial P_{loss}}{\partial V} \end{bmatrix}.$$

The Q_{inj} for the SSTs are then updated as

$$Q_{SST}(k+1) = Q_{SST}(k) - \nabla f \cdot \beta$$

at each control update step [1]. To improve the performance of the method, a search is needed in order to determine the proper step length β^* . For this purpose, a search method has been developed. The method starts with a small β and updates it iteratively as follows:

$$\beta(j+1) = 1.1\beta(j)$$

at each update a power flow is run to determine if the new β improves the objective function – power loss in VVC. Iterations stops when the power loss stops decreasing.

Since, the gradient represent the sensitivity of the controls Q_{inj} to objective function, the gradient elements with sensitivities which are close to each other can be grouped to identify groups which can be controlled with a local controller. On a radial distribution feeder, it has been observed that nodes close to each other have similar sensitivities. Fig. 1 illustrates the groups obtained on the prototype LSSS test system. These two observations motivated us to develop a Master-Slave based decentralized control scheme. The master will be a controller at the substation and it calculates the gradient, and then sends the control update ΔQ_{inj} to each local control which acts like a slave and controls the SSTs within the group. The main structure of the scheme is as follows [2]:

Master

- o Calculates gradients and determine the optimal step-size
- o Sends the new updates to all slaves

Slaves – Group Control

- o Each VVC slave controls the nodes with similar sensitivity
- o After receiving gradients of the nodes under the same VVC slave, each VVC slave averages gradients and multiplied by step-size to get ΔQ_{SST} and then send the updated control command Q_{SST} to the nodes.

Test results using the LSSS test feeder are given in Figures 2 and 3. As the figures shows, this is a simulation of VVC on the test feeder for a day. The control update rate is xx min. The results in Fig. 3 show that the proposed method is quite effective in following the load and making the necessary Q_{inj} adjustments for SSTs in order to keep the power loss on the system minimum while keeping the node voltages within limits. Figure 3a shows the improvement in power loss as compared with the default control of unity power factor for SSTs.

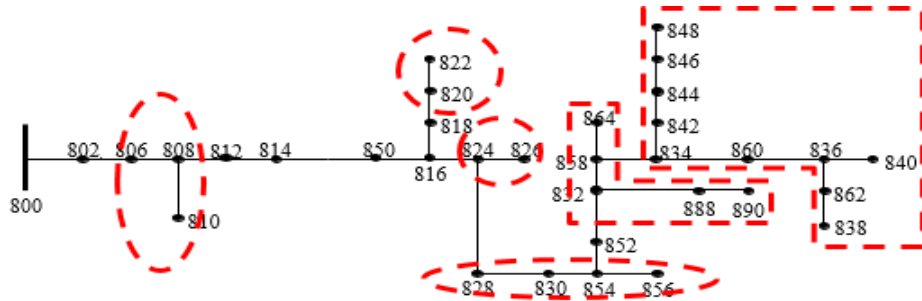


Figure 1: Grouping of SST nodes on LSSS test feeder based on gradient

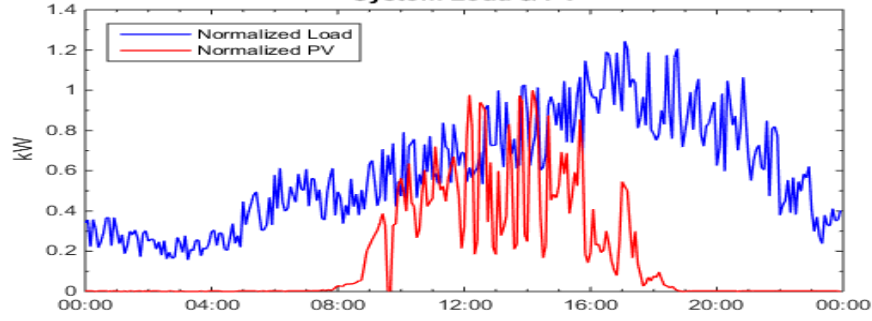


Figure 2: Load and PV profile for the test feeder

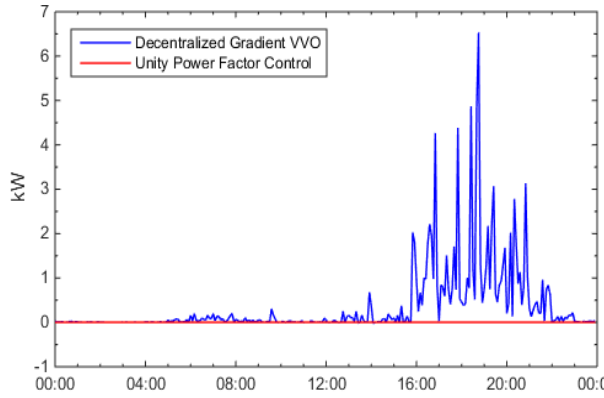


Figure 3a: Power loss reduction

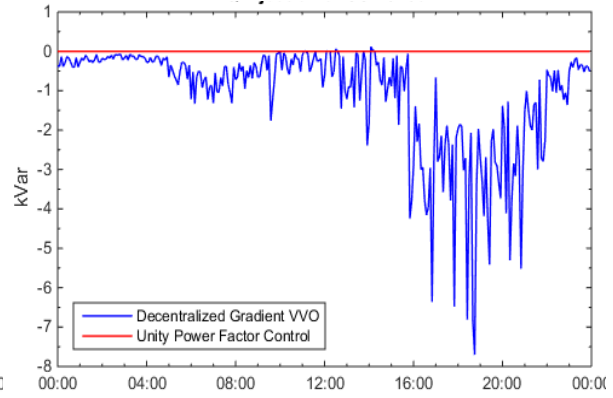


Figure 3b: Qinj for SST at node 840 phase C

4.2. VVC Implementation Using DGI

This subtask aims at implementing the proposed decentralized scheme on the FREEDM DGI platform. This is achieved in two steps. The first step involved migrating the VVC algorithm which is originally written in Matlab to C++ so that it can be integrated to DGI platform. To facilitate this step, a PSCAD based tested is used. Once the method is tested, the method is migrated to hardware based DGI controllers and tested in HIL. These steps are summarized below.

4.2.1. VVC migration to DGI

The VVC module has been created in DGI 2.0. To implement master-slave control scheme, communication between two DGI nodes has been established. Also, to receive data from the feeder, interface between the DGI software and the simulation software which simulates the feeder has been established. For the initial testing, PSCAD based platform is used. Fig.4 shows the simulation platform. Data exchanges shown in the figure is as follows: (i) Send/receive float number and/or string between a DGI node and PSCAD; (i) Array data exchange between DGI nodes so that Master can send data to slaves and Slaves can receive the array sent by Master.

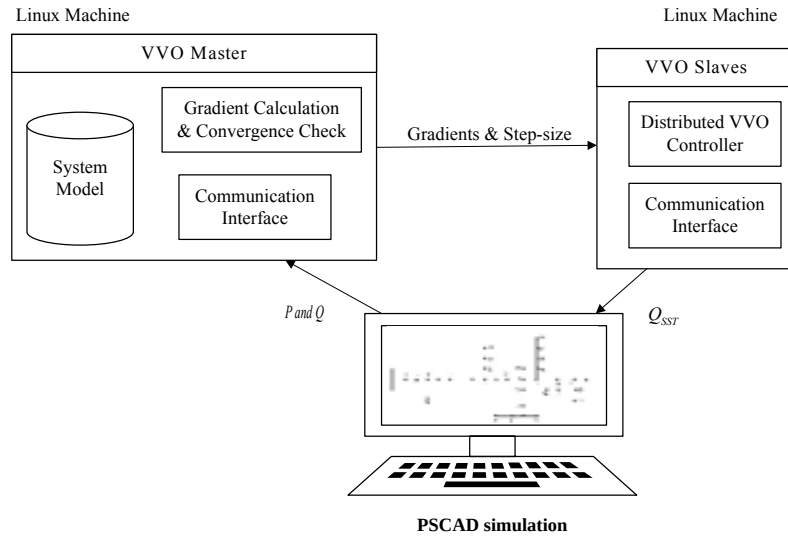


Figure 4: PSCAD based Test platform for VVC testing

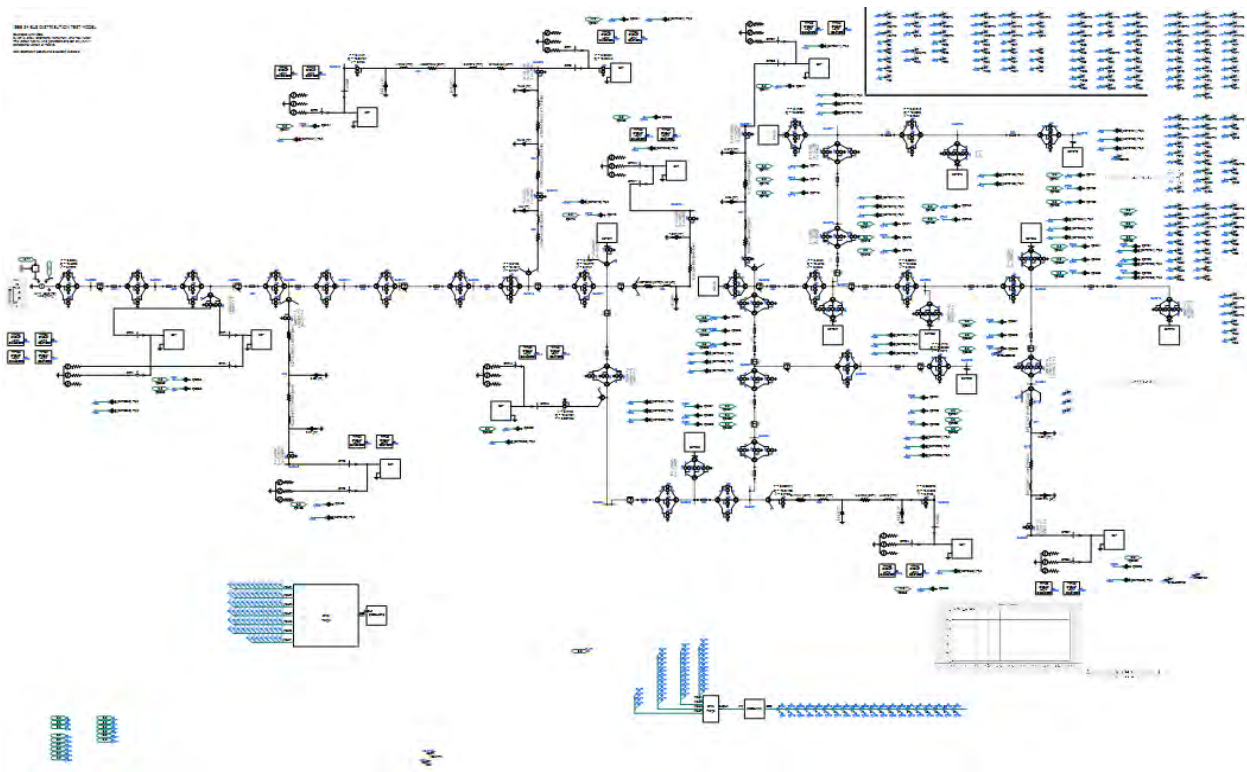


Figure 5: LSSS system simulation in PSCAD

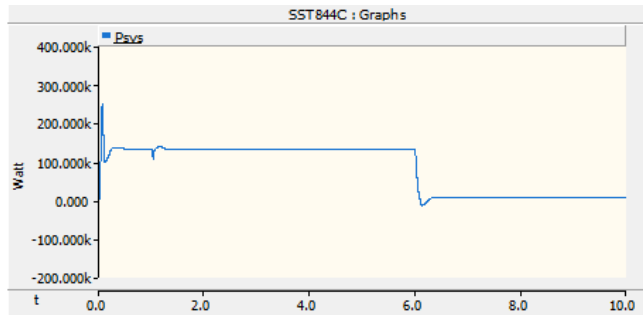


Figure 6a: Load change at Node 844

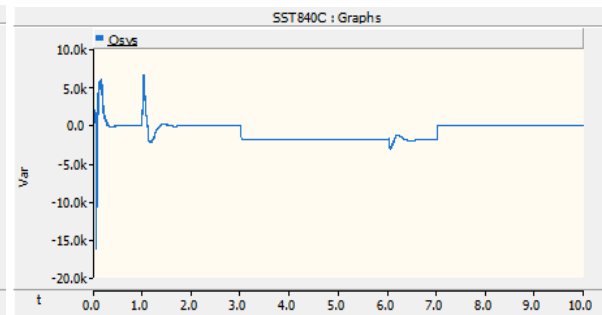


Figure 6b: Qinj from SST at node 840 phase C

Figure 5 shows the LSSS prototype system simulated on PSCAD, and Fig. 6 shows the test results on this platform for a case of load change on the prototype test feeder. As the figure shows, system sends data to DGI at $t=2s$ and receives the new control set points from DGI at $t=3s$. As three phase load at Node 844 decreases at $t=6s$, the VVO master calculates the new gradient based on the data received, and sends the updated adjustments to the slave nodes. Slave nodes then in turn send the updates Qinj settings to SSTs in the group. The actual reactive power injection from SST at node 840 is shown in Fig. 6b. As the figure shows, the SST injects less reactive power into the system as the load decreases.

4.2.2. VVC migration to HIL

As a first step of migrating VVC to HIL, the seven node system in RSCAD (RTDS simulation software) has been revised to obtain a more realistic feeder for VVC. Fig. 7 shows this reduced system. Currently working on the second step, which involves porting of VVC code to microprocessor, based DGI nodes (Mambo boards) so that VVC can be tested in HIL set up at FSU. This is a collaborative effort between NC State, FSU, and MST, and it is expected that the work will be completed at the end of April 2016.

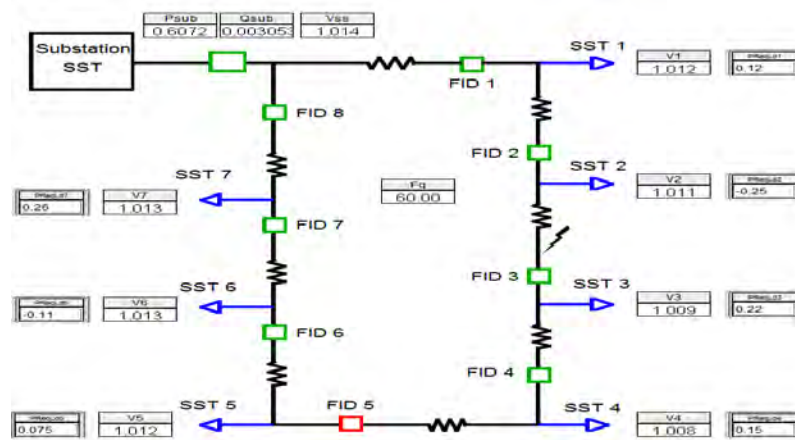


Figure 7: Test System on RTDS for HIL testing

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Volt-Var control is currently an active research area, and also being implemented and integrated into the new advanced DMS systems.

6. Milestones and Deliverables

Q3 (9/30/2015) – Port the Volt/Var control program to DGI 2.0

Q4 (12/31/2015) – Implement the Volt/Var program on the ARM board

Q1 (3/31/2016) – Demonstrate Volt/Var control on HIL

Deliverable (04/2016) – Volt/Var control demonstration on HIL and GEH

Final Deliverable (08/2016) – A report and a journal paper

7. Plans for Next Five Years

Next year, we are planning to field test the VVC on GEH.

8. Member Company Benefits

Duke energy has implemented a VVC using a centralized SCADA system. Will contact Duke R&D team about their interest in the proposed scheme.

9. References

- [1] Z. Shen; M. E. Baran, "Gradient based centralized optimal Volt/Var control strategy for smart distribution system", IEEE PES Conf. on Innovative Smart Grid Technologies (ISGT), 2013.
- [2] Z. Shen, Y. Shi, M. Baran, "A Decentralized Volt/Var Optimization Scheme for Smart Distribution Systems", to be submitted to IEEE PES Conf. on Innovative Smart Grid Technologies (ISGT), 2016.

Y8.HIL.4: Multi-SST Cooperative Distributed Energy Scheduling

Team Members

Project Leader: Dr. Mo-Yuen Chow

Students: Yuan Zhang

1. Project Goals

Research and develop Cooperative Distributed Energy Scheduling (CoDES) algorithm version 2.0 with the following features:

- Consider DESD charging/discharging efficiencies in scheduling
- Consider DESD degradation factors in the scheduling process
- Integrate load balancing algorithm with CoDES algorithm to do real-time adjustment through collaboration with MST
- Consider demand charge in the objective function to do peak shaving
- Investigate efficient strategies/algorithms to incorporate plug-and-play features such as addition/removal of devices into CoDES in Distributed Grid Intelligence (DGI) 2.0

2. Role in Support of Strategic Plan

This project provides an algorithm that demonstrates the cooperative distributed energy management for FREEDM system in HIL testbed

3. Fundamental Research, Technological Barriers and Methodologies

The fundamental research component of this project in Y8 is to add new features into the CoDES algorithm, the framework of which has already been developed in previous years of the project. The features to be added into this algorithm in Y8 are as described in the project goals.

The major technological barrier of this project is how to solve the energy management problem when new features are included in the problem formulation using the CoDES framework. The methodology to deal with this barrier is to use various techniques in operation research to convert the nonlinear constraints into linear constraints.

Another technical barrier of this project is how to extend the CoDES for system real-time operations. The methodology being used currently is to incorporate the load balancing algorithm developed in MS&T to do real-time adjustment of the DESD dispatch command when there is a mismatch between the forecasted profiles (DRER generation and demand) and the actual system operation profiles.

4. Achievements

4.1. Cooperative distributed energy scheduling algorithm (Y7)

The first version of the CoDES algorithm was developed in Y7. It calculates the charging and discharging schedule of DESDs in a FREEDM system that minimize the total electricity bill of the system for a certain time period (e.g., 24 hours) in a distributed way.

Consider a simple 4-node system as shown in Figure 1. The objective of the problem is to minimize the electricity bill for the entire system, as described in (1).

$$\min \sum_{t=1}^T p(t)P_{grid}(t)\Delta t \quad (1)$$

where $p(t)$ is the utility electricity cost, $P_{grid}(t)$ is the power drawn from the grid, and Δt is the time interval of the energy management.

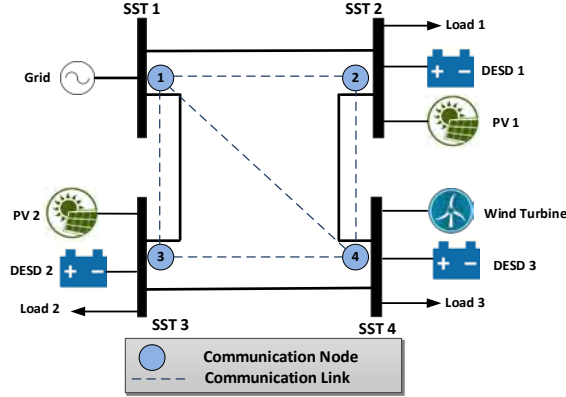


Figure 1 - Simple 4-node system

For $\forall 1 \leq t \leq T$, the problem is subjected to the following constraints:

a. Power balance:

$$\sum_{i \in B} P_{i,B}(t) + \sum_{i \in R} P_{i,R}(t) + P_{grid}(t) = \sum_{i \in D} P_{i,D}(t) \quad (2)$$

where $P_{i,B}(t)$, $P_{i,R}(t)$, $P_{grid}(t)$, and $P_{i,D}(t)$ are the DESD charging and discharging power, forecasted DRER generation, grid power drawn, and forecasted load during time step t . B , R , and D are the set of DESD, DRER, and demand, respectively.

b. DESD capacity for $\forall i \in B$

$$E_{i,B}^{min} \leq E_{i,B0} - \sum_{s=1}^t P_{i,B}(s)\Delta t \leq E_{i,B}^{max} \quad (3)$$

where $E_{i,B}^{min}$ and $E_{i,B}^{max}$ are the minimum and maximum energy limit.

c. DESD power rating for $\forall i \in B$ and grid power rating

$$P_{i,B}^{min} \leq P_{i,B} \leq P_{i,B}^{max} \quad (4)$$

$$P_{grid}^{min} \leq P_{grid} \leq P_{grid}^{max} \quad (5)$$

where $P_{i,B}^{min}$ and $P_{i,B}^{max}$ are the minimum and maximum of DESD charging and discharging power, and P_{grid}^{min} and P_{grid}^{max} are the minimum and maximum grid power.

In the CoDES algorithm, each SST is modeled as an agent which has access to the information of connected local devices. The agents also form a communications network to exchange information with each other. By utilizing the primal-dual gradient descent method and consensus algorithm, the CoDES algorithm is able to solve the optimization problem as formulated previously in a distributed way as long as the communications network formed by the agents is connected. Please refer to paper [1] for details on the CoDES algorithm.

4.2. CoDES with charging/discharging efficiency and battery degradation cost (Y8)

One natural extension of the CoDES algorithm is to consider the DESD charging and discharging efficiencies and degradation cost in the optimization problem formulation.

Assume η_i is the efficiency of the i^{th} DESD, the energy in each of the DESD follows the dynamic:

$$E_{i.B}(t+1) = \begin{cases} E_{i.B}(t) - \frac{P_{i.B}(t)}{\eta_i} \Delta t, & P_{i.B}(t) \geq 0 \\ E_{i.B}(t) - \eta_i P_{i.B}(t) \Delta t, & P_{i.B}(t) < 0 \end{cases} \quad (6)$$

where $E_{i.B}(t)$ is the energy stored in battery during time step t . By considering the DESD efficiencies, the DESD capacity becomes:

$$E_{i.B}^{\min} \leq E_{i.B0} - \sum_{s=1}^t \frac{[P_{i.B}(s)]_{[0,\infty]}}{\eta_i} \Delta t - \sum_{s=1}^t \eta_i [P_{i.B}(s)]_{[-\infty,0]} \Delta t \leq E_{i.B}^{\max} \quad (7)$$

where $[x]_{[a,b]}$ is the projection function

$$[x]_{[a,b]} = \begin{cases} a, & \text{if } x \leq a \\ x, & \text{if } a < x < b \\ b, & \text{if } x \geq b \end{cases} \quad (8)$$

As can be seen from equation (7), the DESD capacity constraint becomes a nonlinear constraint. Denote two new variables $P_{i.B}^{(+)}(t)$ and $P_{i.B}^{(-)}(t)$ as:

$$P_{i.B}^{(+)}(t) = \begin{cases} P_{i.B}(t), & \text{if } P_{i.B} \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

$$P_{i.B}^{(-)}(t) = \begin{cases} 0, & \text{if } P_{i.B} \geq 0 \\ P_{i.B}(t), & \text{otherwise} \end{cases} \quad (10)$$

Then, the actual $P_{i.B}(t)$ becomes $P_{i.B}(t) = P_{i.B}^{(+)}(t) - P_{i.B}^{(-)}(t)$. As a result, the constraint (7) becomes:

$$E_{i.B}^{\min} \leq E_{i.B0} - \sum_{s=1}^t \frac{P_{i.B}^{(+)}(s)}{\eta_i} \Delta t - \sum_{s=1}^t \eta_i P_{i.B}^{(-)}(s) \Delta t \leq E_{i.B}^{\max} \quad (11)$$

and the constraint (2) becomes:

$$\sum_{i \in B} (P_{i.B}^{(+)}(t) - P_{i.B}^{(-)}(t)) + \sum_{i \in R} P_{i.R}(t) + P_{grid}(t) = \sum_{i \in D} P_{i.D}(t) \quad (12)$$

Based on [2]–[5], the battery degradation cost of a battery in \$/kWh can be modeled as follows:

$$c_d = \frac{\text{Battery replacement cost}}{\text{Total energy throughput during lifecycle}} \quad (13)$$

Denote $C_{i.B}$ as the cost of the battery (\$/kWh), $E_{i.B}^{\text{full}}$ as the capacity of the battery in kWh, $L_{i.B}$ as the battery lifetime in terms of cycles as a function of depth of discharge (DoD), and $DoD_{i.B}$ is the DoD of the battery. The battery degradation cost of the battery at i^{th} bus can be calculated as:

$$c_{i.B.d} = \frac{C_{i.B} E_{i.B}^{full}}{2L_{i.B}(DoD)E_{i.B}^{full} DoD_{i.B}} = \frac{C_{i.B}}{2L_{i.B}(DoD)DoD_{i.B}} \quad (14)$$

By modeling the battery degradation cost in this way, the long-term battery wearing can be quantified to each kWh that it is charged and discharged daily. As a result, the battery degradation cost can also be included into the problem formulation, and the objective of the scheduling problem becomes:

$$\min \sum_{t=1}^T \left(p(t)P_{grid}(t) + \sum_{i \in B} c_{i.B.d}(P_{i.B}^+(t) + P_{i.B}^-(t)) \right) \Delta t \quad (15)$$

The same CoDES framework as described in 4.1 is used to solve the new optimization problem in distributed way. A paper has been accepted by IEEE 2016 International Symposium of Industrial Electronics (ISIE).

4.3. Implement the CoDES algorithm in DGI 2.0 (Y8)

The CoDES algorithm described in 4.1 and 4.2 is implemented using DGI 2.0. The DGI code is deployed and executed in Beaglebone Black boards. The program is able to calculate the 24-hour charging and discharging schedule of DESDs of the 4-node system as shown in Figure 1 within five minutes.

4.4. CoDES using load balancing for real-time tuning (Y8)

What the CoDES algorithm calculates are the charging and discharging schedules of the DESDs installed in the system. As described in section 4.1, some of the inputs to the CoDES algorithm are the forecasted DRER generation and load profiles. However, the real-time operational status of the system may deviate from the forecasted profiles. In order to handle this mismatch, the Load Balancing [6] algorithm previously developed by MS&T can be utilized as a preliminary approach. The approach for integration of CoDES and DGI's Load Balancing algorithm is shown in Figure 2.

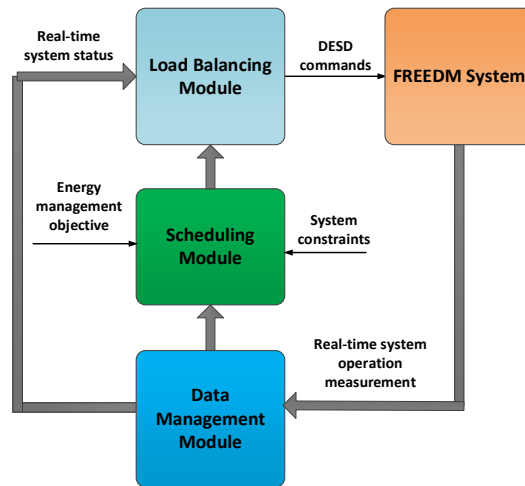


Figure 2 - CoDES real-time operation with DGI Load Balancing algorithm

4.5. CoDES with demand charge consideration (Y8)

Another natural extension of the version 1 CoDES algorithm is to consider the utility demand charge into the problem formulation. Denote p_d as the demand charge of the utility tariff, the objective of the scheduling problem becomes:

$$\min \sum_{t=1}^T p(t)P_{grid}(t)\Delta t + \max_{0 \leq t \leq T} P_{grid}(t)p_d \quad (16)$$

It is clear that the objective function becomes nonlinear. As can be seen from section 4.1, one of the inputs to the CoDES algorithm is P_{grid}^{max} , the current approach to handle this is to adjust this value as the CoDES algorithm is running. In CoDES algorithm, the P_{grid}^{max} only affects the updating rule of $P_{grid}(t)$ for each time step. So, the idea is to let the grid interface agent determine the convergence of the CoDES algorithm. If the P_{grid}^{max} is too small and the algorithm is diverging, we increase the P_{grid}^{max} ; if the algorithm is converging, we decrease the P_{grid}^{max} to see if the algorithm can still converge. The specific approach we are currently using is similar to dichotomy, as shown in Figure 3.

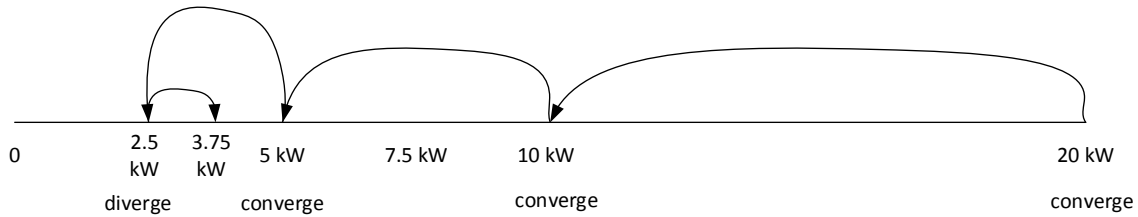


Figure 3 - Maximum grid power adjusting for peak shaving

5. Other Relevant Work Being Conducted Within and Outside of the ERC

N/A

6. Milestones and Deliverables

- Added the DESD charging/discharging efficiency consideration feature in CoDES
- Added the battery degradation consideration feature in CoDES
- Integrated the MST load balancing algorithm as a real-time tuning feedback
- Implemented the CoDES algorithm in DGI 2.0
- Related publications

7. Plans for Next Five Years

The plan of this project for the next five years will be:

- Add more features into the CoDES algorithm, such as microgrid line capacities
- Develop tuning methodologies to tune the CoDES algorithm parameters in real-time
- Develop methodologies that improves the CoDES execution efficiency
- Further develop the real-time operation strategy that integrates with the CoDES algorithm
- Demonstrate the CoDES algorithm in both simulated environment and real physical system

8. Member Company Benefits

By demonstrating the operation of the CoDES algorithm, the member company will be able to see the potential of the technologies that are used to develop this algorithm and may use the same technology for other similar applications.

9. References

- [1] N. Rahbari-Asr, Y. Zhang, and M.-Y. Chow, "Cooperative Distributed Scheduling for Storage Devices in Microgrids using Dynamic KKT Multipliers and Consensus Networks," in *2015 IEEE Power and Energy Society General Meeting*, 2015, pp. 1–5.
- [2] S. Han, S. Han, and H. Aki, "A practical battery wear model for electric vehicle charging applications," *Appl. Energy*, vol. 113, pp. 1100–1108, 2014.
- [3] J. Eom, Y. Noh, S. Lee, B. Choi, and C. Won, "ESS operation algorithm for economics considering battery degradation properties," in *Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2014 IEEE Conference and Expo*, 2014, pp. 1–5.
- [4] J. Tomić and W. Kempton, "Using fleets of electric-drive vehicles for grid support," *J. Power Sources*, vol. 168, no. 2, pp. 459–468, Jun. 2007.
- [5] W. Zeng and M.-Y. Chow, "Economic Benefits of Plug-in Electric Vehicles using V2G for Grid Performance-based Regulation Service," in *41st Annual Conference of the IEEE Industrial Electronics Society (IECON)*, 2015, pp. 1–6.
- [6] R. Akella, F. Meng, D. Ditch, B. McMillin, and M. Crow, "Distributed Power Balancing for the FREEDM System," *2010 First IEEE Int. Conf. Smart Grid Commun.*, pp. 7–12, 2010.

Y8.LSSS.1: Validation of 100% PV Penetration in the LSSS – Inverterless PV

Team Members

Project Leader:	Mariesa Crow
Faculty:	Mariesa Crow
Students:	Gautham Ashokkumar (MS)

1. Project Goals

The objective of this project is to provide system level validation of the ability of SSTs to enable 100% PV penetration.

2. Role in Support of Strategic Plan

From the initiation of the FREEDM center we have maintained that the deployment of SSTs in the distribution system will enable 100% penetration of PV systems; however we have not fully validated this claim. In this project, we are taking the LSSS system with 100% PV penetration and SSTs and then removing all SSTs to see if we can return the system to full 100% PV penetration through traditional means (capacitor banks for voltage control, etc).

3. Fundamental Research, Technological Barriers and Methodologies

In a traditional feeder system, the PV is connected to the AC system through an inverter (either micro-inverter or system inverter). With SSTs, the PV system can be directly tied to the SST low voltage DC link and can be controlled via the SST. This allows the SST to function as both the inverter and the voltage control/reactive power support system.

4. Achievements

The SST control was modified to permit the PV array to be connected directly to the LVDC SST link as shown in Figure LSSS.1.1. This eliminated the need for an additional inverter and inverter control. This approach also allowed for the direct connection of other DC voltage sources, such as batteries (included PHEV in V2G mode).

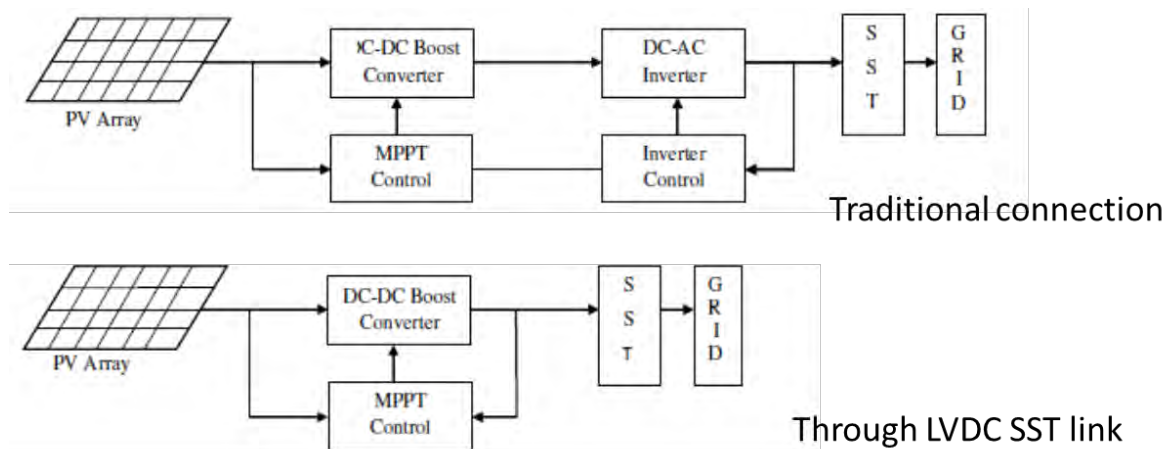


Figure LSSS.1.1. Proposed PV array connection using the LVDC SST link

The computer model of the PV array shown in Figure LSSS.1.2. has been built in PSCAD and intended to be able to simulate most types of PV arrays on the market. The simulation is based on a solar cell I-V characteristic equation using PV terminal voltage, cell temperature and solar insolation as inputs and providing the PV current as output. One PV panel of 175W (Suntech-STP175S-24/Ab-1) has been modeled with the manufacturer's data entered as simulation parameters.

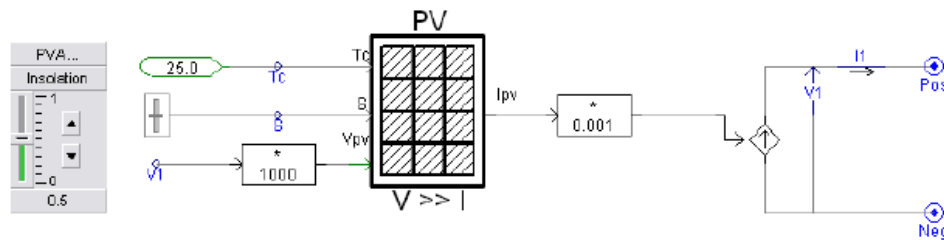


Figure LSSS.1.2. PSCAD PV array model

The model was validated against a series of actual insolation profiles obtained with a weather station at Missouri University of Science and Technology in Rolla as shown in Figure LSSS.1.3.

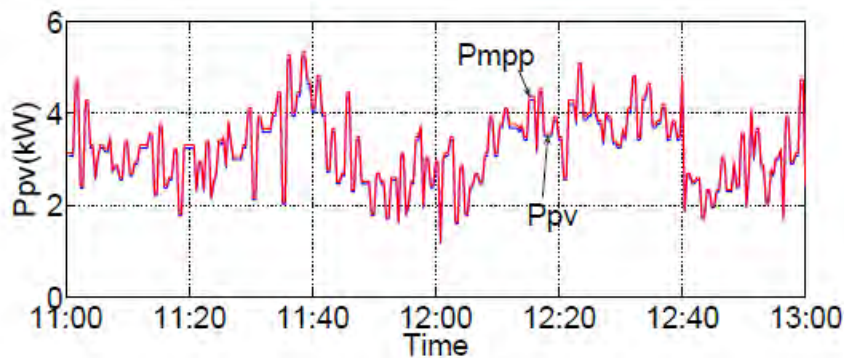


Figure LSSS.1.3: PV array output power (maximum power and actual power)

Figure LSSS.1.4 shows the impact of 100% PV penetration on the power flow at the system bus. The time has been scaled for computational efficiency. Note that between 15 and 18 seconds, the system power is negative; this indicates that during this period the PV arrays are producing sufficient capacity that power is injected back into the utility system. SST-based Volt-var control is used to maintain the voltage levels as shown in Figure LSSS.1.5.

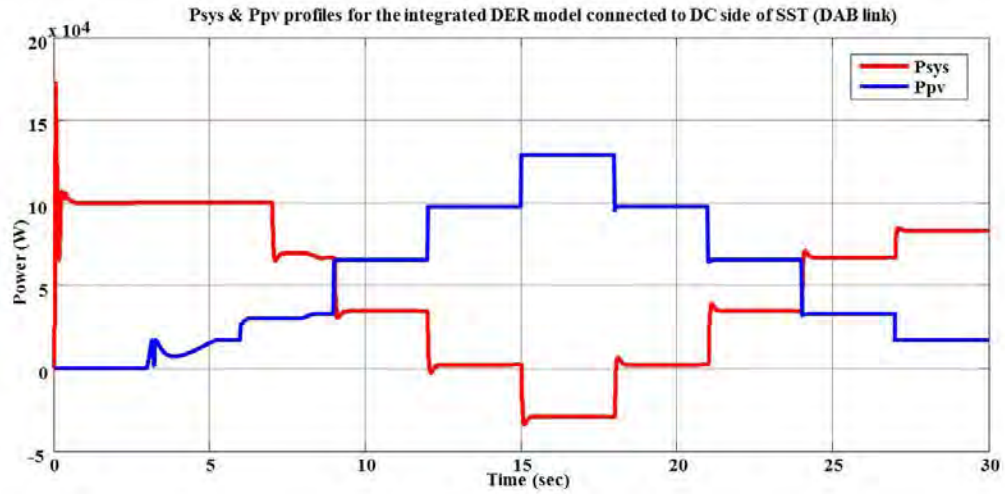


Figure LSSS.1.4. Validation of 100% PV Penetration

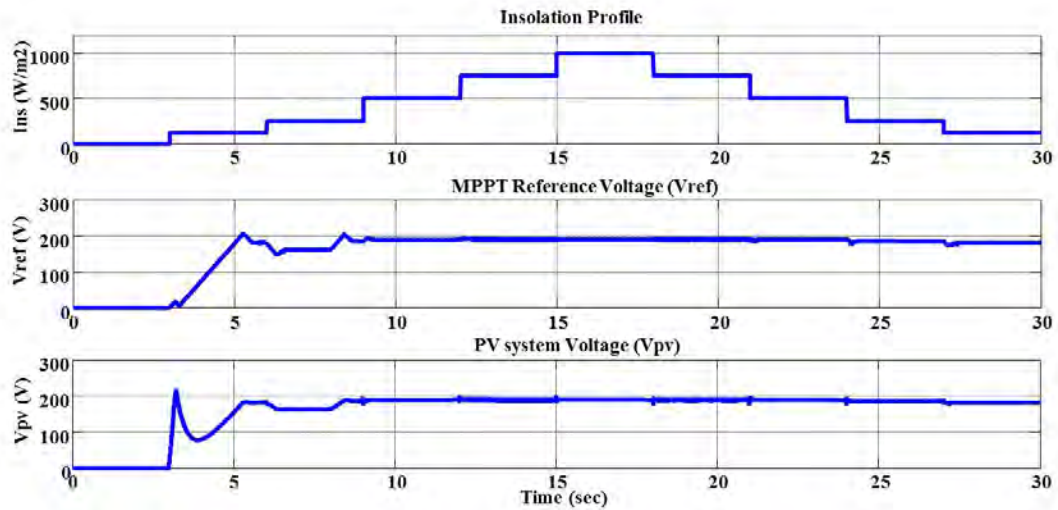


Figure LSSS.1.5. System voltage at the PV array and on the high-voltage system side

5. Milestones and Deliverables

The primary deliverable is a study of the ability of the system to support 100% PV penetration and whether or not this could be achieved without the use of SSTs.

6. Plans for Next Five Years

It is expected that this specific project will terminate at the end of this year.

Y8.LSSS.2: Islanded operation of LSSS

Team Members

Project Leader:	Mariesa Crow
Faculty:	Mariesa Crow
Students:	Phani Marthi (Ph.D.)

1. Project Goals

Integrate frequency control into the LSSS for islanding applications. During islanded operation, the feeder must recognize that it has been islanded, one SST must be designated as the master for frequency regulation, and all other SSTs will synchronize to the master. Droop control is frequently the underlying construct by which active power is allocated between devices.

2. Role in Support of Strategic Plan

This is on the critical path of the LSSS to validate autonomous feeder operation during islanded operation

3. Fundamental Research, Technological Barriers and Methodologies

To ensure plug and play capabilities of the FREEDM architecture, a FREEDM distribution feeder with a high penetration of SSTs, PV, and energy storage must be able to seamlessly connect and disconnect from the main system. The technological barriers that must be addressed relate to the timeframe of focus: power or energy. For intelligent power management, the islanded system must operate autonomously and stably at 60 Hz (or other specified frequency). This requires an updated control approach such that the system determines its own reference frequency and synchronization. In the FREEDM system, this is achieved by designating a master SST that provides an independent reference. The master SST may be selected using a consensus algorithm or other distributed decision making approach. At the energy time frame, the islanded system must operate under a management scheme that balances available resources and loads to maintain stable operation. If the loads and resources are not carefully regulated, energy will be injected or absorbed from the dc-link of the SSTs causing instability.

4. Achievements

This particular effort began in earnest this year. There were several major modifications that had to be made to the LSSS to accommodate islanded operation. First and foremost, the SST controls had to be upgraded to permit bi-directional power flows so that energy management strategies could be realized. Secondly, a control scheme to determine a master SST had to be implemented and the master SST control adapted to maintain a constant frequency voltage. Figures LSSS.2.1 through LSSS.2.3 show the output of the master SST during islanded operation. The system disconnects from the main system at 5 seconds at which time the master SST seamlessly takes over to provide control. Figure LSSS.2.1 shows the load side power (i.e. to the consumer). Note that there is little disturbance in the power provided. Figure LSSS.2.2 shows the high side voltage with relatively small excursion. Figure LSSS.2.3 shows an expanded view of the high-side (i.e. feeder side) voltage which illustrates that the frequency is closely maintained at 60 Hz.

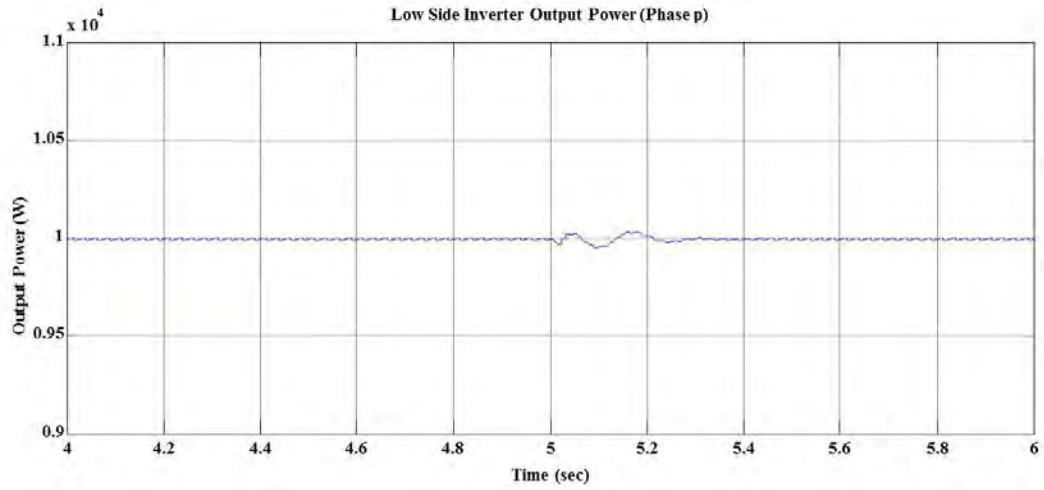


Figure LSSS.2.1. Master SST Power

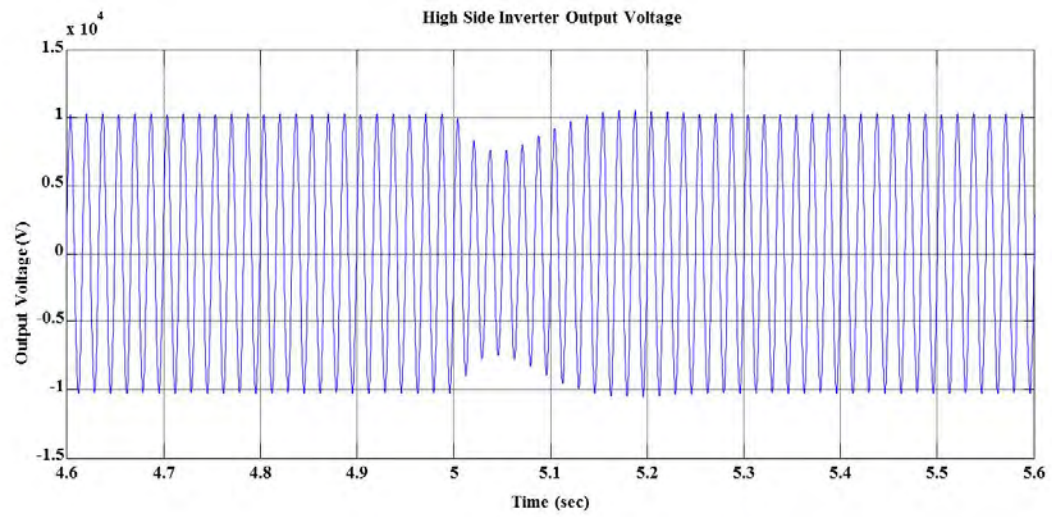


Figure LSSS.2.2. Master SST Voltage

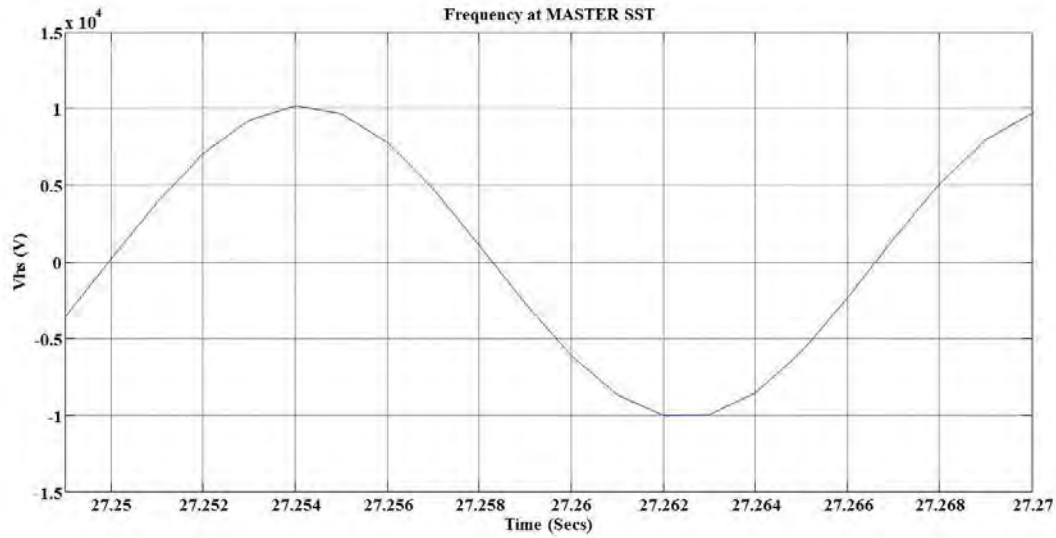


Figure LSSS.2.3. Master SST Frequency

5. Other Relevant Work Being Conducted Within and Outside of the ERC

A variety of researchers are investigating microgrid autonomous operation. The FREEDM system (and LSSS in particular) are unique in that we are using the SST as the means by which the system frequency is synchronized as opposed to microturbines or other rotating generation. Other researchers have also proposed using PV inverters, but that would negatively impact the MPPT of the unit. This work is coordinated with the consensus algorithm development, controls development, and droop control development within the FREEDM Center.

6. Milestones and Deliverables

The primary deliverables for this project year were to demonstrate seamless connect and disconnect and frequency control which have been met.

7. Plans for Next Five Years

The next step is to implement a power/energy management control such that the master SST does not have to assume all power variation in the system. This needs to be coordinated with any distributed generation resources (such as PV), energy storage, and deferrable loads (demand response).

Y8.LSSS.3: Development Pilot Directional Differential Protection Interaction with the FREEDM loop

Team Members

Project Leader:	Mariesa Crow
Faculty:	George Karady
Students:	Zhenmin Tang

1. Project Goals

The major objective of Year 8 is the validation of the system protection interaction with the Fault Identification Device (FID), solid state transformer (SST) and the Distributed Grid Intelligence (DGI) system.

- a) Test the protection operation in the Hardware–in-the-Loop system in different transient conditions
- b) Develop reliable interaction with the FID electronic circuit breaker
- c) Develop communication with the DGI system to record protection operation and permit
- d) Develop a simplified protection unit, which can be included in each FID device
- e) Develop back up protection

2. Role in Support of Strategic Plan

The developed protection is a major component of the FREEDM system. No distribution system can operate without independent selective protection.

3. Fundamental Research, Technological Barriers and Methodologies

This work grew out of earlier LSSS work in which the pilot directional differential protection scheme was developed and tested. After favorable system level results in which it was verified that the protection scheme was able to identify a fault less than 5 ms, then we proceeded with the hardware development of the real-time pilot protection.

4. Achievements

- a) The pilot directional protection system has been tested at ASU in a newly developed analogue test bed.
- b) The protection has been successfully tested at FSU's Hardware–in-the-Loop system.
- c) The interaction with the FID has been developed. The protection generated trip signal will be sent by fiber optic links to the FID control system.
- d) The interaction with the DGI system is defined. The protection operation will be sent to the DGI for recording. This will include current and voltage wave forms during the fault and the fault clearing time.

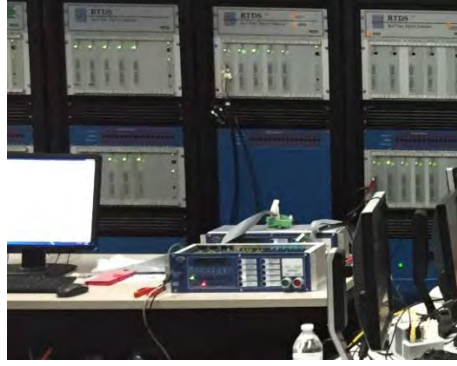


Figure 1: RTDS and pilot protection relays in the Hardware-in-the-loop system at FSU

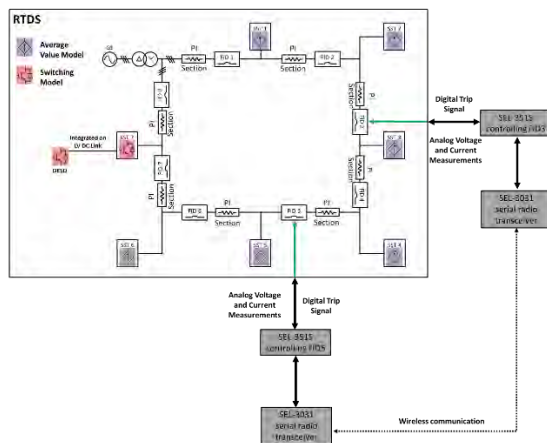


Figure 2a: FSU-CAPS HIL Testbed Diagram for ASU Protection Hardware Testing

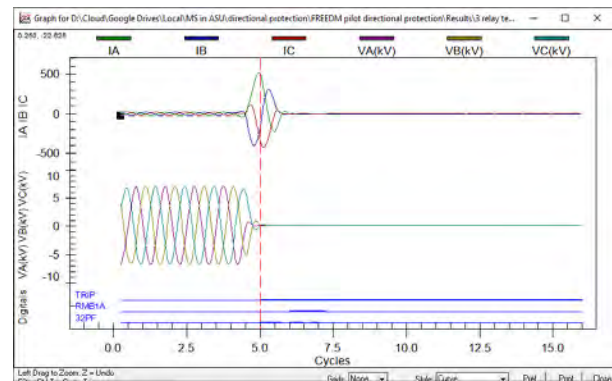


Figure 2b: Typical relay operation

The tests proved the proper operation of the Directional Pilot Protection system, which has been tested for single phase ground faults, phase to phase faults, phase to phase to ground fault, three phase fault and three phase and ground faults. It was proved that the phase angle (0, 90, 180, 270 degree) of fault occurrence has practically no effect on the system operation.

5. Milestones and Deliverables

- Development of the interconnection with the FID devices and GID system completed.
- Testing the Protection system in Florida using the RTDS completed
- Verification of protection operation in transient conditions completed.
- Presentation of the simplified protection system in progress.

6. Plans for Next Five Years

The directional pilot protection is fully developed and documented. The protection system must be interconnected with the FID and the total system operation must be tested using the FSU Hardware-in-the-Loop system.

ASU also developed a backup protection, which is a time delayed overcurrent protection. This also must be interconnected with the FID and the total system operation must be demonstrated also using the Hardware-in-the-Loop system.

7. Member Company Benefits

Member companies like Duke Energy can evaluate the extremely fast working FID in conjunction with the Directional Pilot Protection.

8. References

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Core Projects

Enabling Technology

Y8.ET1.1: DGI Integration with GEH & HIL & LSSS and Application Support

Project Leader: Bruce McMillin

Faculty: Jonathan Kimball, Mesut Baran, Mo-Yuen Chow, Isaac Leonard

Students: Li Feng, Stephen Jackson, Geoffrey Cline, Jace O'Brien, Tom Roth (S&T), Jie Duan, Yue Shi, Yuan Zhang (NCSU), Sindhu Sundarajan (FSU)

1. Project Goals

The primary goal of this project is to integrate DGI into the testbeds and to support DGI application development. For several years, the DGI and HIL teams have worked closely together to co-develop the HIL testbed and DGI. In year 8, we intend to carry this work forward to fully integrate DGI into the GEH and to link DGI with the LSSS.

2. Role in Support of Strategic Plan

DGI is a critical element of the FREEDM System, and thus integration of DGI into each of the testbeds allows for this critical element to be validated and tested in modeling, hardware testing and the overall physical testbed.

3. Fundamental Research, Technological Barriers and Methodologies

3.1 Replace DGI's PnP with MQTT (Message Queueing Telemetry Transport). MQTT is a publish/subscribe, extremely simple and lightweight messaging protocol, designed for constrained devices and low-bandwidth, high-latency or unreliable networks.

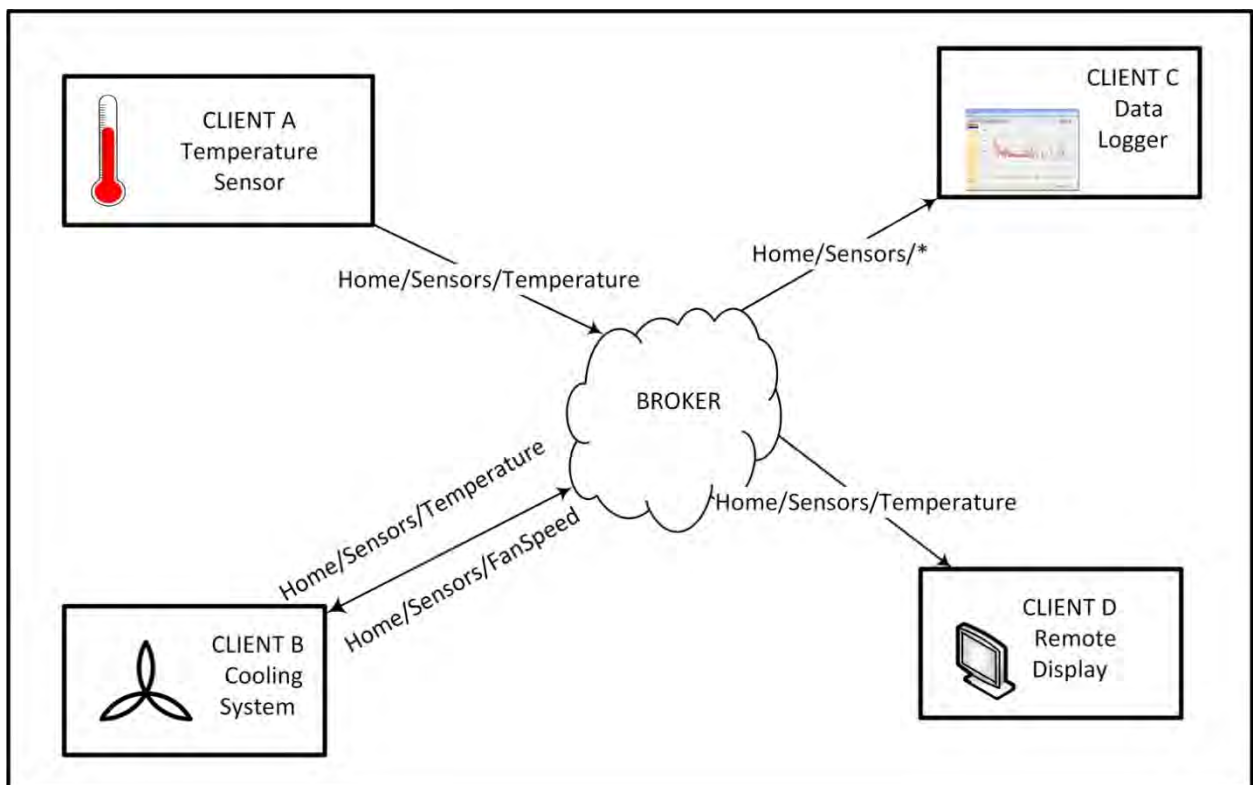
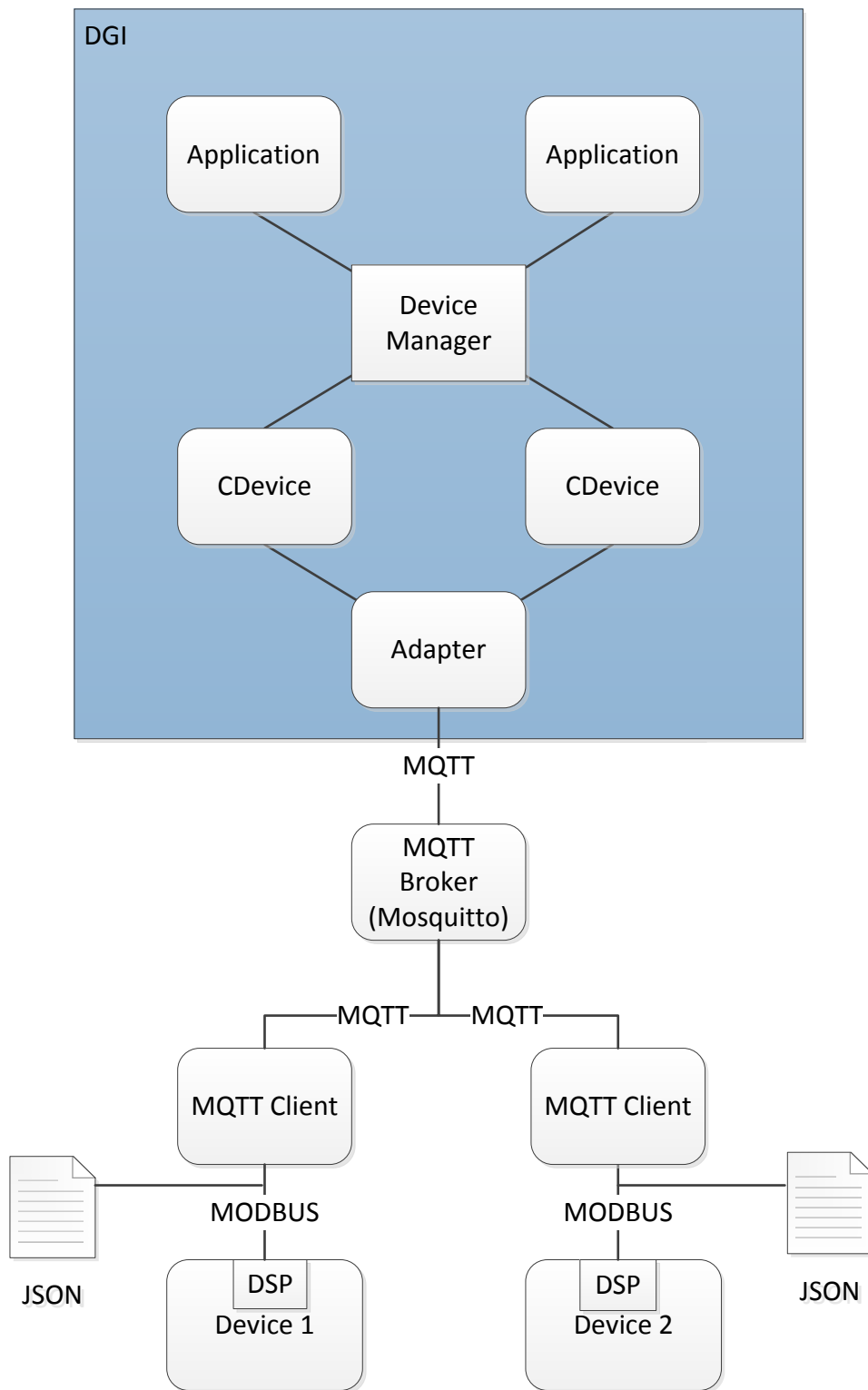


Fig. 1. Example of MQTT network using hierarchical topics to organize messages

The MQTT implementation in DGI is described by the following diagram:



Fi. 2. MQTT Integration with DGI

- Broker hosted in DGI
- Device attributes sent to DGI and made available to applications
- Standardize a device profile

3.2 Federated Groups and Group Models

- Federated groups use a virtual device to transfer power between groups trying to afford hard real-time within a group and soft real-time across multiple groups
- Markov Model of Group Performance
- Adaptive Protocols will apply ECN – notification of impending congestion, so reconfigure the groups to require less messaging

4. Achievements

- MQTT implementations on DGI could show that DGI could recognize and output the information to the MQTT device with type DESD connects to the broker.

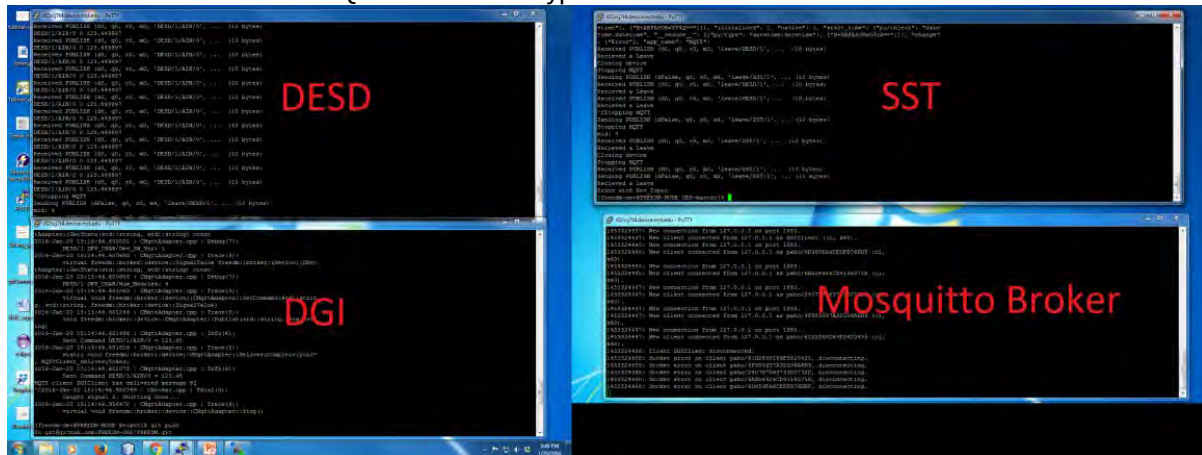


Fig. 3. MQTT Implementations with DGI

- Experiments on Markov models of group behavior can help us estimate the optimal group size:
The DGI employed a round-robin schedule where each module is given a predetermined amount of time to execute. This schedule was determined by the number of DGI that could be grouped together and the expected cyber network conditions. Additionally, the Load Balance module, which managed the power resources, was scheduled to run multiple times in a long block before the group was evaluated for failure. The schedule is depicted in Figure 4.

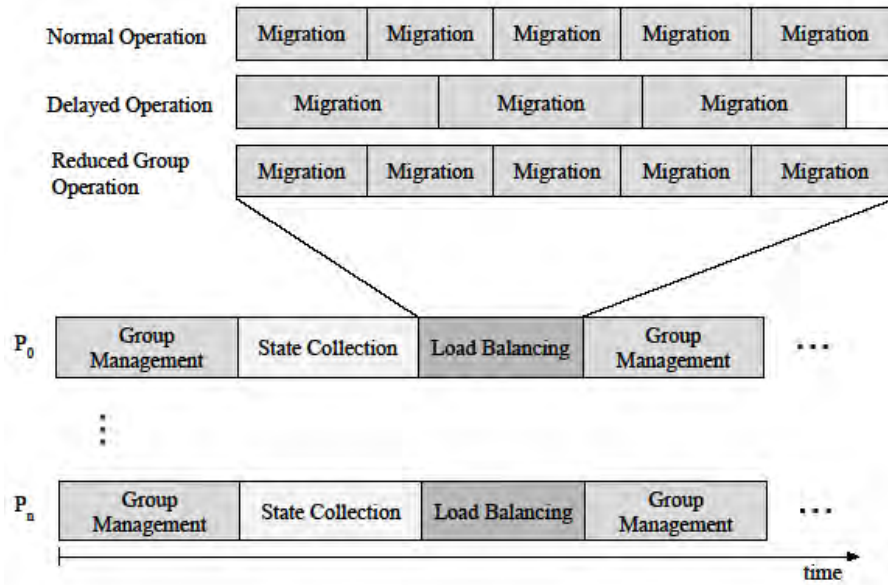


Fig. 4. Example DGI schedule.

Normal operation accounts for a fixed number of migrations each time the load balancing module runs. Message delays reduce the number of migrations that can be completed each round. However, reducing the group size allows more migrations to be completed (because fewer messages are being exchanged) at the cost of flexibility for how those migrations are completed.

The steady state distributions are presented as stacked bar graphs in Figure 5 and 6.

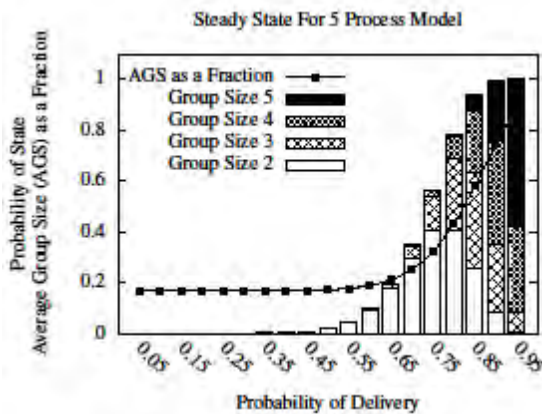


Fig. 5

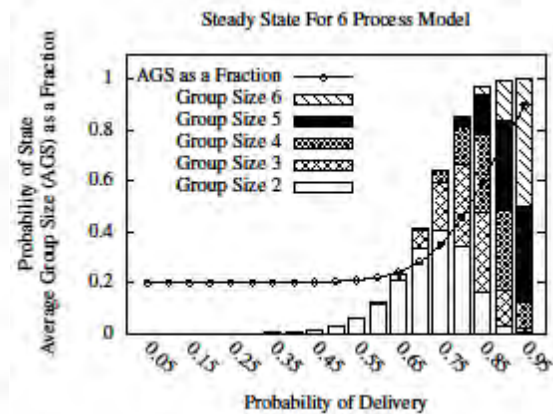


Fig. 6

Steady state distribution for 5 and 6 processes as well as the Average Group Size (AGS) as a fraction of total processes.

Figure7 shows the average percentage of total processes that will be in the group in a steady-state system. This information can also be used to anticipate faults and mitigate them before they occur.

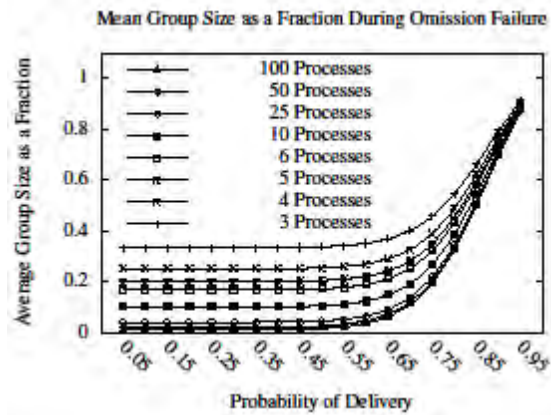


Fig. 7. Average group size as a percentage of all processes in the system for larger systems

5. Other Relevant Work Being Conducted Within and Outside of the ERC

The SGIP openFMB led by Duke is the closest related activity

6. Milestones and Deliverables

Q3 (9/30/2015) – Federated DGI testing. GEH BeagleBone implementation

Q4 (12/31/2015) – MQTT and Triangle Works implementations, LSSS Support

Q1 (3/31/2016) – Expanded number of signals in HIL, Federated DGI

Q2 (6/30/2016) – DGI implemented in GEH

Y8.ET1.2: Secure System-Level Invariant Derivation and Validation

Team Members

Project Leader:	Jonathan Kimball
Faculty:	Jonathan Kimball, Bruce McMillin
Students:	Bokang Zhou, Tom Roth (graduated)

1. Project Goals

This project extends the results achieved in year 7 and focuses on expanding the scope of invariants. Specifically:

- Improve line flow limit invariant to account for multiple simultaneous transactions.
- Improve dynamic invariant to be less conservative (and therefore more useful). Find boundary cases.
- Implement improved invariants in DGI, and test on HIL.
- Implement improved invariants as attestation protocols for DGI's inherently secure algorithms
- Investigate the effect of uncertainty on all derived invariants.
- As the HIL matures, test all invariants on bigger systems.

The current focus is on making sure all invariants are evaluated in a distributed fashion. The previously-implemented voltage invariant was pseudo-distributed: all information ultimately flowed to a single DGI node to perform the calculation. However, there is no fundamental barrier to distributing the computation among all of the DGI nodes. This is a test case; the same methodology will be used for future invariants as well.

2. Role in Support of Strategic Plan

This work is a crucial link between physical system analysis and the operation of the DGI. The specific details are unique to FREEDM. However, it also demonstrates general principles and a framework applicable to other cyber-physical systems. The use of invariants for security furthers the field of cyber-physical security.

3. Fundamental Research, Technological Barriers and Methodologies

The key technological barrier is one of developing a solid understanding of physical system properties that can be used as invariants and it requires a significant level of mathematical maturity. As such, new students on the project have a long learning curve, although professionals in the field can pick up the concepts quickly.

4. Achievements

The invariant approach has been previously demonstrated as a guard against incorrect actions by various DGI nodes. Specifically, the voltage invariant can block power transfers that will cause voltage collapse and the line flow invariant can block power transfers that would overload any line.

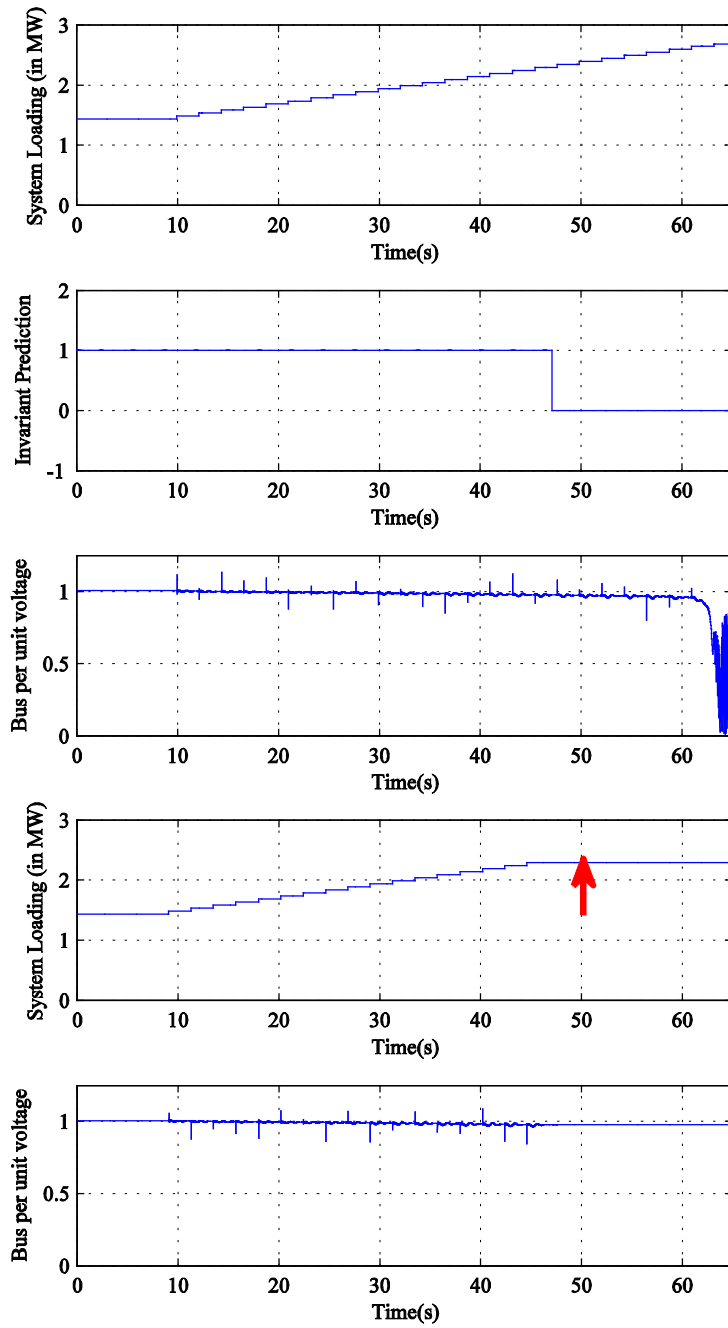


Fig. 1. Example operation of voltage stability invariant. The top three graphs indicate load, the invariant truth value, and the bus voltage. In this case, the invariant is evaluated but not used, and the voltage collapses. In the bottom two graphs, the invariant truth value is used to guard against an incorrect transaction, and the bus voltage remains stable.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

This project is related to an affiliated project that was funded by NSF this year, a collaborative project led by Kimball and also including McMillin and Chow: "Collaborative Research:Breakthrough:Secure Algorithms for Cyber-Physical Systems." In the affiliated work, the invariants are being integrated with Chow's reputation algorithm and invariants are being developed for other non-power system infrastructures. The security analysis forms an aspect the NIST CPS Public Working Group (PWG) on Cyber-Physical Security.

6. Milestones and Deliverables

Q3 (9/30/2015) – Improved line flow limit invariant derived and implemented in DGI

Q4 (12/31/2015) – Line flow limit validated on HIL; improved dynamic invariant derived

Q1 (3/31/2016) – Improved dynamic invariant validated with DGI/HIL; testing begins on bigger systems; Improved invariants integrated with power and energy management DGI algorithms for security

Q2 (6/30/2016) – Testing complete on bigger systems with respect to SGIP/ CPS PWG use-cases

7. Plans for Next Five Years

The focus now is on integrating multiple invariants with real algorithms developed on a distributed computing platform. This is expected to extend beyond the FREEDM system to include other cyber-physical systems.

8. References

- [1] Tamal Paul, Jonathan W. Kimball, Maciej Zawodniok, Thomas P. Roth, Bruce McMillin, and Sriram Chellappan, "Unified Invariants for Cyber-Physical Switched System Stability," *IEEE Transactions on Smart Grid*, Vol. 5, No. 1, January 2014, pp. 112-120, [10.1109/TSG.2013.2283171](https://doi.org/10.1109/TSG.2013.2283171).
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- [3] Li Feng; McMillin, B., "Information Flow Quantification Framework for Cyber Physical System with Constrained Resources," in *Computer Software and Applications Conference (COMPSAC), 2015 IEEE 39th Annual*, vol.2, no., pp.50-59, 1-5 July 2015, [10.1109/COMPSAC.2015.92](https://doi.org/10.1109/COMPSAC.2015.92)

Y8.ET1.3: Resilient Energy Management Operation in FREEDM Systems

Team Members

Project Leader:	Dr. Bruce McMillin
Faculty:	Dr. Mo-Yuen Chow
Students:	Jie Duan

1. Project Goals

Research and develop a resilient neighborhood-watch algorithm to secure the Cooperative distributed Energy Scheduling (CoDES) algorithm in FREEDM system.

- Investigate the vulnerabilities of CoDES by designing different types of attack on it;
- Analyze the potential impacts of the attacks on CoDES;
- Develop a resilient neighborhood-watch algorithm to counter the potential attacks.

2. Role in Support of Strategic Plan

This project adds the resilience feature to the distributed energy scheduling algorithm against malicious cyber attacks. The attack-resilience feature is essential for ensuring the optimal energy management operation in the presence of faults and adversaries.

3. Fundamental Research, Technological Barriers and Methodologies

The fundamental research of this project in Y8 is to build an attack-resilient control mechanism that could fit into the distributed power system framework to promote the paradigm shift from centralized energy management to distributed energy management.

One of the technological barriers of this project is how to build a distributed monitoring system to replace the conventional control center. The methodology to deal with it is to develop a neighborhood-watch mechanism in which each node is responsible for monitoring its neighbors. A reputation index is introduced to reflect the credibility of the neighbors, if one neighbor is continuing to send out false information, the reputation index will indicate that it is compromised.

Another barrier of this project is how to estimate the neighbors' behavior given that all private information (e.g. load profile, DESD capacity, power rating) are kept undisclosed to neighbors in the CoDES algorithm. The methodology we apply is to modify the augmented Lagrangian to add in the dual variables corresponding to private information. In the iterative process, the dual variables are shared with neighbors during each iteration. These variables do not disclose any private information, but help us to predict the neighbors' future information.

The third barrier is how to respond to the malicious node to mitigate the impact of cyber attacks. The methodology we currently apply is that all the well-behaving nodes discard the false information sent from the malicious node and use the estimated information for the malicious node to continue the iterative process in CoDES algorithm. A more promising methodology is to develop a defense algorithm in which the malicious node does not need to be isolated, instead, all the well-behaving nodes will exploit the latest collected information about the adversary and adapt their information accordingly to induce the malicious node to perform in a correct way.

4. Achievements

4.1. Vulnerability of CoDES algorithm

The CoDES algorithm is applied in the FREEDM system to determine the optimal charging/discharging schedule of DESDs with the objective of minimizing the total electricity bill over a specified time horizon. It considers three classes of constraints: 1) power balance constraints; 2) energy capacity constraints for DESDs; 3) power rating constraints for DESDs and grid.

Three major steps are included in CoDES algorithm in order to solve the optimization problem in a fully distributed way, as shown in Fig. 1. For more detailed information, please refer to [1].

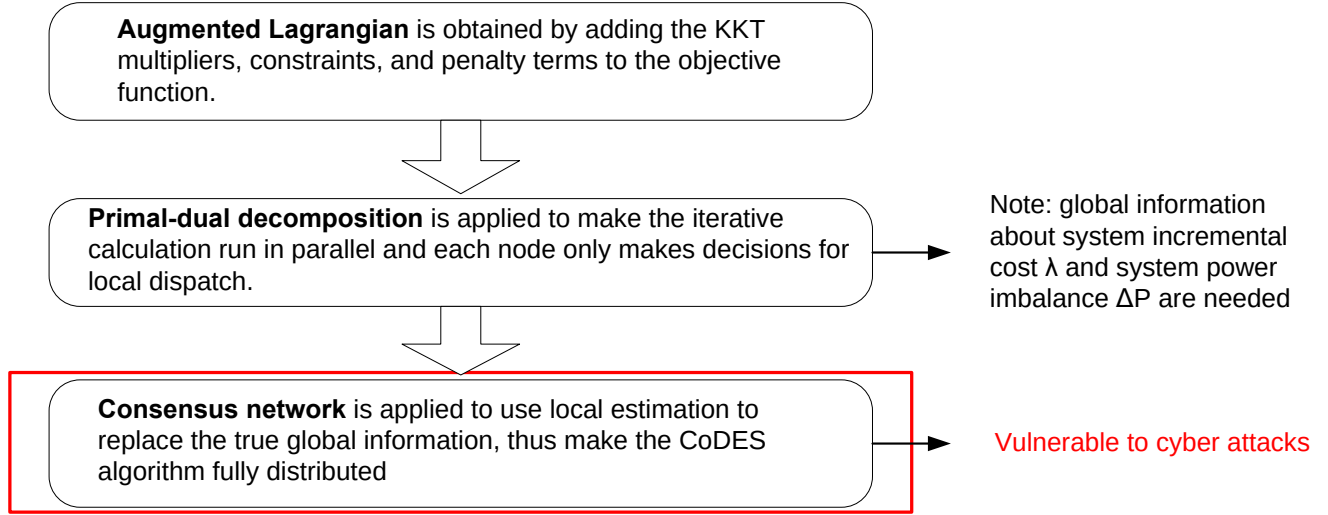


Fig. 1. Steps of CoDES algorithm

The vulnerability of the CoDES algorithm lies in the third step – consensus network. In the consensus network, each node shares and coordinates its local estimation about global information with its neighbors. The shared information include λ_i^k and ΔP_i^k , which denote the estimations of node i about the system incremental cost λ and system power imbalance ΔP at iteration k , respectively.

Because of the absence of control centers to monitor the correctness of shared information λ_i^k and ΔP_i^k , it is possible that one node in the consensus network is compromised by an attacker and sends out false local estimation to other neighbors. The compromised node in the system will lead all the nodes to operate at a non-optimal, or even unstable condition.

4.2. Attack model of the adversaries

The compromised node can be modeled as one whose controller suffers from a malicious input caused by malicious adversaries. The updating rule of the compromised node i is formulated as:

$$\lambda_i^{k+1}(t) = \lambda_i^k(t) + \sum_{j \in N_i} w_{ij} (\lambda_j^k(t) - \lambda_i^k(t)) + \eta \Delta P_i^k(t) + u_{mi}^k(t) \quad (1)$$

where $u_{mi}^k(t)$, the adversary input, is modeled as a malicious exogenous input to node i 's updating rule. The adversaries can be classified into two categories depending on their capabilities [2]:

- Fault attack: the adversary stops updating the local information λ_i of the compromised node and maintain λ_i as a constant. In this case, the adversary input of $u_{mi}^k(t)$ can be denoted as:

$$u_{mi}^k(t) = c - \left(\lambda_i^k(t) + \sum_{j \in N_i} w_{ij} (\lambda_j^k(t) - \lambda_i^k(t)) + \eta \Delta P_i^k(t) \right), \quad (2)$$

where $c \in R$ is an arbitrary constant value.

- Random attack: the adversary injects random false data into the controller of node i and makes it behave in an arbitrary manner. In this case, the adversary input of $u_{mi}^k(t)$ can be denoted as:

$$u_{mi}^k(t) = c^k. \quad (3)$$

Figure 2 compares the impact of fault attack on the CoDES algorithm, we can see that the adversary will lead all the nodes in the system to operate at a non-optimal condition as the incremental costs of all the nodes diverge.

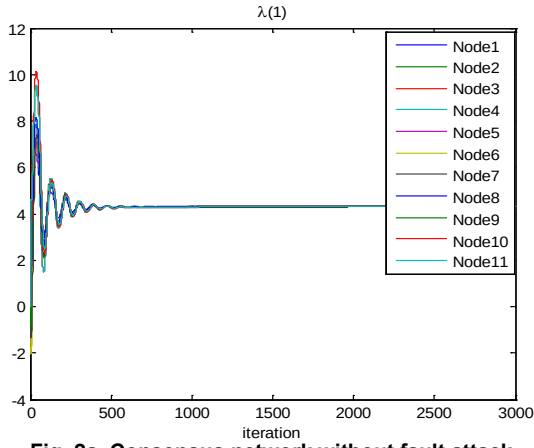


Fig. 2a. Consensus network without fault attack

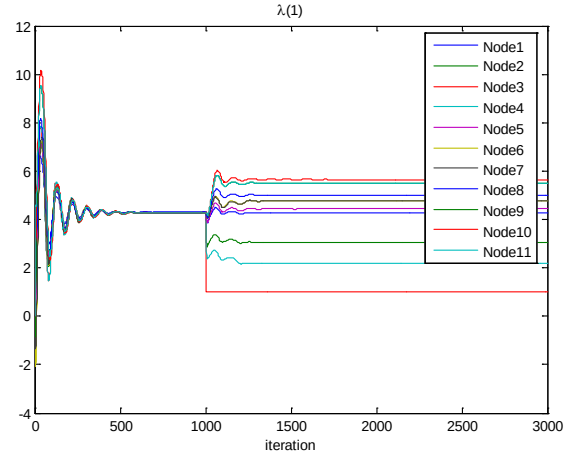


Fig. 2b. Consensus network with fault attack

4.3. Reputation-based neighborhood-watch algorithm

We proposed a reputation-based neighborhood-watch algorithm in which every node could monitor the correctness of the shared information from its neighbor and counteract the attacks. A similar concept is available in our previous work [3], [4]. The objective of the proposed resilient control mechanism is twofold: 1) to detect the presence of any manipulated information; including λ_i^k and ΔP_i^k ; 2) to recover the optimal energy schedule from the malicious impact of the attack. The framework of the reputation-based neighborhood-watch algorithm is shown as Fig.3. In the following the details of each steps are described.

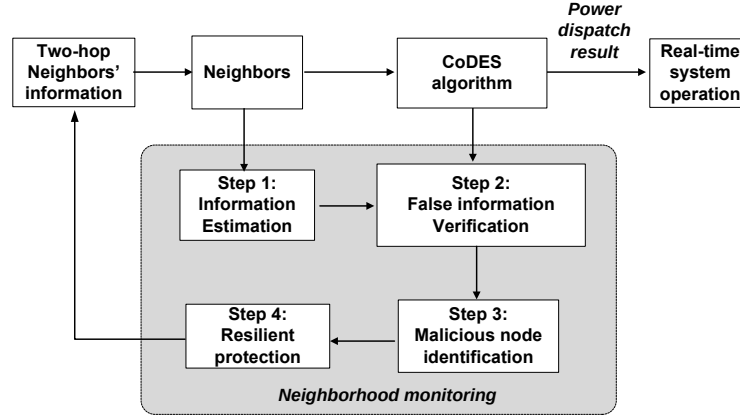


Fig. 3. The framework of neighborhood-watch algorithm

- Step 1: Based on two-hop neighbors' shared information in iteration k , each node estimates its neighbors' shared information in the next iteration $k + 1$, where the estimated information includes λ_i^k and ΔP_i^k .
- Step 2: Each node detects the false information from its neighbors by comparing the estimated value with the actual received value.
- Step 3: Adjust the credibility of neighbors via the Local Reputation Index. Identify a malicious bus if the corresponding reputation drops below a threshold.
- Step 4: Information from the malicious bus is discarded by neighbors, and the other normal buses use estimated information to continue the iterative process

Fig. 4 compares the performance of the neighborhood-watch algorithm against fault attack. As shown in Fig.4b, with the help of the neighborhood-watch algorithm, the malicious node – node 3 could be detected and the other well-behaving nodes will use the estimated information for node 3 and continue the iterative process until the system converge to the optimal operation point, as the incremental costs of all the nodes converge again.

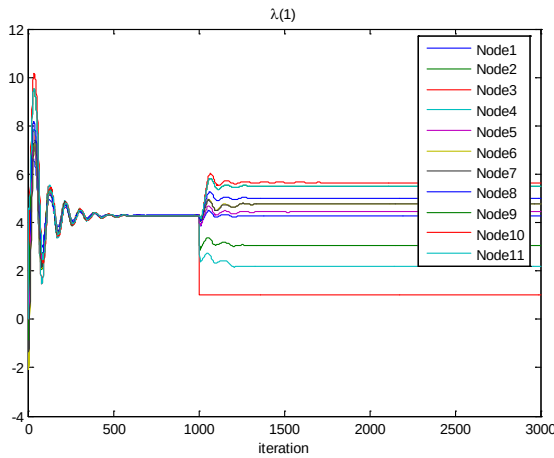


Fig. 4a. Fault attack without neighborhood-watch algorithm

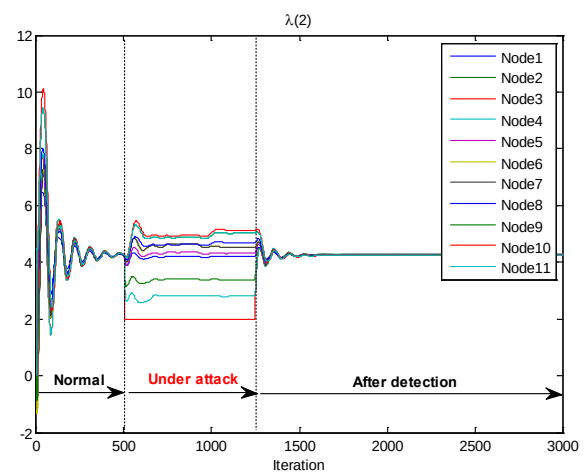


Fig. 4b. Fault attack with neighborhood-watch algorithm

5. Other Relevant Work Being Conducted Within and Outside of the ERC

NSF program: Secure Algorithms for Cyber-Physical Systems under Award Number 1505610.

6. Milestones and Deliverables

- Discovered the vulnerability of CoDES algorithm to data integrity attacks
- Built a reputation-based neighborhood-watch algorithm to counteract the data integrity attacks
- Related publications [2], [4], [5]

7. Plans for Next Five Years

- Consider collusion of misbehaving nodes in the system
- Adapt the detecting threshold considering the effect of communication noise and disturbance
- Analyze the optimal number of hops required to exchange information under different attack scenarios.

8. Member Company Benefits

By applying the reputation-based neighborhood-watch algorithm into the distributed energy management operation, member companies are able to run the system at the optimal operation conditions in the presence of faults and adversaries and thus prevent potential economic loss.

9. References

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Y8.ET1.4: Design of Distributed Resilient Sensing Systems FREEDM System

Team Members

Project Leader:	Dr. Bruce McMillin
Faculty:	Dr. Chris S. Edrington
Students:	Huawei Yang
Staff:	Dr. Touria El-Mezyani

1. Project Goals

The increasing penetration of distributed energy resources into the electrical grid have raised several technical challenges for the control, monitoring, and state estimation. One of these challenges is the system reliability, which depends on real-time data. Intelligent sensor placement into power grids will play a vital role in solving these challenges. Sensor placement into power grids plays a vital role in solving these challenges. Adequate placement of sensors is necessary not only for state estimation but also for Fault Detection and Isolation (FDI).

Sensors are prone to failures, which lead to loss of sensors and bad/missing measurements, and contingencies. The conventional way to detect sensor failures is based on physical (hardware) redundancy. This method consists of using multiple sensors to measure a particular variable and thus identify a faulty sensor. However, the extra equipment of sensors necessary for hardware redundancy usually leads to a high risk of bad data contingencies, and extra cost of maintenance. More sensors lead to more possible faults. Analytical models offer the possibility to use Analytical Redundancy (AR) for the detection and isolation of sensors' failures. The AR-based approach is seen to be a more cost effective approach compared to the hardware redundancy approach as it does not require additional sensors.

The focus of this research is the development and integration of a distributed sensor intelligence module that is responsible for assessing the health of existing sensors, isolating the faulty sensor, eliminating contingencies by reconstructing new healthy data and mitigate effects on the system due to the to the sensor fault(s) by detecting and isolating the faulty sensor(s).

2. Role in Support of Strategic Plan

This project supports the core mission of FREEDM by developing methods to create a more resilient grid structure via intelligent management of the sensors utilized in control of system and device level electrical apparatus. Thus the work aids in ensuring that the system not only intelligently manages the power and energy of the system but that it does it even in the presence of faulted sensor(s) conditions.

3. Fundamental Research, Technological Barriers and Methodologies

3.1 Fault Detection and Isolation of Sensor Failures

The model used for FDI is developed based on a DC model of the power grid. It has been proven that even though the DC model is an approximate model, it still a good choice for the SE problem and contingency analysis [1-2]. Neglecting all shunt elements and branch resistances $X_{lm}/R_{lm} \gg 1$, the real and reactive power flow equation from bus l to bus m can be approximated in (1) – (2) by using the first order Taylor expansion of the power flow equations [4].

$$p_{lm} = Y_{lm}(\delta_m - \delta_l) \quad (1)$$

$$q_{lm} = Y_{lm}(v_m - v_l) \quad (2)$$

where, v_m and δ_m are the voltage magnitude and phase angle at bus m , p_m and q_m are the real and reactive powers respectively injected into the bus m , and p_{lm} and q_{lm} are the real and reactive power flowing out of the bus l toward the bus m along the transmission line L_{lm} ($l, m \in \{1, 2, \dots, n_b\}$ and

$l \neq m$). Therefore, using the equality constraints in (1)-(2) and Kirchhoff's current law we define a state model of power grid [3], which is described, in (4), by a set of algebraic equations.

Two types of models can be considered for model-based FDI: a healthy model describing nominal behavior and a faulty model describing the behavior under failures. The usage of these two types of models depends on the objectives of the FDI procedure. The FDI procedure based on the healthy model is able only to detect faults. When information is provided about which constraint of the healthy model is unverified in presence of faults, isolation of the faulty component becomes possible. The fault model represents the system model with consideration of faults. This model is used when the aim is the fault identification and diagnosis.

The power grid model with faults can be defined by taking explicitly into account the influence of the faults on equality constraints (3)-(4), as follows:

$$0 = \aleph_{\gamma \times \lambda} x^t(t) + F_1 \phi(t) \quad (3)$$

$$\begin{bmatrix} y_1(t) \\ \vdots \\ y_{n_s}(t) \end{bmatrix} = Cx(t) + F_2 \varphi(t) \quad (4)$$

Where, $x = [i_{j1}, \dots, i_{jm}, \dots, i_{jn_b}, v_1, \dots, v_{n_b}, \delta_1, \dots, \delta_{n_b}, p_1, \dots, p_{n_b}, p_{1,2}, \dots, p_{i,j}, \dots, p_{n_b, n_b}]^t$ are the system state variables and i_{jm}, v_j are the current and voltage magnitudes at the line L_{jm} and bus j respectively, $y(t) = [y_1(t), \dots, y_i(t), \dots, y_{n_s}(t)]^t$ is the measurements vector; $y_i(t)$ is the measurement from the sensor S_i , $S_i \in \{S_1, \dots, S_{n_s}\}$, $\aleph_{\gamma \times \lambda}$ is the matrix of the system parameters, $\phi = [f_1^{sys}, f_2^{sys}, \dots, f_{n_t}^{sys}]^t$ is the vector of system failures, which is related to the line outages in transmission lines. These faults affect the equality constraint in (4), $\varphi = [f_1^{sen}, \dots, f_i^{sen}, \dots, f_{n_s}^{sen}]^t$ is the vector of sensor failures; f_i^{sen} is the fault in sensor S_i , $C = [c_{ik}]_{n_s \times \lambda}$ is the sensor topology matrix, F_1 and F_2 are the faults influence matrices. When the fault in a sensor S_i occurs, the i^{th} equality constraints $y_i(t) = c_i x(t) + d_i f_i^{sen}(t)$ is affected by this fault; where y_i is the measurement from sensor S_i and f_i^{sen} is the vector of the fault that affected the measurement.

Analytical Redundancy Relations (ARR) are analytical reconstructions of the model constraints of a system, by eliminating the unknown variables. Various algorithms can be considered for variable eliminations [4-5]. In this research, we apply the parity space approach for variables elimination in the model constraints and ARR generation [5]. This method is suitable as it is easy to implement and does not require extensive modeling effort and implementation. ARR can be computed online, based on the measurement signals $y_i(t)$, to generate a set of signals called residuals. A residual vector, denoted by $R = [r_1, r_2, \dots, r_{N_R}]^t$, reflects the discrepancy between the expected and actual system behavior. In the absence of a disturbance, the deviation from normal behavior is noticed when the residual becomes different from zero.

In this study we investigate the IEEE 14-bus test system (Fig. 1) to test and validate our developed approach. The system is simulated in the Matlab/Simulink platform. For this illustration, we consider an exhaustive sensor deployment (Fig. 1). Using a parity space approach to the models in (3)-(4) we can generate 23 residuals able to detect different sensor failures. Let S_{ij}^s and S_{ij}^r be the sensors placed on line L_{ij} at the respective sending and receiving points of the line. In order to validate our residuals in simulation, we propose to apply three failures to the sensors $S_{1,2}^s$ at the time interval $[0.1 \ 0.3s]$, $S_{6,11}^s$ at the time interval $[0.4 \ 0.6s]$, and $S_{4,7}^s$ at the time interval $[0.7 \ 0.9s]$.

The real signature table is developed from the online reading of residuals. The comparison of the theoretical signature table with the real signature allows us to identify the faults. By using these signatures of faults, we can easily identify the faulty sensor.

Due to noise and uncertainty, the values of the residuals are not often equal to zero under normal operating conditions. In a power system, due to the high effect of noise and uncertainty, the fault could not be easily discriminated from noise and then the risk of a false alarm is very high. Fig.2 shows the residuals r_i ($i = 1,2,3$) response to the noise. The effect of fault and noise on residuals cannot be distinguished as depicted in Fig. 2. To overcome this problem, a more sophisticated decision using the Page-Hinkley algorithm called CUSUM (Cumulative Sum) algorithm is applied [6]. Using the CUSUM algorithm, we can generate two values from each residual, $\chi_p(t_k, R)$ and $\chi_n(t_k, R)$ related to the positive and negative variation of the residual means with positive and negative boundaries respectively. The decision procedure may be implemented using the CUSUM filter to decide whether the residual values correspond to failures or noise. Fig. 3 shows the evolution of $\chi_p(t_k, r_i)$ and $\chi_n(t_k, r_i)$ ($i=1,2,3$) linked respectively to the residuals r_1, r_2 and r_3 . From the new signals $\chi_p(t_k, r_i)$ and $\chi_n(t_k, r_i)$, we can easily discriminate noise from faults by considering a decision threshold.

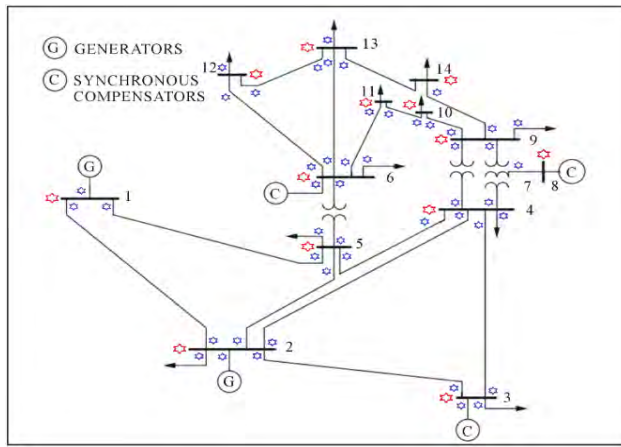


Fig. 1. IEEE 14-bus with full sensor coverage

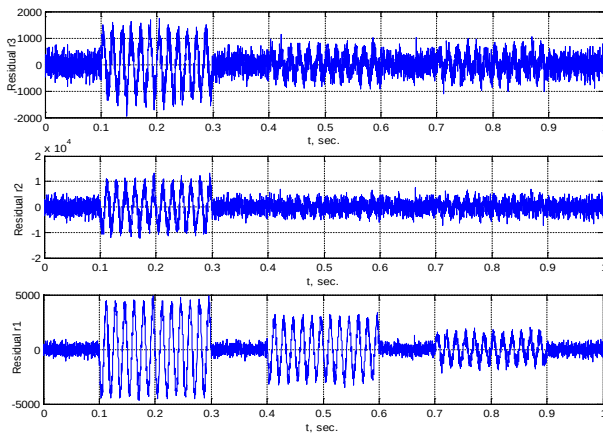


Fig. 2. Residuals r_1, r_2 and r_3 in presence of sensor failures and perturbations

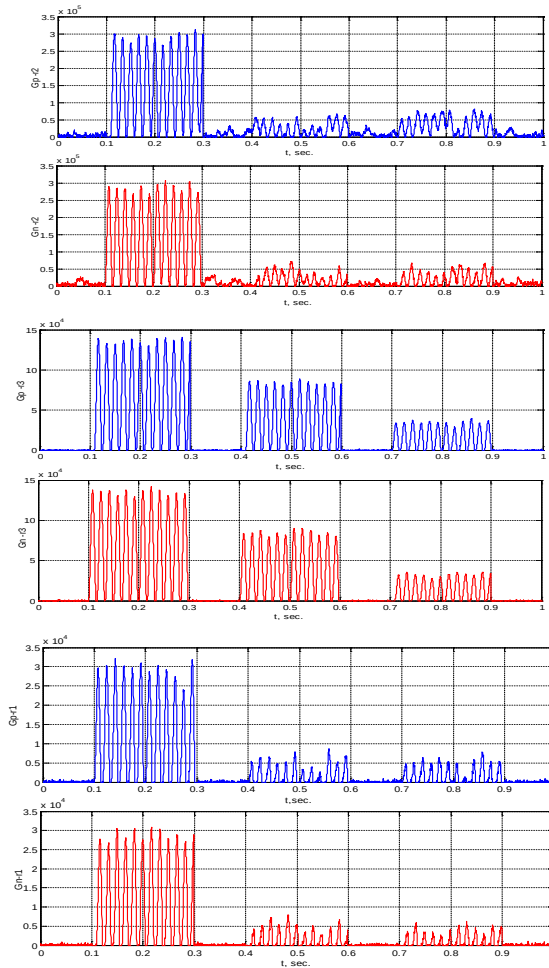


Fig. 3. Residuals r_1, r_2 and r_3 after applying application of CUSUM algorithm

3.2 Optimal sensor placement algorithm using genetic algorithm

The sensor placement problem is formulated as an optimization problem, which consists of defining a topology matrix C with respect to observability and diagnosability conditions. A necessary and sufficient condition for sensor diagnosis is developed based on the condition of existence of residuals.

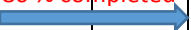
Let's consider $C = [C^{obs} \ C^{AR}]^t$, a diagonal matrix with the diagonal elements $diag(C^{obs}) = [c_1^1, \dots, c_{n_y}^1]^t$ and $diag(C^{AR}) = [c_1^2, \dots, c_{n_y}^2]^t$ respectively. Each element in the diagonal of C^{obs} and C^{AR} is equal to 0 or 1. To solve this optimization problem we apply a Genetic Algorithm (GA). We consider at each generation Gen , a population of a hundred individuals. The population Pop in the GA is defined by $Pop: \{X_p = [c_{p1}^1, \dots, c_{pn_y}^1; c_{p1}^2, \dots, c_{pn_y}^2]^t; \text{ with } c^{1,2} \in \{0,1\} \text{ and } p = \{1, \dots, 100\}\}$. The algorithm starts by considering a random population, where each individual X_i in the population is defined by random elements c_{pj}^1 and c_{pj}^2 . At each iteration, the elements c_{pj}^1 and c_{pj}^2 are updated. The stopping criterion of the algorithm is when the system iteration reaches 1000.

4. Achievements

- Development of a metric to design optimal sensor placement
- Development of algorithm for sensor FDI
- Hardware test and Implementation of sensor FDI on Raspberry Pi
- One journal paper (in preparation) and one patent (in progress)

5. Milestones and Deliverables

The table below summarizes the progress and milestones/deliverable for Y8.

Tasks	Description	Oct. 2015	Dec. 2016	Feb. 2016	May 2016
1	Literature survey		complete		
2	Development of algorithm for sensors' FDI			completed	
3	Development of a technique for data reconstruction and uncertainty management under sensor failures		80 % completed		
4	Development of a metric to design resilient sensor network and sensor placement.		50 % completed		
5	Hardware test and Implementation of sensor FDI		20 % completed		

7. Plans for Next Five Years

- Extend the developed tools to a larger system with application of distributed control and communication techniques

8. Member Company Benefits

The development of the intelligent sensor algorithm can be embedded to control systems, which allows users to enhance control, system autonomy and robustness.

9. Major references

- [1] A. Abur and A. Gomez-Exposito, Power System State Estimation Theory and Implementations New York: Marcel Dekker, 2004.
- [2] B. Stott, J.Jardim, and O. Alsac, Dc power flow revisited, Power Systems, IEEE Transactions on, vol. 24, no. 3, pp. 1290 --1300, 2009.
- [3] F. Schweppe and D. Rom, Power System Static-State Estimation, part ii: Approximate model, Power Apparatus and Systems, IEEE Transactions on, vol. PAS-89, no. 1, pp. 125 --130, 1970.
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- [6] M. Basseville and I. V. Nikiforov, Detection of Abrupt Changes: Theory and Application. Prentice – Hall, Englewood Cliffs, N.J. April, 1993.

Y8.ET2.1: FAWG System Level Architecture and Metrics

Team Members

Project Leader:	Dr. Raja Ayannar
Faculty:	Dr. Srdjan Lukic, David Lubkeman, Bruce McMillin, Raja Ayannar
Students:	Likhita Ravuri (NCSU)

1. Project Goals

The FAWG is responsible for facilitating development and documentation of the Hardware/Software/Networking FREEDM architecture in conjunction with subthrust teams. It is the technical owner of the architectural specification owning the Use Cases, Functional Requirements and System Requirements. The primary objective of the FAWG is to create a sustainable system architecture reference process that spans a diversity of domains and intellectual backgrounds. Expected deliverables are: (1) a reference document that is agnostic to hardware, software, network, and embedded systems architectures, and (2) to use this architecture to elicit subsystem requirements, interface specifications, and governing system invariants. The goal of this subtask is to develop the reference document in the form of a website that is available to all the stakeholders and is continuously updated. Additionally, our goal is to fully define, document and validate, through simulation, the FREEDM use cases associated with intelligent energy management and intelligent power management.

2. Role in Support of Strategic Plan

The primary output is a living article elicited from interviews from each subthrust. All future development must reference the architecture. The architecture provides a critical reference for system development, ensuring a common understanding of FREEDM functionality across all aspects of the Center. The architecture, coupled with the Use Cases, provides the input to a distributed smart grid reference standard that could be used worldwide.

3. Fundamental Research, Technological Barriers and Methodologies

The primary barrier in the FAWG has been to develop a systems engineering culture within the center whose culture is now maturing. The systems engineering training that was provided to all faculty and students in years three through five and the process that led to the development of the current Use Cases provided a good starting point for further driving system engineering practices and tools throughout the engineering development and system integration process.

4. Achievements

This is the second official year of this project, although systems engineering efforts preceded it, particularly in generating the Use Cases. The primary objective of this research is to develop a document of the whole system architecture with distinguished hardware/software components which have multiple levels of detail and a hierarchical structure. In the first year, the main emphasis was on the development of an abstract architecture diagram which is built using an extension of the SYSML's class diagram. They are used to define the abstract functionalities of every module and to show the structure and semantics of interaction between various system modules.

The system architecture diagram developed last year was taken as the starting point in the second year to develop more descriptive artifacts, which serve as the knowledge repository for the center. These artifacts include functions-based architecture diagrams; elaborate Use Cases describing system behaviors and requirements in each operating mode; and timing diagrams defining the order and limits on sub-system responses in actuating a Use Case. All this information is compiled in a format suitable for sharing via a Web Portal. The resulting Web Portal will serve as a Wiki-like repository for the FAWG efforts in the future. This way input can be solicited more effectively from all researchers in the Center.

Development of the shared Web Portal for FAWG Documentation: To document and share the developed artifacts, the team has developed a website that documents all of the aspects of the FREEDM Architecture. We are currently in the process of populating the website with information based on the artifacts that have been developed and are still in development this year and last, and with input from researchers and thrust leaders responsible for the development and implementation of these functionalities.

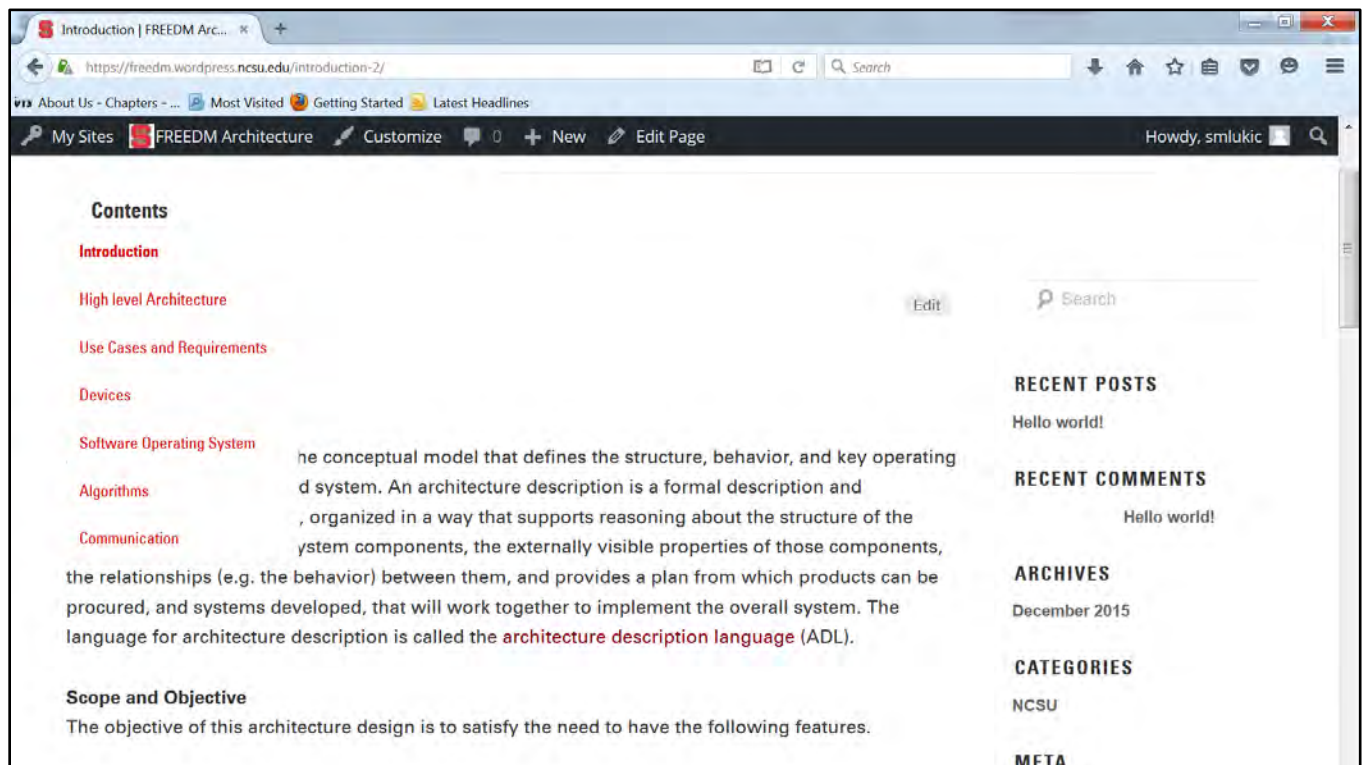


Fig 1: Screenshot of the FREEDM FAWG Website with the pull-down menu visible.

A screenshot of the website [1] is shown in Fig 1, and the website sections are outlined as follows:

1. **Introduction:** This section describes the scope and objectives of the FAWG initiative, our approach towards the case and how the website fits into this mission.
2. **High-level Architecture:** This section discusses the high-level architecture of the FREEDM system where different levels of operation and control are classified and discussed. Schematics and complete architecture diagrams are shown, defining the Categorization of Levels in the architecture as the Energy Cell (level 1) where the coordination of the load, generation and

storage is discussed for power balance; Single SST (level 2) where the interaction of a single SST with medium voltage FREEDM system is described; the FREEDM System (level 3) where the interaction strategy of multiple SSTs and FIDs in a FREEDM system is proposed; and multiple FREEDM Systems (level 4) where the interaction of multiple FREEDM systems interconnected to form a medium-voltage distribution system is managed.

3. **Use Cases and Requirements:** This section describes the eight Use Cases defined in FREEDM. These Use Cases have been defined in earlier years through the System Engineering efforts in the Center. This section of the website describes the interactions between FREEDM systems components under each Use Case. The abstract architecture diagram which is built using an extension of the SYSML's class diagram serves as the reference for how the Use Cases are described, and how the interaction between the components takes place.
4. **Devices:** This sections describes the components unique to the FREEDM center: the solid state transformer, the fault isolation device, the distributed energy storage device, and the distributed renewable energy resources. The section describes the components' desired functionality, interaction with other sub-systems, and implemented controllers for the device.
5. **Software Operating System:** This section describes the FREEDM distributed grid intelligence architecture, as well as the FREEDM Supervisory Control and Data Acquisition (SCADA) implementation.
6. **Algorithms:** This section describes the main FREEDM algorithms: Intelligent Energy Management (IEM), Intelligent Power Management (IPM), and Intelligent Fault Management (IFM)
7. **Communications:** This section defines the Information exchange requirements, methods of communication and selected communication protocols.
8. **Glossary of terms.**

After the first version of the site is complete by the end of year 8, the team will solicit additional input from the team to further refine the website. Our goal is to complete the website by the end of Year 9, and rely on the PIs and the wider FREEDM community to keep the information up to date as the Center evolves.

Development of simulation-based validation of FREEDM Use Cases: In conjunction with the documentation of the current implementation of the FREEDM architecture, the FAWG has embarked on a simulation-based validation of the FREEDM Use Cases. The purpose of these simulations is to validate the Use Case definitions described by the FAWG, and developed by the FREEDM team. The goal of the simulation is to have a common simulation-base repository that will allow for the validation of all aspects of the Use Cases that may be otherwise overlooked.

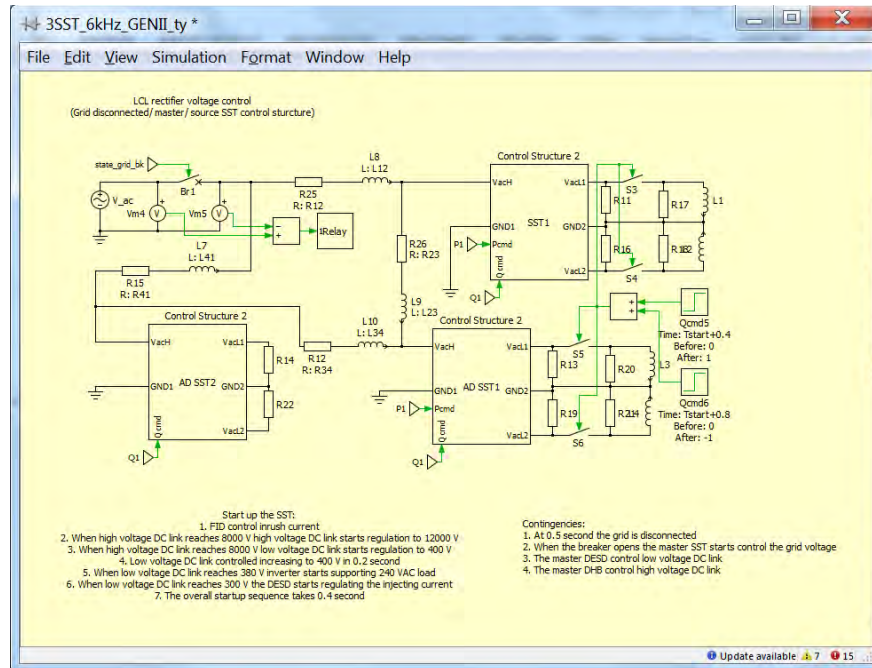


Figure 2: PLECS Model Developed by Dr. Ayannar serves as basis for simulation-based validation of FREEDM Use Cases.

The starting point for the development of Use-Case specific simulation is a PLECS-based switching model of a single SST and three networked SSTs, developed by Dr. Raja Ayannar and his team. This model already includes the lower-level control loops implemented on the physical SST. The work that still needs to be completed is the implementation of the higher level functions, specific to the Use Cases. In developing the models, the FAWG team will document the operation of the model, and therefore the intricacies of the Use Cases. The team will also make the resulting PLECS models available via the Website as a part of the documentation effort.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

As with any engineered system, there is a need to document the system architecture so that future developments can be made in a systematic manner, and so that other individuals and entities can be educated on the current system architecture. Therefore, the FAWG efforts provide a common reference platform for all center investigators and advisory members. Parallels to the FAWG effort can be found for any engineered system of similar complexity.

6. Milestones and Deliverables

- Complete compilation of all center-developed IEM and IPM algorithms, and incorporate the most suitable approaches in the architecture diagram and architecture document.
- Complete development, documentation and wiki webpages of all the Use Cases.

7. Plans for Next Five Years

- Further refine system architecture documents through the interactions with PIs.

- Build detailed system simulation for validation of all the Use Cases.

8. Member Company Benefits

All member companies are intended to be invited to participate in the Architecture Wiki as well as within the FAWG itself.

9. References

[1]. FREEDM Architecture, Available at <https://freedm.wordpress.ncsu.edu/>

Y8.ET2.2: Plug and Play and Power Systems Enhancements to FREEDM Architecture

Team Members

Project Leader:	Raja Ayyanar
Faculty:	Raja Ayyanar
Students:	Tong Yao (ASU), Ziwei Yu (ASU)

1. Project Goals

- Overarching architecture document on description of and interaction among the various FREEDM system components under all expected operating modes
- Link various cyber and physical aspects of FREEDM System including physical components, software, control loops, and communications, with focus on power systems aspects in Y8
- Develop functions-based architecture diagram with inputs from other sub-thrusts
- Validate the proposed architecture in different levels of simulations

2. Role in Support of Strategic Plan

The FREEDM system architecture document developed will provide a common reference platform for all center investigators and advisory members. The FREEDM Architecture Working Group (FAWG) will facilitate center-wide consensus on various operating modes of FREEDM and the control configurations in each.

3. Fundamental Research, Technological Barriers and Methodologies

The approach for the architecture development includes engaging researchers in various thrusts including SMC, SST, DESD, HIL, GEH and LSSS in obtaining overview and details of various IEM, IPM and IFM algorithms developed and securing a consensus on how the overall FREEDM systems should be controlled and operated under different modes and different contingencies. The tasks also include development/refinement of use-cases describing system behaviors, requirements in each operating mode, and timing diagrams. The developed concepts will be validated in detailed simulations in PLECS, Simulink, OpenDSS and other power systems analysis tools and through the HIL testbed. The major barriers include the significant challenges related to the large system being considered that combines aspects of power systems and cyber systems, the wide range of time constants involved, and the different descriptive languages used in different FREEDM disciplines.

4. Achievements

Mode transition and timing diagrams for various control loops and subsystems

Transition diagrams have been developed for the SST to show transitions between different operating modes. As shown in Fig.1, the controller structure for each operating mode and the trigger condition for switching between the different operating modes are included in the diagram. The diagram also fully describes the control objectives in each mode and the subsystems that are responsible for meeting these control objectives.

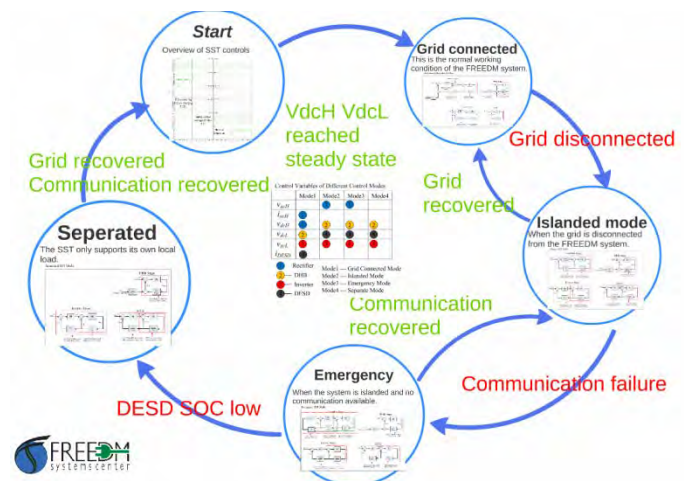


Fig. 1. Mode transition and SST control description diagram

Functions-based diagram

A main objective of this task is to develop various functions-based diagrams. Fig. 2 shows the function diagram for an SST under different modes of operation, and Fig. 3 shows a part of the diagram zoomed-in corresponding to a load SST with DESD in grid emergency mode.



Fig. 2. Functions-based diagram of an SST cell

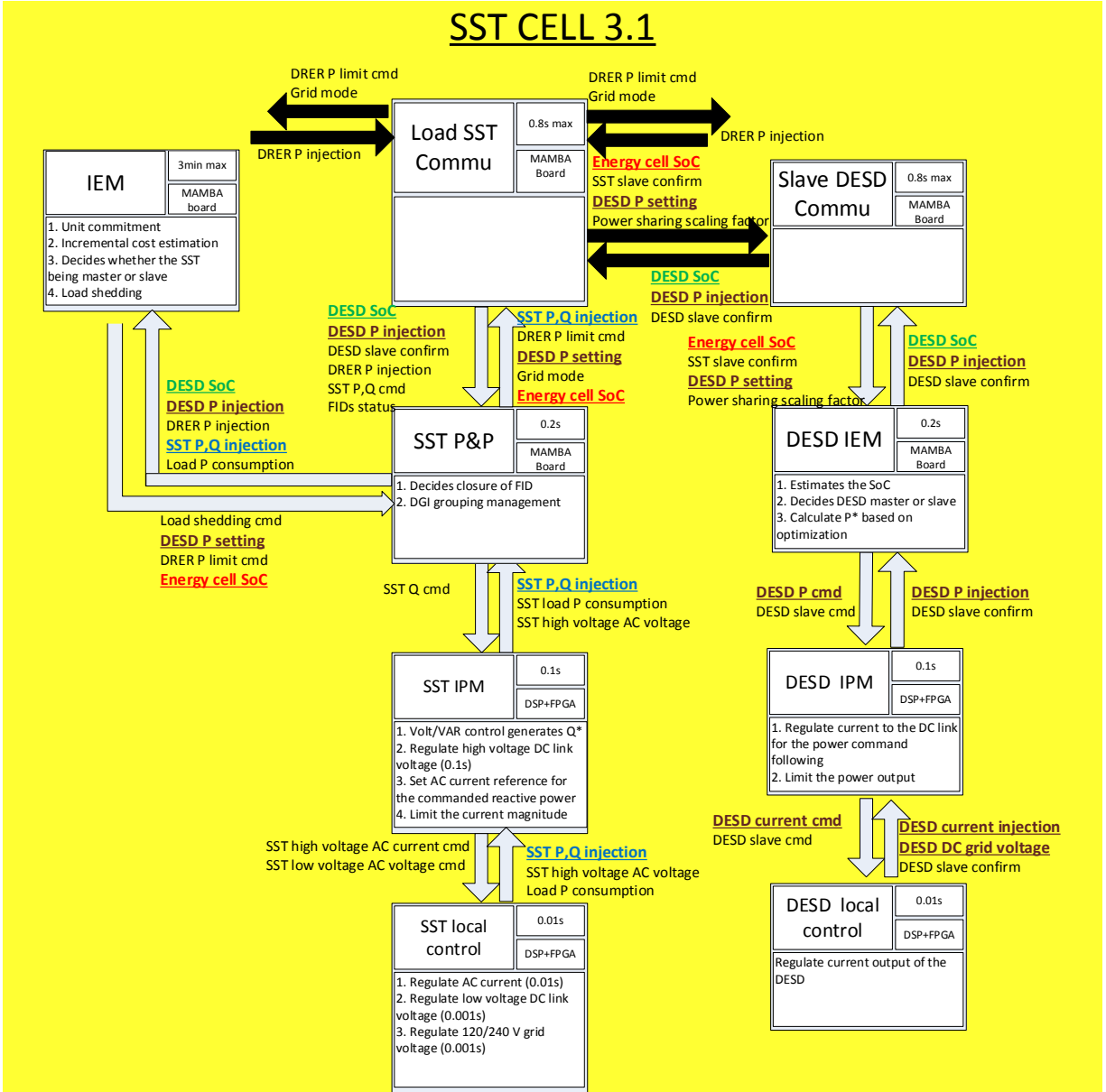


Fig. 3. Part of the functions-based diagram of an SST cell zoomed-in to show emergency mode operation

With changing grid conditions, there will be significant changes in the functions of the devices and the control structures under different grid conditions. In Fig. 2 from top to bottom there are device functions in grid-connected mode, grid-islanded mode and emergency mode. From left to right in grid-connected mode, there are AC DRER without communication, DC DRER without communication, a follower SST cell, and a leader SST cell. While for grid-islanded mode, the SST cells are called slave SST cell and master SST cell from left to right. Lastly, in emergency mode the SST cells are categorized into load SST cell and source SST cell. Within each mode, from bottom to top, the function time constant is marked from small to large. It illustrates the response speed of each function. And it also helps checking the information integrity by following the information flow lines connecting different function blocks. The black flow lines highlight the information exchanges with device-to-device communication.

System description document

The system description documents are being developed focusing on the various use cases. An elaborate format of the use case description has been finalized to summarize the requirements of each hardware/software component under different system operating modes. Per the finalized format, a complete FREEDM System use case document should include the following contents:

- A general description of the system operating mode, role and actions of each component under the specific operating mode. A summary of FREEDM system functions with general description on the basic concept and requirements
- Detailed step-by-step actions that define the system behavior
- A list of information exchange among FREEDM System components with basic information on the communication method and specifications
- A general description of each of the required sub-functions with at least one possible implementation approach, along with process timing diagram

The use case document for the system operation under islanded mode has been developed, and included here as an example. The table of contents is given in Fig. 4 and a part of the step-by-step actions description in the document is given as Fig. 5. The implementation approach of the required sub-functions has also been included in the last section of the document. Fig. 6 gives the flowchart of SST IPM functions under islanded mode, and Fig. 7 gives the block diagram of a proposed control scheme for the slave SST local controller. The document will be linked to other documents which contain detailed descriptions of the hardware components, control algorithms and communications.

Table of Contents

Description	
General Description	
Summary of FREEDM system functions under islanded mode.....	
Technical Details	
Actors	
Step-by-step actions	
Information exchange.....	
Function Description	
1. SST IPM.....	
2. SST Local Control.....	
3. DESD Local Control.....	
4. IEM functions	
5. Communication	

Fig. 4. Table of contents for islanded operation use case document

#	Step	Actor
1	SST IPM collects local information from the SST and DESDs of that SST node	SST-DESD Communication SST IPM
2	Calculate the available energy storage of the SST node based on the information from its attached DESDs and send it to the other SST nodes	SST IPM
3	Determine the operating mode of the SST node and send the corresponding commands to the attached SST and DESDs	SST IPM SST-DESD/DRER Communication
4	SST IPM waits for the response of SST local controller and attached DESDs, sends a confirmation message to the other SST nodes after receiving the response from the SST and DESDs.	SST IPM SST-DESD/DRER Communication
5	SST local controller starts to control the SST with the given operating mode and control references and sends a confirmation message to the SST IPM	SST Local Control
6	DESD local controller starts to control the SST with the given operating mode and control references and sends a confirmation message to the DESD IPM	DESD Local Control

Fig. 5. Step-by-step actions in islanded operation use case document

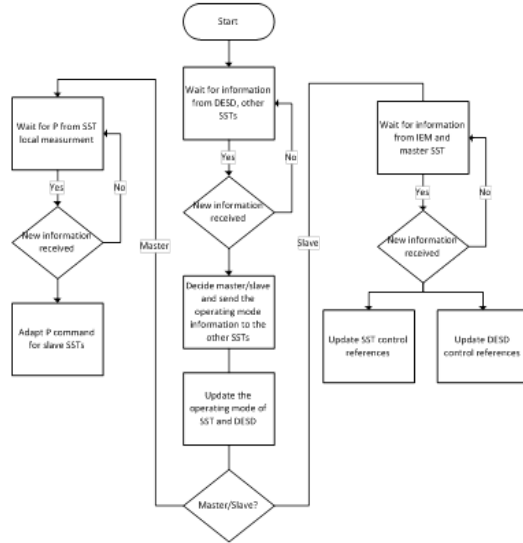


Fig. 6. Flowchart of SST IPM function under grid islanded mode

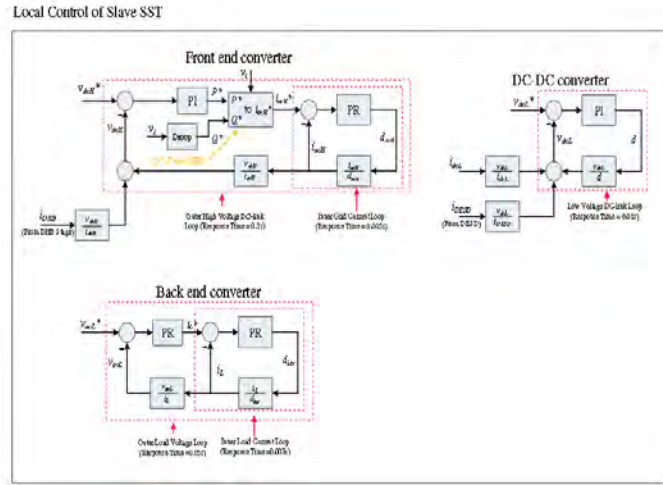


Fig. 7. Block diagram of slave SST local controller under grid islanded mode

A 3 SST system simulation and CHIL built for validating the proposed architecture

The functions proposed in the function diagram are validated using detailed simulation in PLECS and in controller hardware in the loop (CHIL) testbed. In each SST block, a 3-stage SST with DESD switching model and digital controllers are modeled. With the C-code based digital controller simulation capability in PLECS, advanced controllers such as IEM algorithms can be implemented for validation. The controller hardware in the loop testbed is setup for function tests also. The setup has one actual SST controller board sending PWM pulses to a real time digital simulator (RTDS). The simulated power hardware values are then fed back to the controller board by an analog voltage. The sampled analog quantities are processed by DSP to control one switching SST model simulated in RTDS. In RTDS, there are two other SSTs modeled in full average model forming a 3-SST system as in PLECS. So far, the SST start up and SST with DESD function changes from grid connected to grid islanded mode have been validated. In CHIL, with a manually controlled toggle switch in RSCAD (RTDS graphical user interface), random grid connection and disconnection have been demonstrated without jeopardizing the system stability.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Similar efforts related to defining the architecture of smart grid are being conducted elsewhere, notably the Smart Grid Interoperability Panel (SGIP), EPRI working group on Enterprise Integration Functions for Distributed Energy Resources, and different IEEE Standards committees.

6. Milestones and Deliverables

- Complete information about all the center-developed IEM and IPM algorithms and include this in the FAWG documentation
- Complete the description of all the use-cases in the new format

7. Plans for Next Five Years

The FREEDM architecture development is a continuous process. The FAWG will continue to gather and include the new IEM, IPM, IFM and plug & play algorithms and their communication requirements and timings, continue refining the use-cases and focus more in future years on validation through GEH and HIL testbeds in addition to detailed simulations on large scale systems.

Y8.ET3.1: Design and Development of Generation III SST

Team Members

Project Leaders: Alex Huang (ECE/NCSU)

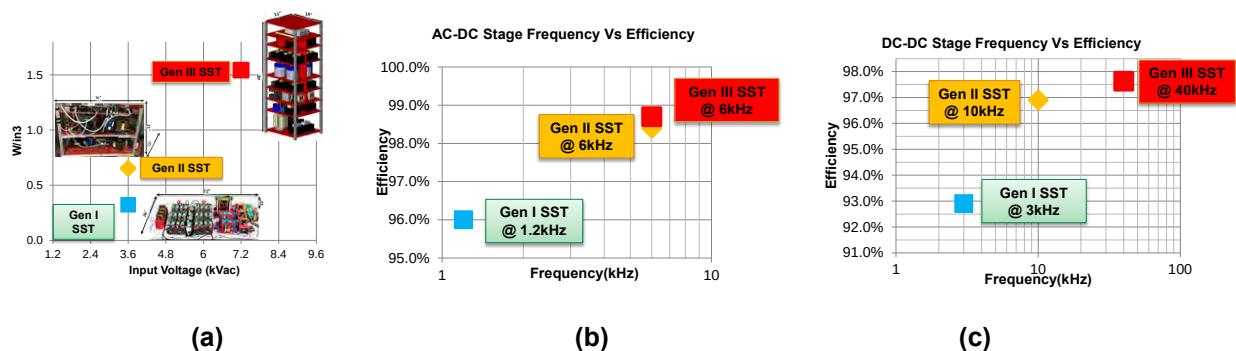
Other Faculty: Wensong Yu (ECE/NCSU)

Students: Li Wang (PhD), Qianlai Zhu (PhD)

Industry Participants: Medium Voltage Working Group and Cree Inc.

1. Project Goals

The overall objective of this project is to improve the ruggedness, efficiency and power density of the single phase 7.2 kV, 20kVA Gen-III Solid State Transformer (SST). Both the input voltage and rated power of Gen-III SST have been doubled compared with the 3.6 kV, 10 kVA Gen-I and Gen-II SST. The higher voltage level increases the challenges of insulation design for the package of the 15kV SiC devices, construction of medium frequency inductance and transformer etc. Greater clearance and creepage distance between discrete components are needed at the medium voltage (MV) side. Despite all the former mentioned obstacles, the overall Gen-III system has a power density of more than twice the Gen-II SST's as shown in Figure.1 (a). To reach this target: 1) the operating frequency of the DC-DC converter is pushed up to 40 kHz, so that the value and size of magnetic and capacitance components can be reduced; 2) a 'wireless' transformer that can achieve ultra-high voltage insulation without sacrificing the small volume of medium frequency volume is built. In the meantime, the efficiency of the AC-DC and DC-DC stage have been improved to 98.7% and 97.5% respectively as shown in Figure. 1(b) and (c).



(a) Power density versus input voltage; (b) Efficiency versus switching frequency of AC-DC stage; (c) Efficiency versus switching frequency of DC-DC

Fig. 1. Comparison of Gen-I, Gen-II and Gen-III SST stage.

2. Role in Support of Strategic Plan

As a key enabling technology platform, the SST serves as a platform for fundamental science technologies such as Post Silicon Devices developed in the center and by industry partner Cree. It also provides DC and AC interfaces for center developed DESDs, DRERs and smart loads. The Si-IGBT based multi-level Gen-I SST and 15kV SiC-MOSFET based Gen-II SST have been developed

and delivered as revolutionary smart interfaces at 3.6kV and 10 kW level in the previous three years. According to the strategic research roadmap and the feedback from the Y7 site visit team, the role of the Gen III SST is to improve efficiency and to reach an input voltage 7.2 kV level.

3. Fundamental Research Barriers and Methodologies Used to Address Them

The main challenges for this Gen-III SST project are to develop reliable, high power density, efficient and cost-effective power electronics for 7.2kV smart grid applications. Since the power and voltage level are twice as high as the Gen-II SST, research barriers related to high voltage (12 kV) solid state power conversion need to be addressed: 1) Reliable and cost effective >5 kV AC and DC voltage sensors without paying a high cost penalty. In this project, sigma-delta based fiber optic high voltage (> 10 kV) sensors are developed to solve this issue. 2) For the AC-DC inverter/rectifier, because of the hard switching at 6 kHz/6 kV, the significant amount of energy stored in parasitic capacitors of inductance induce failure causing the destruction of components. In this project, improved inductances with low parasitic capacitance are developed. 3) Medium frequency bidirectional DC-DC converters that provide ultra-high voltage galvanic isolation have to be constructed. Soft switching of all the 15 kV SiC semiconductors are mandatory for ruggedness as well as efficiency considerations. 4) Another fundamental barrier is to achieve a highly reliable start up and fault protection of the whole system.

4. Achievements in Previous Three Years with an Emphasis on the Current Year

In the previous three years, the team reported that an overall efficiency of 95% for three power stages at 10kW power level and 3.6kV RMS grid voltage were successfully achieved and demonstrated in the Gen-II SST. In year 6, we have already reported breakthrough improvements in high frequency transformer design (20-40 kHz) that has an ultra-high isolation voltage. In Year 7, a unique customized 10kV SiC module without the risk of shoot-through of high voltage has been designed and fabricated for the proposed AC-DC inverter/rectifier. In Year 7, a novel isolated bidirectional DC-DC converter for medium voltage applications is proposed to combine the advantages of the resonant converters and those of dual active bridge (DAB) converters. The operation and short-circuit protection function have been experimentally verified at 3kV/2.5kW. In the current year, the major achievements made are summarized below.

4.1 Controller and Advanced fiber optic high voltage (> 10kV) sensor

Figure 2(a) shows the controller hardware that is based on TI digital controller IC TMS320F28377D. Figures 2(b) and (c) illustrate the proposed (>10kV) fiber optic sensor (left), and the existing (5kV or less) voltage sensor (right). It should be emphasized that the developed fiber optic sensor is based on the Σ - Δ communication principle and can achieve 16-bit analog-to-digital (A/D) conversion with no missing data, has a compact structure and is easy to expand to more than 10kV while remaining a low cost solution. Moreover, with the integrated Σ - Δ peripheral circuit of the DSP, it can greatly simplify hardware design and software coding as well. Figure 2(c) shows the test result for the proposed high isolation voltage sensor. The sensed signal follows the original signal very well. Even at a sharply rising edge, the sensing delay is only 70 μ s.

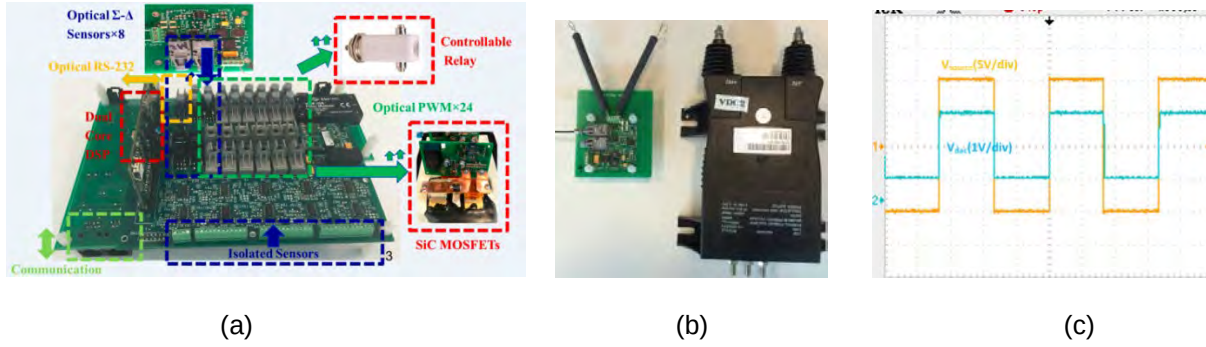


Fig. 2

4.2 Novel Bidirectional Medium-Voltage AC-DC Converter

SST III is required to reach 7.2kV AC input voltage, a task that has not been achieved so far, partly due to the immature prototype SiC device technology. To handle such high voltages and to improve the reliability, a 2-stage cascading structure will be used unless a much more robust 15 kV device can be identified. Each stage will transfer 3.6kV ac voltage to 6kV dc bus voltage. Dead time will cause distortion in the input current which will pollute the grid. On the other hand, this shoot through problem will significantly affect the reliability of the converter. To solve these problems, a new proposed topology is used in AC-DC part, in which shoot through di/dt rate is limited by large inductors in series and is readily controlled, allowing zero dead-time operation. The reverse recovery dissipation of the active switch is also greatly reduced because no freewheeling current will go through body diode. The device structure is greatly simplified and 15kV SiC devices are used. A multi-stage inductor is proposed and being designed for size and insulation consideration.

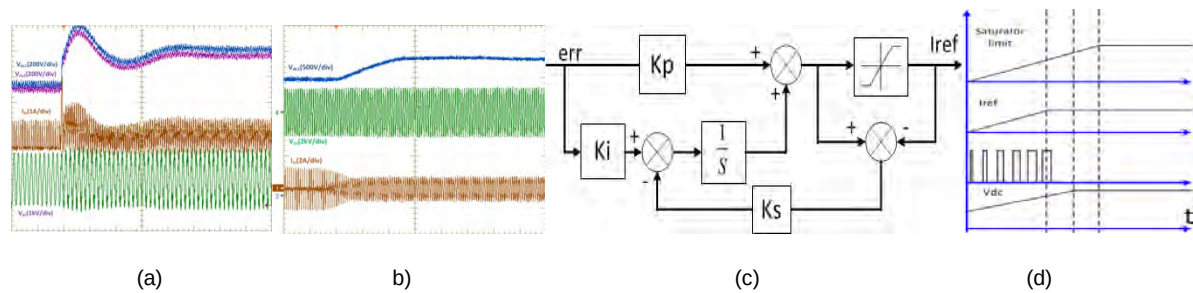


Fig. 3

An anti-windup architecture in Figure 3(c) is adopted for both the output voltage loop and inner current loop. This method uses the difference of the signals before and after the saturating actuator to adjust the control strategy, which helps to improve the system stability and performance. During start up, as shown in Figure 3(d), the saturator's limits increase gradually step by step, generating a low rising rate for the current reference. The current loop's bandwidth is limited by the switching frequency and is designed to

be 700Hz. The slow rising current reference makes it much easier for the current loop to follow and the output voltage of the rectifier is then charged slowly without overshoot.

4.3 Parasitic Capacitance Reduction of MV Inductor

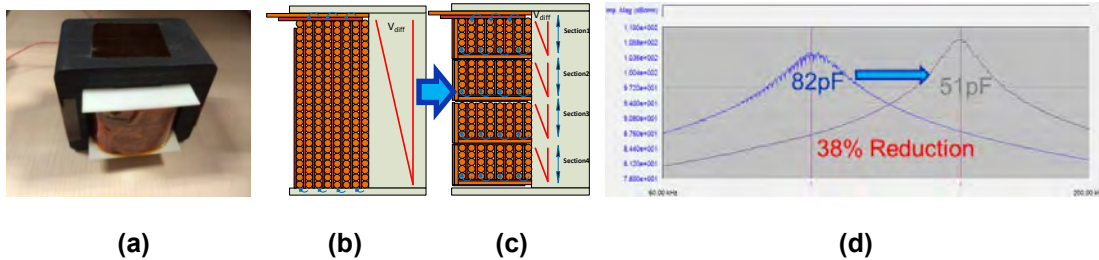
According to the analysis from an impedance analyzer, the parasitic capacitance of the designed boost inductor, C_{p1} is around 80pF with the traditional winding method as shown in Figure. 4 (a), which generates 1.5mJ power loss for the switches during turn on. This loss is comparable to the C_{oss} loss of the MOSFET. Reducing the parasitic capacitance of the inductor will reduce the switching losses on the switches. Equivalent self-capacitance of inductor can be calculated by:

$$E_{ij} = \frac{1}{6} C_{ij} I_{ij} [V_{A,ij}^2 + V_{A,ij} V_{B,ij} + V_{B,ij}^2] \quad (1)$$

$$E_{total} = \frac{1}{2} \sum_{i=1}^N \sum_{j=1}^N E_{ij} \quad (2)$$

$$C_{self} = \frac{2E_{total}}{V_L^2} \quad (3)$$

The equivalent capacitance is proportional to the square of the voltage difference between layer to layer from equation (1). Figure 4(c) shows an improved section based winding method to decrease the inductor parasitic capacitance, the main idea is to divide the winding into several sections to reduce the peak voltage difference between layers, which results in less energy charge during operation and hence less capacitance. In Figure 4(c), we can see the peak voltage difference from layer to layer (as shown in the red line) is a quarter of the one in original winding as shown in Figure 4(b), which will reduce the self-capacitance. Figure 4(d) shows the tested resonant frequency of the traditional wired inductor and the section based wired inductor. The new winding method pushes the self-resonant frequency higher and results in 51pF parasitic capacitance in total, which is 40 percent less than the original capacitance of 81pF. As both the MOSFET C_{oss} and diode capacitance C_d are both around 80pF, this reduction of capacitance helps to reduce the total turn on loss by 13%.

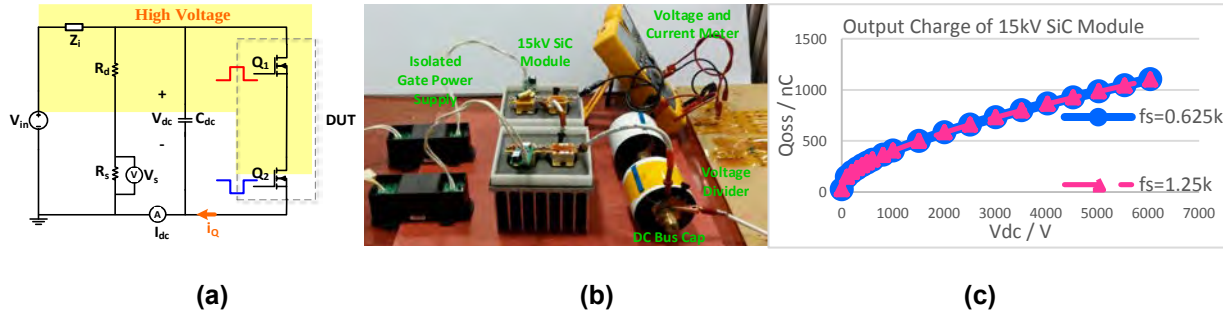


(a) picture, (b) previous winding method, (c) section based winding method (d) resonant frequency of old and new winding inductors

Fig. 4. Inductor

4.4 Output Charge Characterization of 15 kV SiC MOSFET

In medium voltage and high frequency applications, zero voltage switching (ZVS) is necessary since a significant amount of energy is stored in the MOSFETs' parasitic output capacitors. Recovering this energy is important to achieve a high conversion efficiency while ZVS also reduces the dV/dt significant in these devices. To guarantee complete ZVS, it is crucial to accurately characterize the output charge of devices.



(a) Half-bridge dynamic output charge measurement system; (b) High voltage output charge measurement setup; (c) Experimental output charge measurement results of 15kV SiC Module (MOSFET+JBS).

Fig. 5

A dynamic half-bridge test method for 15kV SiC MOSFETs' output charge measurement shown in Figure 5(a) is experimentally verified up to 6 kV. The test circuit not only reflects the realistic ZVS scenario, but also achieves high accuracy ($<1\%$ error) without resorting to special equipment or complex configurations, which are usually necessary for high voltage testing. As can be seen in Figure 5(b), the test setup only needs two multimeters for accurate DC voltage and current measurements. The tested output charge of 15 kV SiC module - MOSFET paralleled with junction barrier Schottky (JBS) from 0 V to 6 kV are given in Figure 5(c), the tested output charge shows very little difference for different frequencies hence validate the measurement method at 6 kV.

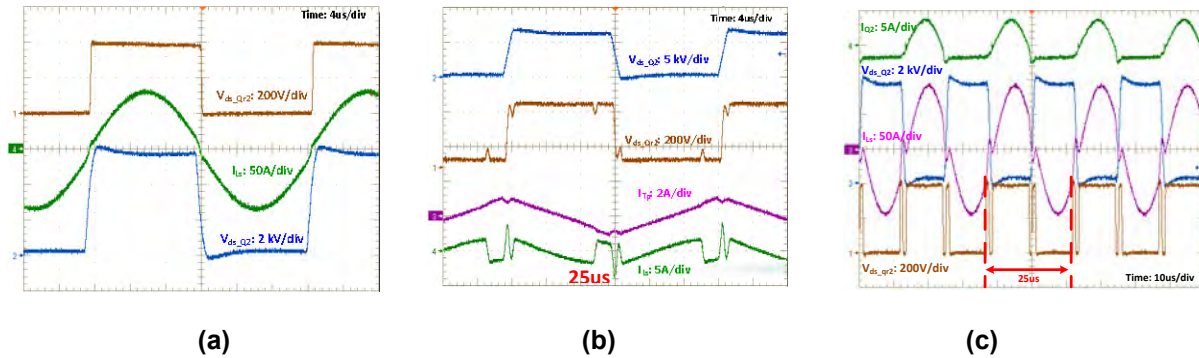
4.5 Resonant and Dual Active Bridge Hybrid Bidirectional 6kV/10kVA DC-DC Converter

The dual active bridge (DAB) bidirectional DC-DC converter has been experimentally verified by both the Gen-I and Gen-II SSTs as one of the most simple and reliable bidirectional converters because of its symmetrical circuit configuration and inherent current limiting capability. However, it suffers from high circulating current and high turn off switching loss, which degrades its overall efficiency. In addition, it will suffer zero voltage switching (ZVS) losses under light loading conditions. This may lead to premature failure of the 15 kV SiC devices operating at 40 kHz as there is a significant amount of energy stored at the semiconductors' output capacitance at 6 kV. A series resonant converter can recycle this energy and ensure the ZVS capability from full to zero load. But this gives rise to high-risk start-up and over load protection issues due to the ultra-low impedance characteristic.

In the Gen-III SST, a novel galvanic isolated bidirectional DC-DC converter for medium voltage applications is proposed to combine the advantages of the resonant converters and those of DAB converters. Together with a developed unique predictive control, both the ruggedness and efficiency have been greatly improved compared with the Gen-I and Gen-II SSTs. Under normal conditions, this hybrid converter operates at a resonant point to achieve ZVS turn on for MV side devices and zero current turn off for low voltage side devices. Thus, the highest efficiency operation the resonant converter can be kept.

Whenever over load happens, the resonant capacitors will automatically bypass their paralleled diodes. The converter will then shift into a resonant and DAB hybrid mode, therefore cycle-by-cycle over load protection can be achieved. The proposed predictive control is adopted to further benefit the system in terms of seamlessly realizing a soft startup, normal ZVZCS operation, over-current limits, short-circuit fault protection and fault auto-recovery without resorting to high bandwidth current sensors, or complex control strategies. In this case, only a low DC voltage sensor and a look up table are needed.

The experimental results at 6 kV to 400 V are illustrated in Figure 6(a)(b). It can be seen from Figure 6(a), that soft switching is realized at full load operation. Figure 6(b) shows the waveforms when the load is zero, where ZVS and ZCS are also achieved. The soft switching capability is therefore verified from full to zero load range. Figure 6(c) gives the waveforms of the proposed converter working at 400 V – 6 kV /10 kW condition, which proved the reverse power flow operation. The efficiency comparison of the DC-DC stage of Gen-II and Gen-III SST is shown in Figure 7(a). Not only the does the operating frequency have be increased from 10kHz to 40kHz, the Gen-III DC-DC converter's efficiency also improved more than 0.5% in all load ranges compare with Gen-II.



Experimental results of proposed DC-DC converter (a) 10 kW power flow from 6 kV to 400V; (b) 0 W power flow from 6 kV to 400V; (c) 10 kW power flow from 400V to 6kV;

Fig. 6

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Within the ERC, the Gen-I SST has been developed and delivered to the GEH testbed to demonstrate IEM functionality in the GEH testbed. The Gen-II SST was also developed and delivered to the GEH testbed and has been used to demonstrate a number of IEM and IPM functions. In this reporting year, it has also been tested at an industrial partner site (Eaton) and in the HIL testbed in FSU. Outside of the ERC including Europe and China, there are many new activities underway to develop the SST for power grids, high-speed trains, MV renewable energy systems, electric vehicle charging stations and others applications. Dr. Alex Huang recently attended a global summit on SST technology in Switzerland. There is a global rush to develop SST technology and FREEDM should be proud of being the key driving force behind it. Worldwide developments are mostly taking a low voltage multilevel approach similar to the FREEDM Gen-I approach. The current FREEDM approach is therefore more fundamental and unique because it has the capability to deliver a much simpler and robust solution. This approach is widely supported by industry member companies because of the perceived high reliability. Therefore focusing on our roadmap and the unique capability of 15 kV SiC power devices differentiates our approach from others. In Year 8, one of the Ph.D. students, Ms. Li Wang, also visited ETH for one semester. She worked with ETH researchers on the SST development.

6. Milestones and Deliverables

The expected milestones and deliverables of the SST in Year 8 are:

- Finish the development of the Gen-III SST and its testing, particularly with increased power level and operation of SiC devices at elevated temperatures. Verification of Gen-III SST under the condition of the rated voltage and the rated power levels;
- Start the development of Gen-IV SST that includes additional innovations in medium voltage power electronic topologies with very few active semiconductors on the high voltage side to minimize the cost and to increase the reliability

7. Plans for Next Five Years

Based on the SST strategic research roadmap, comments from the Year 7 NSF site visit team and the SST working group; the SST plans for next five years are as follows:

- Improve the utilization of the SiC power devices in the SST by increasing the operating voltage and current and hence the thermal stress towards higher junction temperature operation. This will result in more compact and more cost effective SST design. This will be demonstrated through the development of a much more radically different Gen-IV SST.
- Unique application opportunities for the SST such as MV chargers or MV PV Inverters (as recommended by the SST working group). Both examples are uni-directional SSTs.
- Knowledge dissemination through publications, technology transfer and commercialization.

8. Member Company Benefits

Member companies benefit from the optimized design and real implementation of >10kV SiC switches and improved MV topologies, the cost-effective fiber optic high voltage (> 10kV) sensor, and practical design of the highly reliable and efficient bidirectional DC-DC converter with the highest switching frequency and >20 kV isolation capability. So far our development also benefits greatly from our partnership from Cree/Wolfspeed. All high voltage devices are delivered by Cree/Wolfspeed. We continue to count on this relationship for future SST development.

9. Publication

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Y8.ET3.2: Controller Hardware-in-the-Loop (CHIL) Development and Demonstration with Plug and Play Features

Team Members

Project Leader: Dr. Huang
Faculty: Raja Ayyanar
Students: Tong Yao

1. Project Goals

A. SST model refinement for HIL test bed

The HIL test bed uses several SST nodes using both average models and detailed switching models. As the Gen-III hardware SST development progresses, the corresponding changes in the controllers, protection and topology need to be updated in the average and switching models used in the HIL-TB. In addition, the year 7 SVT emphasized focusing on incorporating plug and play features in FREEDM components as well as stability demonstration of the FREEDM system under high penetration of DG. While these requirements are addressed in the SMC thrust, this task involves incorporating the resulting changes in the SST models used in the HIL-TB.

B. CHIL development including plug and play features

The primary objective of this task is the continued development of CHIL in the HIL-TB to facilitate the demonstration of several new use cases and scenarios. DSP/FPGA control boards will be programmed to control the SST and DESD nodes (detailed switching models) in the HIL demonstrations. Y8 will focus on incorporating plug and play features, and implementing new IPM developments including Volt/VAR and Volt/Watt control.

C. SST model validation with experimental results

Another objective based on the year 7 SVT report is to validate the switching model of the SST with actual hardware results. The proposed plan is to compare salient time-domain waveforms of the switching model with the corresponding experimental waveforms (Gen II SST and Gen III SST when available), and fine tune the simulation model based on the validation.

D. Implementation of robust controllers in SST

This task involves implementing and validating robust control methods in the latest SST hardware units such that the SST is capable of operating in a wide range of grid conditions and various operating modes.

2. Role in Support of the Strategic Plan

- **What will be delivered to the next Enabling technology or Testbed level (include input from that thrust leader, if applicable)**

Much of the work in this task is in support of the HIL testbed. The results are being communicated to both the Gen-III SST development team and to the GEH testbed to aid in their development.

- **The benefits to the FREEDM system**

Hardware validated models of the SST are a major benefit; it will also help to demonstrate various features developed under the SMC and architecture proposed by FAWG.

- **Plan for Team Work within thrust and among the ERC Planes:**

The team from ASU works closely with the teams from FSU and NCSU in implementing CHIL; regular biweekly meetings as in prior years will be continued; collaboration with SMC, FAWG and GEH thrusts is facilitated through involvement of the PI in those projects and interaction of students from multiple universities

3. Fundamental Research, Technological Barriers and Methodologies

A. Rectifier stage LCL filter design considering robustness to grid impedance uncertainty

Barriers:

- The Inductor-capacitor-inductor (LCL) filter has three degrees of freedom in design
- The LCL filter has a large resonance at a high frequency, which affects system stability
- The grid impedance is uncertain when the SST connected to the grid

Methodologies:

- Design LCL filter with the constraints of current THD requirement, voltage THD requirement and resonant frequency requirement
- Design current controller considering the system in the Z domain, with an active damping method

B. SST regulates the grid voltage with large disturbance and system uncertainties

Barriers:

- When the FREEDM system is disconnected from the main grid, the system has a low inertia
- The SST has to take over the responsibility for regulating the grid voltage
- Large uncertainties on grid impedance
- Large uncertainties in power demand from other SSTs
- The FREEDM system has an uncertain number of SSTs with expansion

Methodologies:

- Use a master and slave control structure for grid islanded mode
- Model a 3-SST system with modular modeling method for easily expanding the system scale
- Use mu synthesis method to design controllers for the master SST considering grid impedance uncertainties, slave SSTs current command uncertainties and master SST DC link voltage uncertainty

C. Artificial loss of 6 kHz SST switching model in RTDS

Barriers:

- The Real Time Digital Simulator (RTDS) has a limited 2 microsecond small time step for the switching model
- A large artificial loss in the PH3LEV2 model has been reported in previous years' work
- The new lossless model, LEV2, has an unavoidable LCL structure in the switching model for decoupling the solution from passive networks brings in uncertain modes in the system

Methodologies:

- Use the inherent LCL structure in switching model to form filter inductor or capacitor
- Reconfigure the model in a symmetrical way, eliminating the artificial ground current
- Build a reference model in PLECS non-real time simulation platform for validation of model

4. Achievements

In previous years:

From the SMC project, the FREEDM system's working modes are categorized into: grid connected mode, grid islanded mode, grid emergency mode and SST islanded mode. In grid emergency mode, a robust dynamic droop control has been designed using a Glover-McFarlane H infinity loop shaping method [1]. It has shown a robust performance regarding load step changes, grid configuration changes and SST disconnection and reconnection.

From the CHIL project, a 2 kHz switching SST model is built. It is able to validate the control functionalities of the SST with the real controller board [2]. Also a remote control of the SST is

achieved by an ARM board communicating with the SST controller board. Then with the new switch model of RTDS, LEV2, a lossless SST model has been built with basic functions implemented. Its topology is shown in Fig. 1 with a three-stage GENII SST and a DESD. The CHIL simulated model achieves 94 % power conversion efficiency.

In this year:

The first achievement is the transplanted model from Simulink to PLECS mimicking the GEN II SST hardware. The MATLAB/Simulink files used at NCSU for design SST hardware and controls are studied. The corresponding PLECS model matching the Simulink model is built. The controller in the PLECS model is written in C which is close to that in real implementation. The model is in a complete PLECS simulation file without separate '.m' files as for Simulink models. This model is easy to use and can be readily adopted by higher level control studies as the control codes are written in C.

The SST rectifier stage LCL filter is redesigned considering three constraints: current THD, voltage THD and LCL resonant frequency. By pushing the LCL resonant frequency to the unstable region and adopting active damping, a robust stability is achieved with respect to the system grid impedance uncertainties. A proportional resonant (PR) controller is designed in a stationary frame fitting in the active damping structure. The poles of the system with changing grid impedance are plotted in Figure 2. The figure shows that the increased impedance damps the system further.

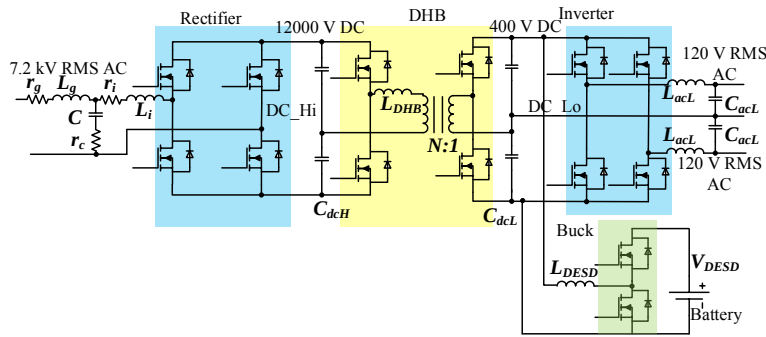


Fig. 1. GENII SST three stages with DESD

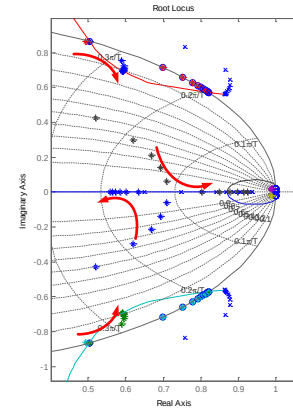


Fig. 2. Root locus with grid impedance increase

Another achievement this year is the robust master SST voltage regulation controller for grid islanded mode operation. The new robust controller not only deals with system parameter uncertainty but also the structure uncertainty. And it is validated in both PLECS and CHIL platforms. For the grid islanded mode, a master and slave structure is adopted taking advantage of the communications between SSTs. The system being considered is shown in Fig. 3 which is a 3-SST system. Considering a large resistance, such as surge arrestor, at the terminal of the SST, the system is decoupled into different modules as shown in Fig. 4. There are three basic building modules: current control SST, voltage control SST and system network. By reusing the SST modules, a larger scale FREEDM system can be modeled. Also, a structure uncertainty of the system can be easily modeled. For the parameter uncertainties, there are 12 system uncertainties modeled for mu synthesis controller design namely 9 grid impedance uncertainties, 2 slave SSTs current command uncertainties and master SST DC link voltage uncertainty. For the system structure uncertainty, the no load condition is considered for loop shaping. The designed robust controller has a high order of 57. The controller is reduced to 10 orders with an integrator for digital implementation.

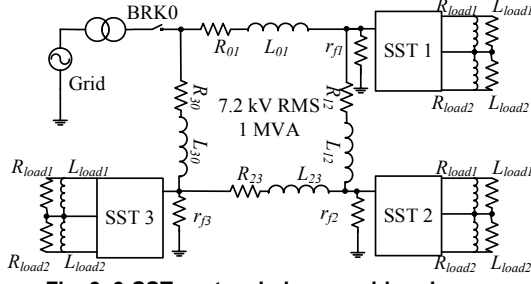


Fig. 3. 3-SST system being considered

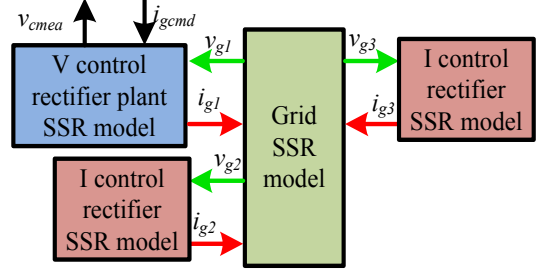


Fig. 4. Modeling blocks

Another major achievement is the detailed PLECS model for the 3-SST system which validates the designed robust controllers. For the purpose of validating the robustness of the digital controllers, a PLECS model is built with full switching details. C-script block in PLECS is used to mimic the DSP board in a real SST. The robust controllers designed for grid connected and grid islanded modes are implemented in C-script by C code. The simulation results of the system going from SST startup to steady state and multiple contingencies are shown in Figure 5. This figure shows the responses of the master SST (SST1), to all of the contingencies from the other 2 slave SSTs. It validates the robust controllers designed earlier. The contingencies shown In Figure 5 are listed below:

- (1) System startup with SST regulating the inrush current by its FID thyristors and regulating the high voltage DC link low voltage to a nominal value. The SST works at nominal condition with its low voltage load supplied;
- (2) The main grid is off and SST1 regulates the grid voltage;
- (3) SST3 is off the grid;
- (4) SST2 is off the grid and SST1 supports voltage with no load;
- (5) SST3 comes back onto the grid;
- (6) SST2 comes back onto the grid, completing the black start process;
- (7) SST2 DESD draws extra 5 kW and SST1 delivers 20 kW full load to 7.2 kV grid;
- (8) SST2 DESD is fully charged and SST1 low voltage side load increases;
- (9) SST2 injects 5 kW back to grid;
- (10) SST2 injects 10 kVar back to grid.

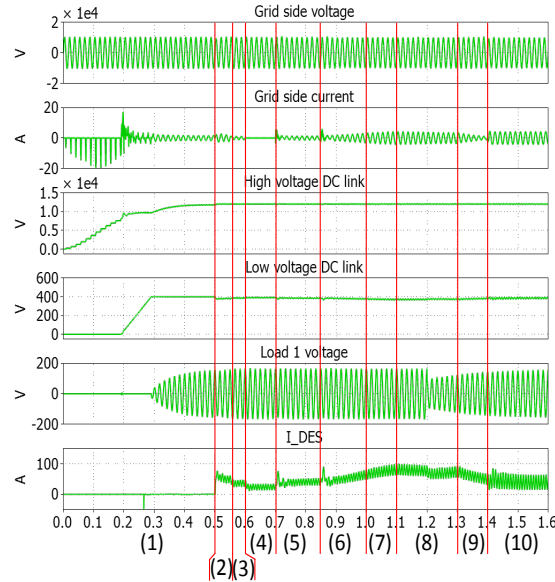


Fig. 5. Simulation of SST1 (master) with contingencies

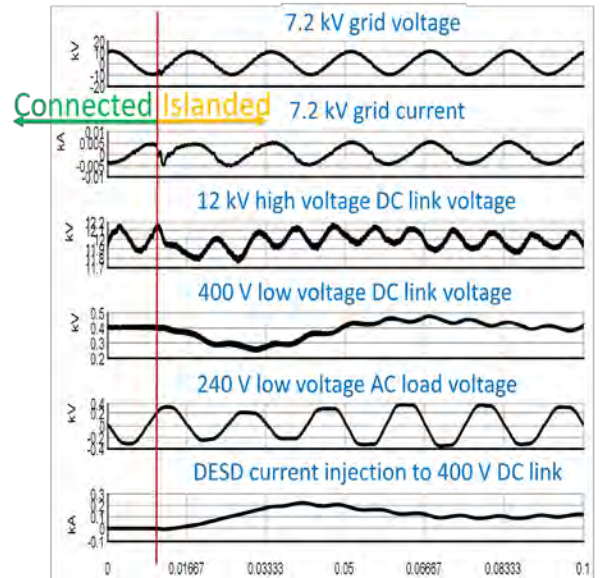


Fig. 6. CHIL master SST response to islanding

The 3-SST system built in the CHIL environment is another significant achievement for this task, which validates the robust controllers. Considering the calculation capability of the RTDS, one switching model switching at 6 kHz is modeled along with two full average models. The switching model is controlled by the real controller board with one DSP and two FPGAs. RTDS receives the PWM pulses from the controller board and simulates the switching events in real time. The full average model has all the stages modeled numerically with the switching period cycle by cycle average. It has the controller implemented in an analog form due to RTDS fixed time step constraints. The robust controllers are implemented in the controller board, and the full average model has the robust current controller in the S domain. The results corresponding to transition from grid connected and islanded modes are shown in Figure 6. As seen a smooth transition is obtained verifying the controller design.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Researchers outside of the ERC have worked on the active damping control structures. But our work is from the angle of designing a robust controller considering both LCL filter design and active damping controller design. Some outside work has also introduced mu synthesis methods for inverter control. But the considered uncertainties in those works are limited compared to our work which goes beyond the grid impedance uncertainties.

6. Milestones and Deliverables

Q3 (9/30/2015) – Complete development of refined SST models including start-up procedures (completed)

Q4 (12/31/2015) – Complete development and programming of controller boards for SST and DESD to support new use cases in CHIL (completed)

Q1 (3/31/2016) – Complete validation of SST model with Gen-II/Gen-III hardware results (in progress)

Q2 (6/2/2016) – Validation results of SST switching model with hardware (in progress)

Refined average and switching models of SST corresponding to the latest controllers and topology (completed)

Demonstration of CHIL to SV with new use cases, and support for GEH demo to SV

Q3 (8/30/2016) –Support for GEH testbed and demonstration through CHIL testing

Feedback and recommendations to Gen-III SST development team based in HIL testing

7. Plans for Next Five Years

Y9 of this work will focus on GEN-III SST controller designs.

Y10 of this work will be implementing the robust controller into GEN-III SST.

8. Member Company Benefits

Access to validated switching models of SSTs with different control structures; access to robust controller design methods and design tools

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Y8.ET3.3: Enhanced Integration of DESDs to SST

Team Members

Project Leader:	Dr. Hui Li
Faculty:	Dr. Hui Li
Students:	Qing Ye, Ran Mo, and Thierry Kayiranga

1. Project Goals

The objectives of this task are: (1) to develop resonance mitigation methods for SST-DESDs to solve the harmonics instability especially in high frequency range, therefore to improve the SST-DESDs system stability; (2) to provide a stability-oriented design guidelines for SST-DESDs; and (3) to design a HIL test bed to demonstrate the stability and enhanced integration capability of SST-DESDs.

2. Role in Support of Strategic Plan

This work will provide an application case for HIL SST-DESDs test bed task. With this test bed, the stability analysis of SST-FC can help better understanding of harmonics instability mechanism of FREEDM system. To ensure the stability and reliability of FREEDM system, control-based solutions are derived and implemented. In addition, a comprehensive stability-oriented design guideline is developed so that the instability issues can be predicted and avoided at design stage. This work benefits research within and outside of SST thrust by maintaining the FREEDM system stability.

3. Fundamental Research, Technological Barriers and Methodologies

The fundamental challenges facing the development of SST-DESDs HIL test bed are summarized as three aspects, which are a) modeling and analysis of the resonance mechanism due to the interactions among SST and DESDs for further addressing the instability issues; b) develop control-based instability mitigation techniques to enhance the SST integration capability considering filter design and controller design, and increase the maximum number of integrated DESDs that allowed to be connected to the SST; c) formulation of a system level stability-oriented design criterion to achieve robust SST-DESDs.

4. Achievements

4.1 Resonance mechanism and control-based instability mitigation techniques

In year 8 we analyzed the harmonics instability issues that exist in an SST-DESD system which is quite different from those of multiple inverters connected to the grid. The output impedance characteristics of the SST are frequency-dependent. In addition, the dynamic interactions among the advanced controllers together with the output filters deployed in SST and DESDs aggregate the harmonics propagation in the SST-DESD system. To understand the mechanism of the severe resonances observed, a unified impedance based stability criterion (UIBSC) had been proposed in our work to analyze the unique harmonics instability in SST-DESDs system [1], and it was found that multiple resonances could happen in the SST-DESD system based on the output impedance of SST and DESD as shown in Fig. 1 [2].

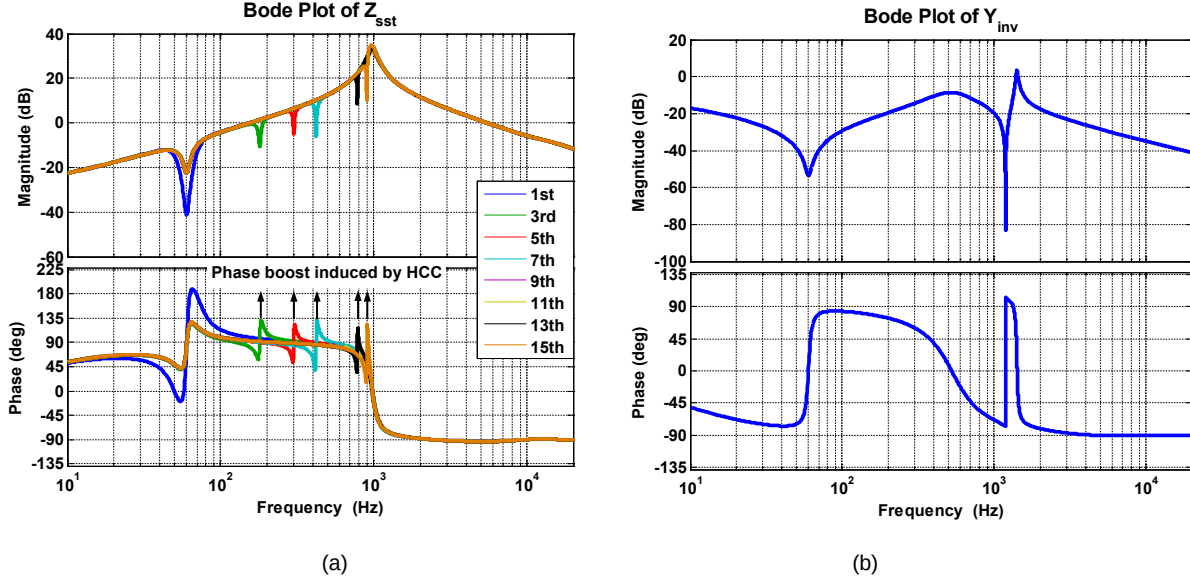


Fig. 1. Bode plot of (a) SST output impedance and (b) DESD output admittance.

A virtual impedance control (VIC) was developed last year to mitigate the resonance. However, the VIC method can only dampen the low frequency resonance induced by the harmonics compensation controller (HCC) in SST. On the other hand, the high frequency resonance beyond SST current control loop bandwidth is more complicated, and the proposed VIC is no longer effective to dampen out the high frequency resonance. Besides, the digital control delay deteriorates the functionality of active damping techniques at high frequency range, which pose a great challenge on design of the resonance mitigation technique for SST-DESDs system. Therefore, a negative impedance feedback control (NIFC) is developed to stabilize the SST-DESDs system. The proposed method does not requires any extra sensors, and it is less sensitive to digital control delay.

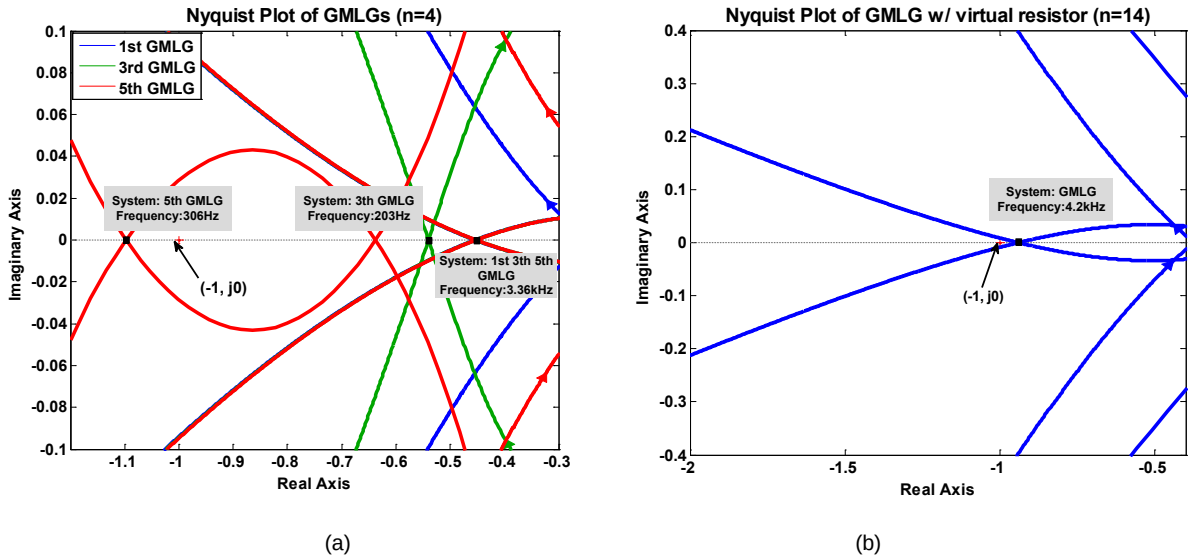
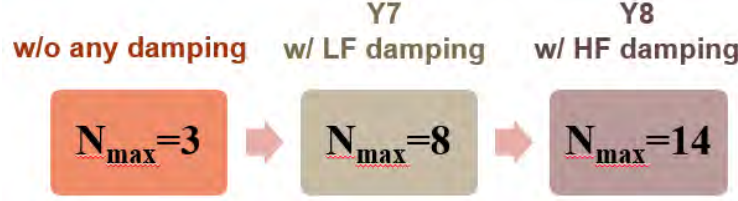


Fig. 2. Nyquist plot of GMLG (a) w/o any control, $N_{max}=3$ and (b) with proposed control this year, $N_{max}=14$.

With the proposed method, the maximum number of integrated DESDs N_{max} has been increased from 3 to 14. The SST integration capability has been enhanced and the SST-DESD has better stability and reliability than before.



4.2 Proposed system-level stability-oriented design guideline

In addition, a system-level stability-oriented design guideline is proposed to predict and avoid possible instability at the design stage. An application of using the proposed design guideline to design and achieve stable grid-tied paralleled inverters is shown below, which is also applicable to the SST-DESD. With the proposed guideline, a specific stability margin, 6 dB gain margin in this example, can be achieved at the design stage to ensure system stability robustness.

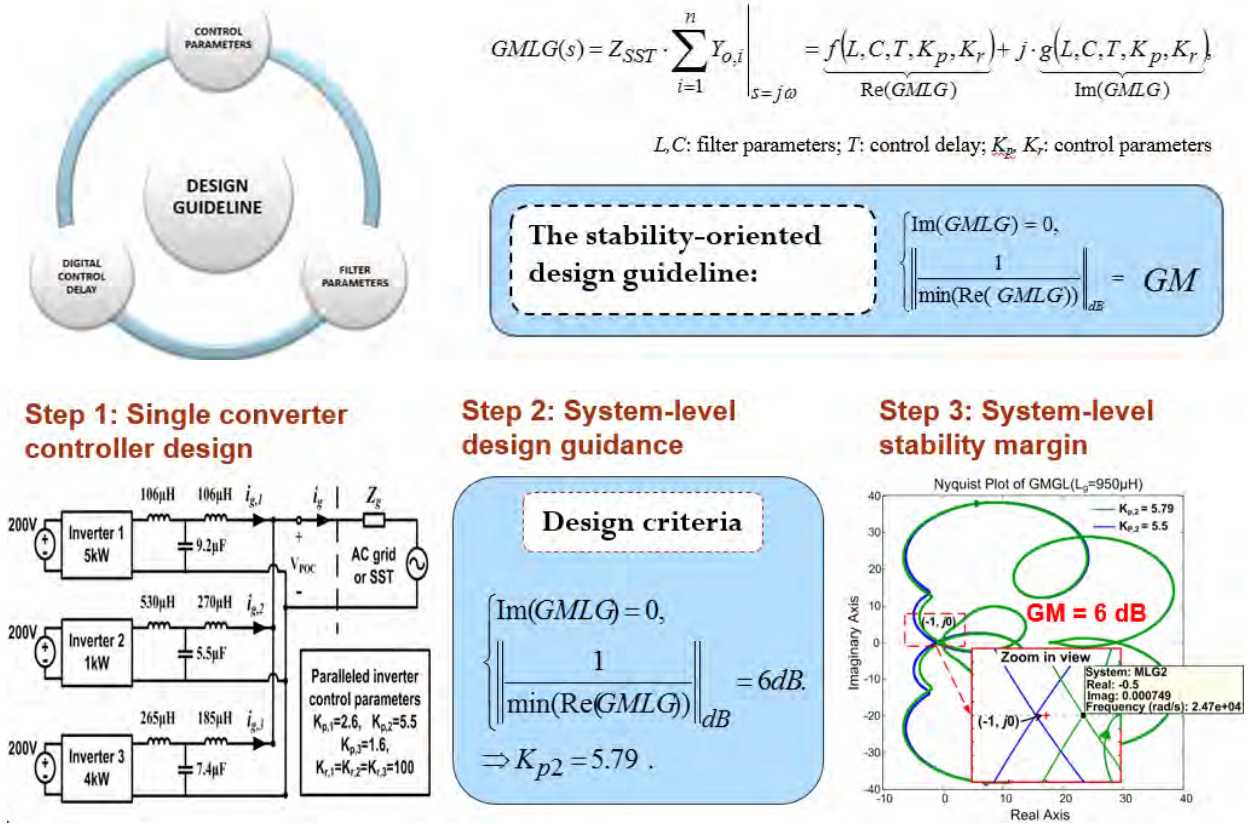


Fig. 3. The proposed system-level stability-oriented design guideline.

4.3 HIL test bed for verification

3.a) Hardware setup of one SST+ one DESD

A hardware testbed is built to integrate one SST from NCSU with one DESD from FSU. The experimental results in this hardware testbed have been reported on Oct. 2015, and the integrated system works fine after several issues solved.

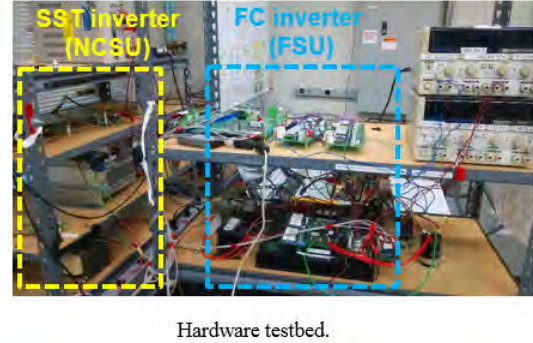
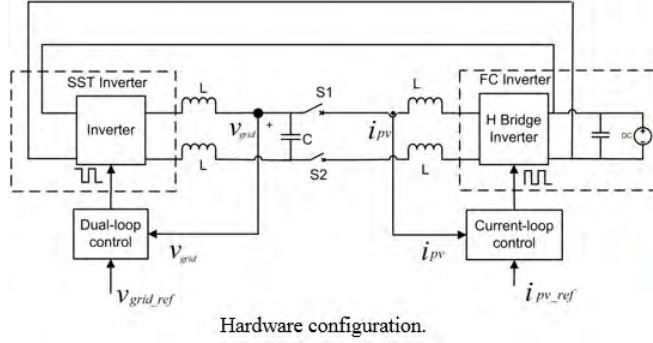


Fig. 4. Hardware configuration and testbed of one SST + one DESD.

3.b) HIL setup of one SST + multiple DESDs

A HIL test bed is built to validate proposed methods in one SST+ multiple DESDs configuration. Impedance measurement unit is included in the loop to perform the online impedance extraction function.

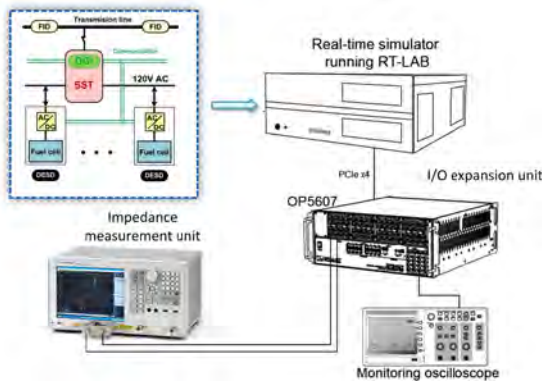


Fig. 5. HIL testbed of one SST + multiple DESD.

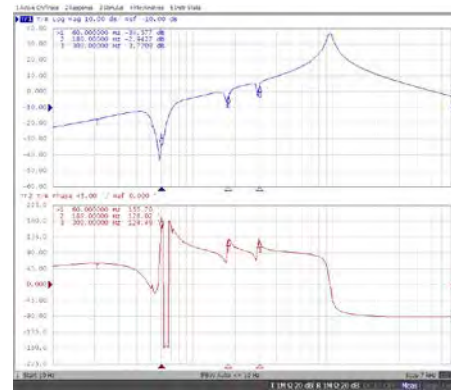


Fig. 6. Online impedance measurement of SST.

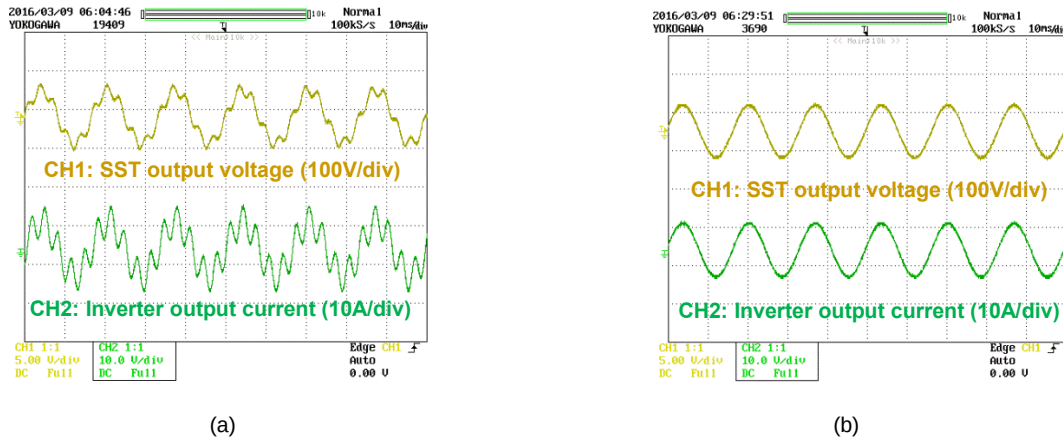


Fig. 7. Real-time simulation results for (a) system is unstable without any control when $n=4$, and (b) system is stable with proposed control when $n=14$.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

The stability issue has also been researched on MVDC system on Electrical Ship sponsored by ONR/ESRDC program.

6. Milestones and Deliverables

Milestones:

Q1 (9/30/2015) – A high frequency resonance mitigation method will be conducted.

Q2 (12/31/2015) – A high frequency resonance mitigation solution will be developed.

Q3 (3/31/2016) – A stability-oriented design guidance will be developed.

Q4 (6/30/2016) – A paper design of HIL test bed will be finished.

Deliverables:

Deliverable for SV (04/2016): A control method and a design guideline.

Final Deliverable (08/2016): A control method, a design guidelines and a test bed paper design.

7. Plans for Next Year

The DC grid enabled by SST also faces instability issues due to interactions among SST, DESDs and load converters. Different from the SST-DESDs at AC terminal, the power converters such as the dual active bridge (DAB) DC/DC converters have totally different impedance characteristics in this DC grid. This could result in a different resonance mechanism compared to that in the SST-DESDs. In addition, the power management strategy to realize intelligent power flow in the DC grid also adds more challenges when addressing the DC grid stability. Therefore, it is necessary to analyze and enhance the integration of SST-DESDs in the DC grid.

8. Publications

[1] Q. Ye, and H. Li, "Stability Analysis and Improvement of Solid State Transformer (SST)-Paralleled Inverters System using Negative Impedance Feedback Control," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2016.

[2] Q. Ye, R. Mo, Y. Shi, and H. Li., "A unified impedance-based stability criterion (UIBSC) for paralleled grid-tied inverters using global minor loop gain (GMLG)," in *Proc. IEEE ECCE*, Sep. 20–24, 2015, pp. 5816-5821.

Y8.ET4.1: Gen III Hybrid FID Development – Piezoelectric Actuated Fast Mechanical Disconnect Switch (PA-FMS)

Team Members

Project Leader:	Mischa Steurer (FSU)
Faculty:	Lukas Graber (at Georgia Tech, consulting)
Students:	Samantha Smith (FSU), James Owens (FSU)
Staff:	Matthew Bosworth, Dionne Soto

1. Project Goals

The Fault Isolation Device (FID) as a fast opening and reclosing device is a critical component in a fault current limited power grid or DC grid. In particular, this project develops the Piezoelectric Actuated Fast Mechanical Disconnect Switch (PA-FMS) portion of the hybrid FID described in the Vol-I report. The specific goals for this project year are:

- Full characterization of voltage withstand capability in the improved vacuum vessel
- Dynamic testing of switching action under vacuum at potential
- Purchase and assembly of duplicate parts for the unit to be integrated into the system at NCSU
- Delivery of completed unit to NCSU for integration and testing (incl. demonstration of soft start feature for making turn on current)
- Thermal, etc. characterization testing on FSU unit
- Study the lifetime effects of the mechanical switch (fatigue effects on voltage withstand)
- Support a new joint FID/SST working group on BIL hardening and other MV system integration issues
- Continue to support the cost-benefit analysis work (under GEH)

2. Role in Support of Strategic Plan

The FID is one of the enabling technologies of the FREEDM System. In particular, it enables the ultra-fast protection philosophy pursued by the Center in order to maximize system availability by minimizing fault clearing time.

3. Fundamental Research, Technological Barriers and Methodologies

Compared to the fundamental science layer projects, this project resides at the FREEDM enabling technology layer. As such, we do not primarily address fundamental research challenges. However, we focus primarily on the engineering aspects within a multidisciplinary project. In Y6, recognizing the remaining challenges with reducing losses below those of the SiC ETO switch, the idea was to develop a hybrid FID which makes use of a fast mechanical disconnect switch to bypass the ETO switch under normal operating conditions. This hybrid concept is not new in itself, but this specific implementation combined with the goal for a quarter cycle fault clearing is novel. The major challenges of this project are:

- use of a high voltage SiC ETO switch and their relatively high cost
- design and building of the ultra-fast mechanical disconnect switch based on the patented idea of integrating a piezo-electric actuator and the mechanical contacts with a vacuum switching chamber
- design, implementation, and testing of a control algorithm for the integrated Gen-III FID that ensures fail safe operation

4. Achievements

a. PEEK Mechanical Compression Test

The PEEK frame was tested under mechanical compression to understand the force that is applied by the piezo-electric actuator shell during the opening of the contactors. The PEEK frame was compressed to a deflection of 1.2 mm, where the expected deflection will be 1 mm total between both sides. For completeness, COMSOL was used to compare the static force vs deflection of the modeled PEEK frame vs the experimental results.



Fig. 1. Piezo-electric actuator shell compression test

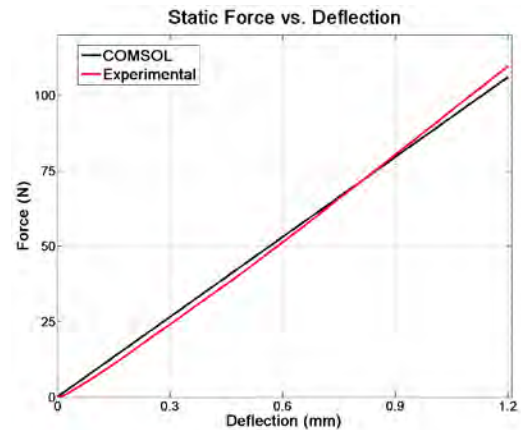


Fig. 2. Compression test results COMSOL and experimental

b. Open-Air Static Contactor Spacing Test

The piezo-electric device is the only device moving the contactors, to disconnect the bus. A preliminary open-air test is necessary to visualize and measure the physical distance between the contactors. With 150 V across the piezo, the contactors on either side are separated at a total distance of 0.8 mm.

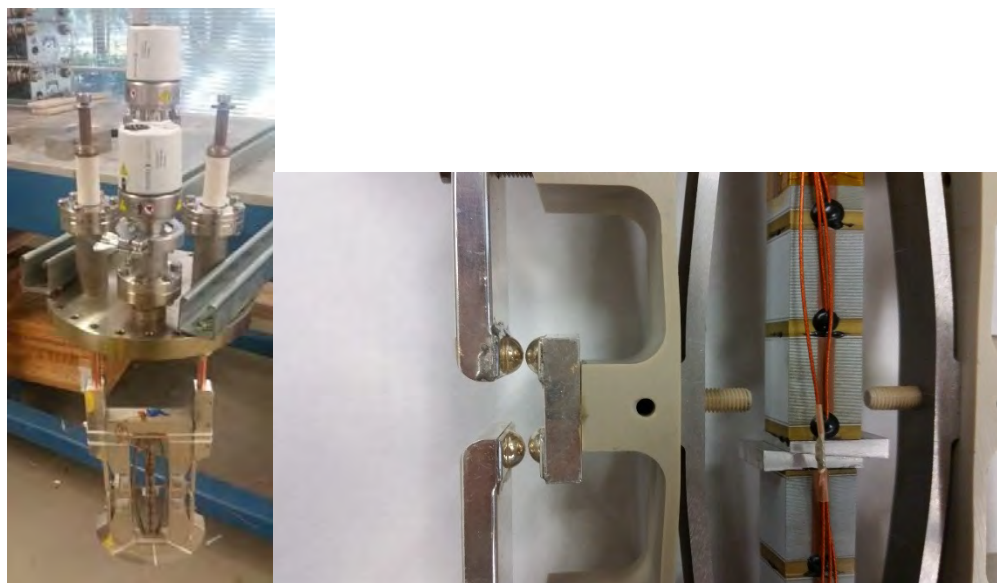


Fig. 3. Open-air static contactor spacing test setup

c. Voltage Breakdown Test Under Good Vacuum

One of the accomplishments from last quarter was achieving a good overall vacuum inside the chamber. After finally finding and fixing a tiny leak, the overall vacuum in the chamber was greatly

improved. The chamber was able to maintain a good vacuum for a long period of time as seen in Figure 4 below. A vacuum of under 3×10^{-5} mbar was maintained. Due to outgassing, the vacuum may degrade overtime but this will be corrected by using the getter pump which will be permanently attached to the chamber.

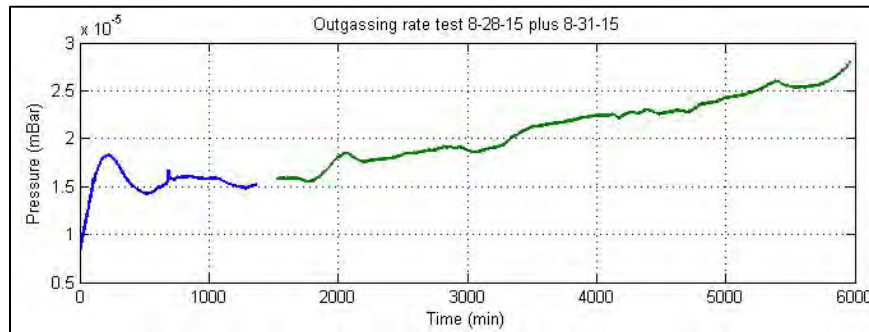


Fig. 4. Outgassing rate during voltage breakdown tests

The improved vacuum conditions allowed for a more accurate testing of the voltage breakdown test. While in vacuum, a mechanical device was utilized to maintain a contact gap between all 4 contacts of 0.5 mm. The voltage breakdown test was conducted, and the results are illustrated in Figure 5. As can be seen here, a maximum breakdown voltage of ~22 kV was achieved and a steady state breakdown voltage of ~15 kV before the vacuum was degraded due to conducting these tests.

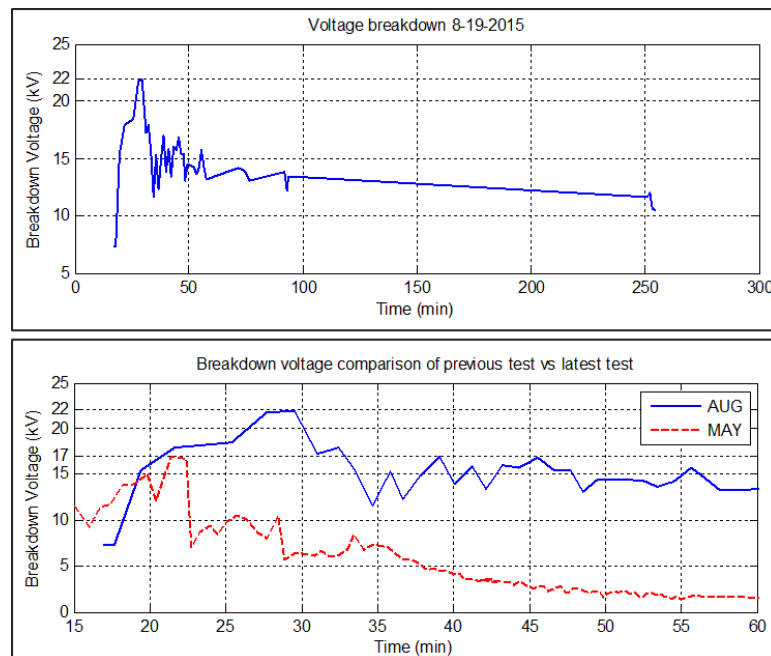


Fig. 5 Voltage breakdown test results

d. Design Improvements/Modifications

One of the design modifications made in order to improve the overall assembly of the switch was drilling a hole through the small contact tabs and the PEEK. This allows for attaching the contact tabs as well as holding the piezoelectric actuator in place without the need for using epoxy. This design modification allows for a cleaner, sturdier, and stronger assembly of the switch.

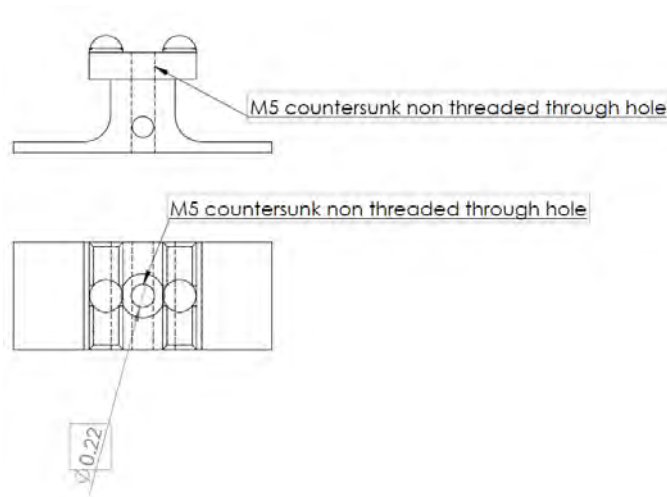


Fig. 6. Contact tab assembly of the PA-FMS

e. FAMU-FSU Senior Design Team

The FID II team at FSU-CAPS determined that undergraduate students will provide a necessary asset to complete FY-8 tasks. The senior design team, consisting of three undergraduates from the FAMU-FSU ECE department are developing, testing and validating a controller for the FMS. The main DSP in use is the TI - F28335, along with power amplifier, interfacing circuit board and other components to interact and respond to the NCSU master FID controller, and monitoring and controlling the FMS.

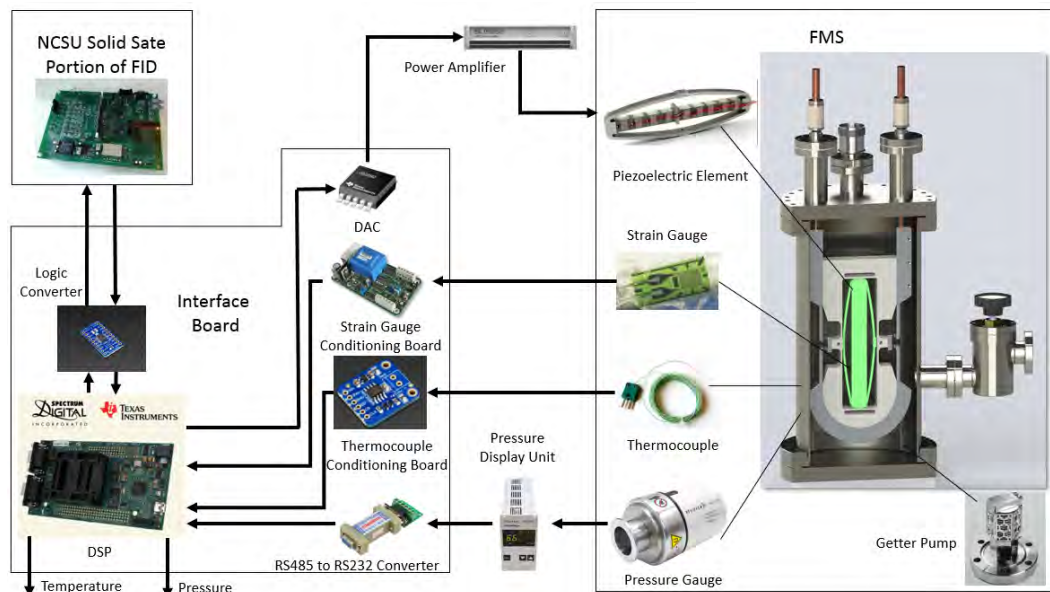


Fig. 7. Gen-III FID control hardware diagram

5. **Other Relevant Work Being Conducted Within and Outside of the ERC**

Ultra Fast Mechanical Switch for Circuit Breaker Applications, PIs – Alex Huang and Iqbal Husain,
Sponsor – State of North Carolina Ocean Energy Program

Based on the patent application for the new FMS design, the FSU team successfully secured additional funding through the FSU internal GAP program, which aims at providing additional funding for prototype development of technology with significant potential for future commercialization. The FSU team utilizes those funds primarily for procuring the high cost items of the FMS.

6. Milestones and Deliverables

- Completion of FMS controller board
- Full voltage and current demonstration of the FMS with piezoelectric actuator
- Completion of solid state switch
- Completion of mechanical switch
- Integration of mechanical switch and hybrid switch

7. Plans for Next Three Years

- It appears that the FMS has great potential as an enabling technology for future FREEDM like systems which do not use the concept of discrete circuit breakers for fault interruption, but rather rely on all the sources in the system to perform a coordinated power system reset with the FMS operating as an ultra-fast disconnect switch to isolate the faulty section w/o current interruption. In that sense, the FMS should be developed into a standalone device to perform such functions in a system.
- In the current FMS design, the voltage distribution between the four sub millimeter contact gaps relies on the capacitive voltage division governed by the parasitic capacitances of the gaps. While this FMS has great potential for medium voltage DC (MVDC) systems, the natural consequence of an “all power electronic” (next generation) FREEDM system, the FMS has to be augmented with voltage grading features suitable for DC systems.

Y8.ET4.2: Fault Isolation Device (FID) Development – Power Electronics

Team Members

Project Leader:	Alex Huang (NCSU)
Faculty:	Mischa Steurer (FSU)
Students:	Chang Peng (NCSU), Xiaoqing Song (NCSU)

1. Project Goals

The Fault Isolation Device (FID) as a fast opening and reclosing device is a critical component in a fault current limited power grid or DC grid. In particular, this project develops the power electronics portion of the hybrid FID described in the Volume I report.

2. Role in Support of Strategic Plan

The FID is one of the enabling technologies of the FREEDM System. In particular, it enables the ultra-fast protection philosophy pursued by the Center in order to maximize system availability by minimizing fault clearing time. The FREEDM System is current limiting; hence the grid voltage will decrease quickly in the event of a fault. Ultra-fast fault isolation is therefore absolutely necessary. In a DC grid, ultra-fast protection is also needed. Our work therefore will also have significant impact to medium voltage DC grid protection.

3. Fundamental Research, Educational, or Technological Advancement Barriers and Methodologies Used to Address Them

This hybrid circuit breaker concept is not new in itself, but our goal of achieving quarter cycle fault clearance time is novel and extremely challenging. Several fundamental challenges exist and therefore require substantial fundamental research to overcome.

1: Fast mechanical switch (FMS): The FMS needs to have a separation speed on the order of 1 ms in order to keep the overall time smaller than 2 ms. Our FMS is based on the patented idea of integrating a piezo-electric actuator and mechanical contacts within a vacuum chamber. The research on this innovative piezo-electric actuated FMS (PA-FMS) is described in detail in section Y8.ET4.1.

2. Main breaker (MB) Turn-off capability: The MB needs to be implemented by a high voltage power semiconductor switch that on one hand has a breakdown voltage higher than V_{RES} (see Fig.4) but also has an interruption current capability (Safe Operation Area or SOA) higher than I_{PEAK} (fig.4). Our design approach was to use a 15 kV SiC ETO which can meet the voltage requirement without connecting any additional devices in series. However, having the turn-off current to be higher than I_{PEAK} is a significant and fundamental challenge from a device point of view. This is also the world's first known fundamental effort in developing and understanding a SiC ETO's turn-off capability.

The methods used to overcome these challenges are based on modeling and simulation combined with hardware testing. To address the high cost of the SiC ETO, the main fundamental approach is to design/verify that the SiC ETO can interrupt a very high fault current therefore a small chip size SiC ETO can be used. This work is also a fundamental contribution to the PSD subthrust since it addresses a scientific challenge for SiC bipolar power devices.

4. Major Achievements

MB Turn-off Capability Study and Progress:

Table 1 summarizes the MB turn-off capability requirement for the Gen-III FID. It is derived based on the nominal 7.2kV/1MVA system. Depending on whether the system is a current limited system like the FREEDM system or a traditional system, a 400A or 1400A current turn-off capability is needed for the MB solid state switch respectively. As mentioned before, this remains a major challenge for any solid state switch to achieve.

Table 1: MB Turn-off Requirement based on nominal FREEDM System	
Feeder Capacity	1000 KVA
Line to line voltage	12.47 kV, rms
Line to neutral voltage	7.2 kV, rms, 10 kV, peak
Current	140 A, rms 200 A, peak
Overcurrent protection setting I_{REF}	400A
MB Interruption Current I_{PEAK} (current limited at 2 pu)	400 A
MB Interruption Current I_{PEAK} in traditional AC system (5% transformer impedance, FMS speed=1ms)	1400A

As reported previously, our approach in the MB implementation is to develop revolutionary >15kV SiC ETO devices. So far, we have successfully demonstrated a turn-off capability around 400A/cm² with a small snubber (Figure 1) and 200A/cm² without a snubber. No failures have been observed so far.

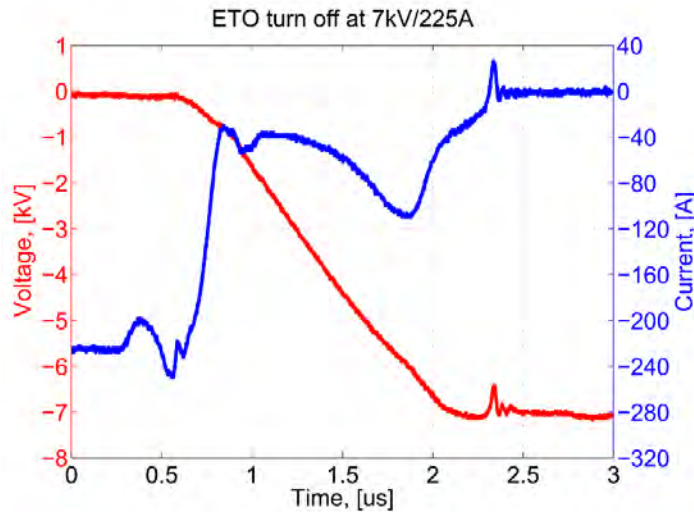


Fig. 1. 7kV/225A (or 400A/cm²) turn-off of the 15 kV SiC ETO

Supported by Cree Inc., our progress in the SiC ETO and its application in a circuit breaker represent a breakthrough in semiconductor technology. Additionally, in order to achieve large turn-off current without the need to parallel several ETOs together, it is important to understand what the turn-off limitation of these devices is. A fundamental theory has been developed by Dr. Alex Huang, which suggests that SiC bipolar devices such as the SiC ETO will have superior turn-off capability when compared with Si power switches. Si bipolar power devices typically fail at around 200 kW/cm². Our theory suggests that the SiC ETO device could have a SOA as large as 10 MW/cm². In other words, the electric current that can be turned off can reach 1000A/cm². Due to limited devices available for this research, we have not attempted to increase the current further. Future work will attempt to test the device at higher currents to validate this theory.

MB Voltage Capability Study and Progress:

The voltage capability of the MB is summarized in Table 2. Again, it is derived based on the 7.2kV/1MVA nominal FREEDM system specification. Based on a conservative 20% over voltage design, the peak voltage of the MB will reach about 12 kV limited by a MOV device that will be placed in parallel with the MB. Therefore a 15 kV SiC ETO device is capable of meeting the voltage requirement if the peak voltage is clamped by the MOV at 12 kV. We have successfully identified and selected a MOV V172BB60 that can easily meet our voltage clamping and energy absorption requirement. Each V172BB60 has a peak voltage clamping capability of about 4000V at 400A and an energy absorption capability of 6000 J. Using three of these in series, we can successfully clamp the voltage below 12 kV and can absorb more than 18 kJ which is far greater than the fault energy $1/2 \cdot 1400 \text{ A}^2 \cdot 6.87 \text{ mH} = 6732 \text{ J}$ in a 1 MVA feeder assuming 5% impedance

Table 2: MB Voltage Withstanding Capability	
Feeder Capacity	1000 KVA
Line to neutral voltage	7.2 kV, <i>rms</i>
	10 kV, <i>peak</i>
Peak Recovery Voltage (V_{RES}): 20% above grid peak	12 kV
FREEDM System: voltage clamping time ($T=t_5-t_4$)	$\ll 1 \text{ ms}$
None-FREEDM system: voltage clamping time ($T=t_5-t_4$) assuming 5% grid impedance	4.8 ms
MB Breakdown Voltage Requirement	15 kV
MOV Voltage (three V172BB60 in series)	12 kV
MOV Energy Absorption (three V172BB60 in series)	18000 J

In Figure 2, the FID operation turns off a 20 A current at 500 V. The trip signal initiated the turn off of the MOSFET (AB) first, followed by the open signal of the mechanical switch with 100 μ s delay. This delay is intended for the AB to finish current commutation. After another 900 μ s, the MB turns off and a transient voltage with an overshoot higher than 500 V can be observed. As the circuit is resistive, the overvoltage duration is very short: less than 100 μ s, which reflects that very little magnetic energy is stored in the system. The hybrid FID has initially been tested with the alternate FMS under an inductive circuit, which represents a more realistic circuit interruption scenario. One MOV is used to clamp the MB voltage. The operation sequence and control algorithm is the same as demonstrated in Fig. 2, but the overvoltage

upon MB turn-off is much higher and lasts much longer. To turn off 24 A current, the overvoltage peaks at 3.5 kV across the FID. In Fig. 2, the FID current starts to decrease slowly at 0 seconds because the current was transferred to the MB which has a higher voltage drop than the power source (which is a high current low voltage power supply); and it drops significantly at 1.0 ms because of the turn-off of the MB. Due to the snubber capacitor, the voltage increases linearly and reaches to 3.5 kV level which is clamped by the MOV. As the current drops to zero, the voltage peak resides and slowly decays from 2.4 kV to zero. The whole operation is finished in about 1.2 ms, demonstrating the ultra-fast interruption speed of the hybrid FID.

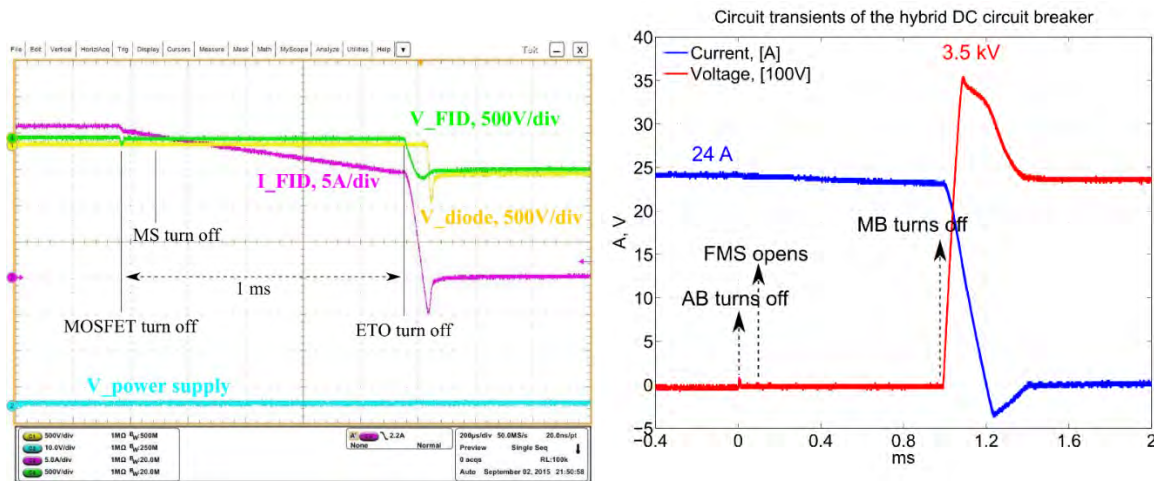


Fig. 2. Gen III hybrid FID test under inductive circuit interruption

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Example of another Hybrid Breaker

- ABB has a HVDC hybrid circuit breaker with a rated voltage of 320 kVDC, a rated DC transmission current of 2 kA DC, and a current breaking capability of 9 kA DC. It is made for HVDC, it uses IGBTs instead of our developed lower loss SiC semiconductors, and has estimated a turnoff time within 2 ms with an upper limit of 5 ms.

Examples of other Fast Mechanical Switches

- Currently, fast transfer switches have been developed from Thomson coils, propellant-based systems, or coupled electromechanical and hydraulic systems. In contrast, the novel FMS described above is compact and does not need high current pulses (as in the Thomson coil designs), is clean, compact, and can be automatically reset (as compared to the propellant based systems), and is expected to be simpler and much faster than the coupled electromechanical and hydraulic systems.

Within the center, another FMS was also developed at NCSU under a sponsored project. It uses a Thomson coil actuator mechanism and has achieved about 1 ms speed.

6. Expected Milestones and Deliverables

- Integration of the MB, AB with FSU developed FMS
- Testing of the Gen-III FID to reach rated voltage and current

7. Plans for Next Three Years

- In order to be applicable for a full scale system, the Gen-III FID needs to carry substantially more current. Future developments should focus on that aspect. The AB switch is considered low risk and the MB is the higher risk area. Additional work is needed to demonstrate much high current interruption capability so that a large operational margin exists for our application.
- The center's PSD Subthrust is aiming at developing the world's first symmetric GTO which will further reduce the cost of the MB used in the FID.

8. Publications

- [1] Chang Peng; Husain, I.; Huang, A.; Lequesne, B.; Briggs, R., "A fast mechanical switch for medium voltage hybrid DC and AC circuit breakers," in Energy Conversion Congress and Exposition (ECCE), 2015 IEEE , vol., no., pp.5211-5218, 20-24 Sept. 2015
- [2] Chang Peng; Husain, I.; Huang, A.Q., "Evaluation of design variables in Thompson coil based operating mechanisms for ultra-fast opening in hybrid AC and DC circuit breakers," Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE , vol., no., pp.2325,2332, 15-19 March 2015
- [3] Chang Peng; Huang, A.Q.; Xiaoqing Song, "Current commutation in a medium voltage hybrid DC circuit breaker using 15 kV vacuum switch and SiC devices," Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE , vol., no., pp.2244,2250, 15-19 March 2015
- [4] Huang, Alex; Peng, Chang; Song, Xiaoqing, "Design and development of a 7.2 kV/200A hybrid circuit breaker based on 15 kV SiC emitter turn-off (ETO) thyristor," *Electric Ship Technologies Symposium (ESTS)*, 2015 IEEE , vol., no., pp.306,311, 21-24 June 2015
- [5] Song, Xiaoqing; Huang, Alex Q.; Lee, Mengchia; Peng, Chang; Cheng, Lin; O'Brien, Heather; Ogunniyi, Aderin; Scozzie, Charles; Palmour, John, "22 kV SiC Emitter turn-off (ETO) thyristor and its dynamic performance including SOA," Power Semiconductor Devices & IC's (ISPSD), 2015 IEEE 27th International Symposium on , vol., no., pp.277,280, 10-14 May 2015
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Y8.ET4.3: Innovative Means of Resolution of Issues with the Basic Impulse Level (BIL) and Other High Voltage Requirements in the FREEDM Distribution System

Team Members

Project Leader:	G. T. Heydt (ASU)
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Students:	Ms. Xuening Rong (ASU)
Staff:	Mr. Dionne Soto (FSU), Mr. Mathew Bosworth (FSU)

1. Project Goals

The central project objective is simply stated as the use of innovation in engineering, components, and materials for the implementation of the FREEDM system taking into account BIL and insulation coordination requirements. This objective is resolved as follows:

- Identification of the BIL levels for the FREEDM system.
- Identification of the points in the FREEDM system and its components where insulation coordination and BIL are problematic, including in a next generation FREEDM system designed around a 37.5 kV distribution primary voltage.
- A thorough investigation of methods to implement the identified BIL and insulation coordination using innovative designs, circuit components, and innovative materials. This objective includes: Zener-like technologies for voltage clamping; ohmic isolation; surge arresters of all types; conductor shielding; utilization of over-rated voltage levels for components; capacitive devices for voltage clamping.
- A thorough revisit of the IEEE standards for distribution class circuit components, with the view to the potential revision of those standards for semiconductor switched systems.
- The design of a 'front end' solid state transformer interface with the distribution primary system.

2. Role in Support of Strategic Plan

This project has a practical role in FREEDM in that the work done will permit connection of the FREEDM solid state transformer to the distribution primary in compliance with the codes and standards in place today.

3. Fundamental Research, Technological Barriers and Methodologies

The fundamental research in this project consists of the following:

- An innovative way of satisfying BIL requirements for a solid state transformer filter and at the same time mitigating the switching frequency components of current injected into the distribution system primary.
- Analysis of single and multistage filters for the purpose cited. This includes an innovative resistive dissipation method which comes into play during impulse inputs.
- An accurate modelling and characterization of parasitic capacitance and inductance in this filter design. Also, a suitable way to circumvent problems created by parasitics.

The technological barriers are:

- No clear accepted way to accommodate BIL requirements for semiconductor switched components that are directly connected to live high voltage conductors.
- The safety requirements are a potential barrier.

4. Achievements

Compliance with codes and standards

It has been identified that the IEC international standard 60071 deals with the impulse testing of low voltage VSC converters [1]. Both voltage levels and the shape of impulses are specified in IEC 60071 (see Figure 1). Both voltage source (IGBT or GTO) and line commutated (thyristor) HVDC valves are subjected to 1.2/50 μ s impulse tests. The test method is described in IEC 62501 [2]. The consensus presented first by CIGRE and confirmed by consultation with FREEDM industry sponsors is that the converter and related network equipped with surge arresters should be simulated using advanced computer methods (EMTD or PSCAD) in accordance with IEC 60071 and 65501 [3,4]. The peak impulse voltage identified for a 15 kV class FREEDM system is identified as 60 kV.

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	$f = 50 \text{ Hz or } 60 \text{ Hz}$ $T_1 \geq 3 \text{ 600 s}$	$10 \text{ Hz} < f < 500 \text{ Hz}$ $0,02 \text{ s} \leq T_1 \leq 3 \text{ 600 s}$	$20 \mu\text{s} < T_p \leq 5 \text{ 000 } \mu\text{s}$ $T_2 \leq 20 \text{ ms}$	$0,1 \mu\text{s} < T_1 \leq 20 \mu\text{s}$ $T_2 \leq 300 \mu\text{s}$	$T_f \leq 100 \text{ ns}$ $0,3 \text{ MHz} < f_1 < 100 \text{ MHz}$ $30 \text{ kHz} < f_2 < 300 \text{ kHz}$
Standard voltage shapes					a
	$f = 50 \text{ Hz or } 60 \text{ Hz}$ T_1^a	$48 \text{ Hz} \leq f \leq 62 \text{ Hz}$ $T_1 = 60 \text{ s}$	$T_p = 250 \mu\text{s}$ $T_2 = 2 \text{ 500 } \mu\text{s}$	$T_1 = 1,2 \mu\text{s}$ $T_2 = 50 \mu\text{s}$	
Standard withstand voltage test	a	Short-duration power frequency test	Switching impulse test	Lightning impulse test	a

^a To be specified by the relevant apparatus committees.

Fig. 1. Classes and shapes of overvoltages, standard voltage shapes, and standard withstand voltage tests, taken directly from IEC 60071 [1]

Identification of the required simulation testing for the FREEDM solid state transformer

It has been identified that the FREEDM solid state transformer should pass an insulation coordination study. Important that the tests should be performed on converters equipped with protection surge arresters. A series of impulse tests have been accomplished in increasing stages of sophistication and modeling accuracy. Figure 2 shows a typical result using a Gen II FREEDM SST model in a 60 kV impulse test.

Ratings of MOVs and lightning arresters

The project considers industry accepted practice in compliance with standards for the use of metal oxide varistors (MOVs) to attain BIL requirements and to protect the semiconductor switches in the SST. Table 1 shows a summary of some commercially available MOVs and similar metal oxide lightning arresters. A technical note in [5] gives a guide for the selection of ratings. Reference [6] gives a guide for lightning arrester specifications in the distribution primary voltages.

Design of an innovative multistage SST front end filter

Figure 3 shows a proposed multistage SST filter. This is a modification of a simple T-configured RLC filter. The modification is a separation of the front end inductor into two units for the purpose of reducing the high voltage stress on this inductor during appearance of a high voltage impulse. The innovation is the use of a resistor only for dissipation of the impulse energy – and not for conduction during normal 60 Hz operation. The active power losses in this filter are described for typical filter component ratings in Table 2. This table also gives a comparison with a single stage front end filter. Larger number of stages have also been studied.

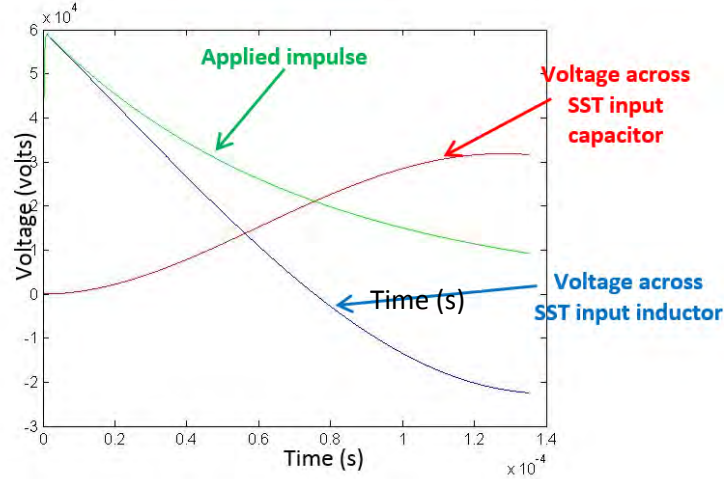


Fig. 2. Typical simulation results, three voltages at the front end of an SST filter that interfaces with the distribution primary (note: scale values shown in volts up to 60 kV, and time in seconds up to 140 μ s)

Type	Voltage ratings for commercially available units	Energy dissipation (maximum)	Comments and characteristics
ZnO ₂ distribution secondary MOVs	440 – 1000 V	About 2.5 kJ	Designed and tested for secondary distribution
Polymer station arresters	3 to 144 kV readily available (RMS line-neutral voltage rating nominal, not the BIL)	Between 1.4 to 3.4 kJ / kV (the voltage is the MCOV)	Most units are available with the following maximum current ratings on breakdown for an 8 / 20 μ s impulse: 10 kA for 8.4 kV crest and 3 kV class unit; 16.7 kA for 6 kV crest; 27.8 kA for 10 kV rating.
Porcelain station arresters	3 to 144 kV readily available (RMS line-neutral voltage rating nominal, not the BIL)	4.9 kJ / kV (the voltage is the MCOV)	Most units are available with the following maximum current ratings on breakdown for an 8 / 20 μ s impulse: 10 kA for 8.4 kV crest and 3 kV class unit; 16.7 kA for 6 kV crest; 27.8 kA for 10 kV rating.

Table 1: Lightning arrester and MOV ratings for various types of technologies

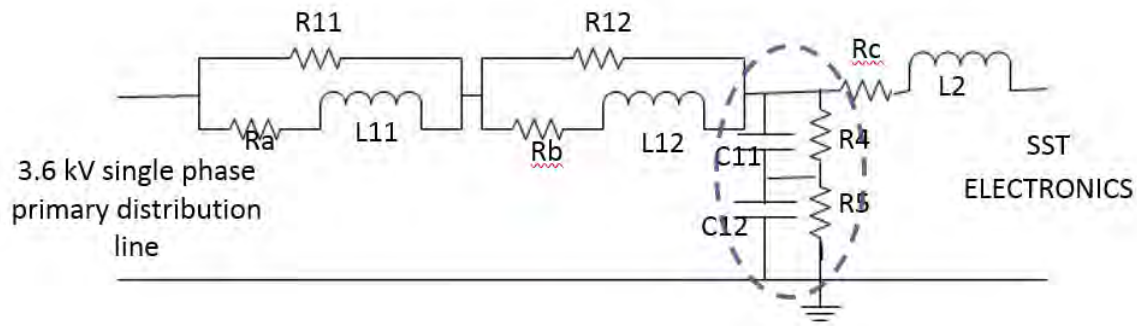


Fig. 3. A two stage front end SST filter. R11 and R12 grade the impulse voltage across inductors L11 and L12. Resistors R4 and R5 grade the impulse voltage across C11 and C12.

Load expressed as a percentage of rating	Active power loss expressed as a percentage of the load active power	
	Single stage filter	Two stage filter
100%	0.42%	0.29%
75%	0.32	0.22
50%	0.21	0.15
No load		

*25 kVA unity power factor assumed

Table 2: A comparison of losses for the single and two stage filters, designed for use with unipolar PWM switching frequency 1.15 kHz at several operating power levels. The data shown are expressed as a percentage of the load active power.

Investigation of parasitics

Because the BIL impulse tests have a leading portion of the wave as 1.2 μ s, parasitic capacitance of the front end inductors (e.g., L11 and L12 in Fig. 3) must be considered. The parasitic capacitance of these inductors is in the order of 10 – 120 pF depending on the construction and core of the inductors. At the time of writing, the research team is considering alternative designs for these inductors to reduce the impact of the parasitic capacitance. Similarly, the parasitic inductance of the capacitors (e.g., C11, C12 in Figure 3) should be considered.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

At this time, the main efforts outside of the ERC on the direct connection of semiconductor switched elements to high voltage (e.g., distribution primaries) occurs in distribution class flexible AC transmission controllers (D-Facts), static var compensators (SVCs), and machine drives. We are using industry accepted codes (e.g., [1, 2, 3]) for the design of the SST-distribution primary interface. Within the ERC, there are a series of developments in the modelling of the SST. These are being used in simulation tests in this project.

6. Milestones and Deliverables

The project tasks are shown in Figure 4. The project is on schedule as of the time of writing.

Task	First	Second	Third	Fourth

	<i>quarter</i>	<i>quarter</i>	<i>quarter</i>	<i>quarter</i>
1. Identification of BIL and insulation coordination requirements				
2. Evaluation of Zener, MOV and related components				
3. IEEE standards revisions – evaluation				
4. Crowbarring, front end filter design, innovation in the filter				
5. Loss evaluation				
6. Simulation testing				
7. Evaluation and applicability of gap type technologies				
8. Managing component voltage ratings				
9. Documentation demonstration of results				

Fig. 4. Project research execution plan. The bold bar indicates the project state as of the time of writing

7. Plans for Next Three Years

In the long run, this project may evolve into a significant effort to guide the design of directly coupled power electronic apparatus for all emerging medium voltage power electronics for AC or DC grids. At the time of writing, this project is in its fifth month. For the remainder of the project year, the following shall be accomplished:

The simulation testing shall be completed using PLECS and a more complete and detailed model of the FREEDM SST.

- The front end filter shall be redesigned as needed as per the simulation tests.
- A loss evaluation shall be updated for the front end filter.
- Actual circuit components shall be impulse tested in the ASU high voltage laboratory.
- A study of the impact of parasitics in the circuit components shall be completed.
- A final report shall be prepared.
- A paper is being prepared for the IEEE Power and Energy Society – Transactions on Power Delivery. This shall be updated and completed with project results.

8. Member Company Benefits

This project is a practical element of FREEDM in that the compliance of the SST and other components with high voltage and safety requirements is mandatory. In order to commercialize this technology, the BIL requirements must be met. The results of this project will set the basis for impulse testing of the FREEDM SST. This is of direct value to industry.

9. References

- [1] International Electrotechnical Commission, "Insulation Co-ordination, Part 1: Definitions, Principles and Rules," IEC 60071-1:2006, Berne, Switzerland.
- [2] International Electrotechnical Commission, "Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission - Electrical testing," IEC 62501:2009, Berne, Switzerland.
- [3] International Electrotechnical Commission, "Insulation Co-ordination Part 5 Procedures for high voltage direct current (HVDC)," IEC 60071-5: 2014, Berne, Switzerland.
- [4] Wolfgang Hauschild, Eberhard Lemke, "High-voltage measuring techniques," Berlin, Springer, 2014.

- [5] Larry Pryor, "The application and selection of lightning arresters," General Electric Co. Application Notes, Schenectady, NY.
- [6] Australian Rail Standard EP 21 00 00 01 SP "Insulation co-ordination and surge arrester selection," Version 3.1, May 2013, NSW Rail Transport, Sydney, Australia.

Y8.ET5.1: Distributed Energy Storage Device (DESD)

Team Members

Project Leaders: Alex Huang (ECE/NCSU)

Students: Fei Xue (Ph.D.), Tianxiang Chen (M.Sc)

1. Project Goals

The FREEDM System calls for plug-and-play of distributed resources into the AC and DC grid interface. More specifically, the Center has strategically decided to develop plug-and-play storage devices as a crucial missing element of a fully dispatchable Energy Cell (microgrid). The DC DESD is focusing on developing a modular, reliable, efficient, high power and high energy density plug-and-play 380Vdc DESD.

2. Role in Support of Strategic Plan

The DESD is a critical enabling technology in the FREEDM System that enables multiple intelligent power management (IPM) and intelligent energy management (IEM) functionalities due to the bidirectional power flow. It is also the missing link in today's grid with high penetration of intermittent renewable energy. Within the Center, DESD is required for the GEH testbed demonstration targeting IPM and IEM functionality, as well as serving as the receiving testbed for center developed battery cells. In Y7, the center stopped developing advanced battery cells for DESD to refocus resources on DESD development based on commercially available Li-ion cells.

3. Fundamental Research, Educational, or Technological Advancement Barriers and Methodologies Used to Address Them

The major challenges in grid storage technology are the high cost and difficulty in grid interface. One innovative approach the Center is focusing on is to develop a plug-and-play DC DESD with high step-up ratio (12V to 380V) bidirectional DC/DC interface so that low voltage battery cells can be utilized. This approach eliminates the battery cell balancing system and improves battery utilization. The projected cost of this solution is lower in this case. The cost estimation figures are provided to conduct the cost benefit analysis of the DESD in a separate project.

The major challenge of the DC DESD approach is therefore the need to have a low cost, highly efficient bidirectional DC/DC converter with high power density. Since the targeted power level (1 kW) is also quite high, thermal management and EMI noise management are major barriers. For 1 kW operation, the low voltage (battery side) current reaches approximately 100A and is a bottleneck in efficiency improvement. Several generations of DC DESD have been developed in the Center to address these issues by utilizing advanced topology, advanced magnetics, as well as advanced power devices. In Y1-Y6, two generations of DC DESD have been developed. Gen-I DESD is based on conventional Si MOSFETs and multi-phase dual-active-bridge topology. Gen-II DESD developed in Y6 proposed a novel half bridge push pull converter with active clamp

topology which has 97.5% peak efficiency and maintains greater than 94% efficiency over a wide load range. This is possible due to the use of ultra-low voltage (30V) MOSFETs on the low voltage side of the converter. In year 7, the Center focused on pushing the technology boundary of power density and efficiency by introducing advanced GaN power devices into the DESD design. Two 650V GaN transistors are used at the high voltage side. The figure-of-merit (FOM) $Q_g \cdot R_{ds(on)}$ and $C_{oss} \cdot R_{ds(on)}$ of GaN power transistors are significantly smaller than that of Si power devices, which directly result in lower gate driver losses, conduction losses and switching losses. Furthermore, the Q_{rr} of the anti-parallel “body diode” is almost zero for a GaN device, so it is ideal for the GaN switches to work in synchronous rectifying mode.

4. Achievements in Previous Three Years with an Emphasis on the Current Year

In the last few years, Gen-I and II DESDs have been developed with record level performance. Gen-I DESD is based on conventional Si MOSFETs and multi-phase dual-active-bridge topology. Gen-II DESD developed in Y6 proposed a novel half bridge push pull converter with active clamp topology which has 97.5% peak efficiency and maintains greater than 94% efficiency over a wide load range. Additionally, Gen-II was also delivered to the GEH testbed and utilized in the plug-and-play demonstration and IPM demonstration. Specifically, in Year 6, it was used to demonstrate the autonomous IPM control of the SST by allowing the SST to dispatch the DESD through the modulated 380Vdc voltage. In year 7, the 650V GaN device was introduced into the high voltage side to improve the efficiency, expand the safe operation range and reduce EMI.

In year 8, the full utilization of GaN devices into the Gen-III DESD further improves the efficiency. As shown in Figure 1, the power conversion efficiency achieved is higher (98.3% peak efficiency) compared to generation II (97.5% peak efficiency). The peak efficiency is 0.8% higher and remains higher than 96% in a wide load range. The rated power is increased from 500W (Y6) to 1kW (Y8).

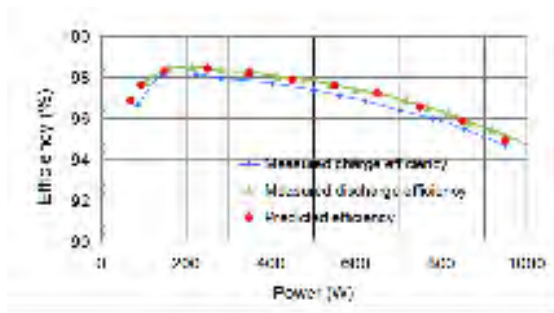


Fig. 1. Efficiency evaluation results under different load (control power excluded)

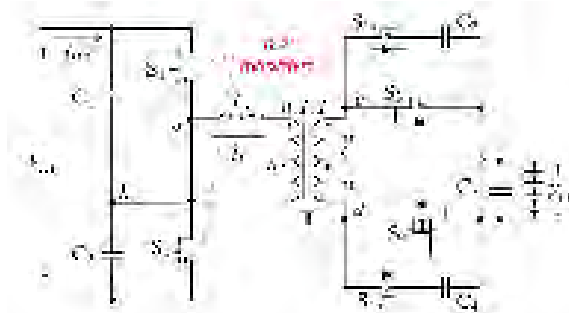


Fig. 2. Topology of GEN III DESD converter based on 650V GaN transistors.

The topology of 650V GaN transistors based bi-directional DC-DC converter is depicted in Figure 2. The prototype of the converter is built as shown in Figure 3. Three highly efficient, compact, 650V GaN HEMT (High Electron Mobility Transistor) based, plug-and-play capable 1kW/1kWh 200/400Vdc DESD are being delivered to the GEH testbed for IEM and IPM demonstration as

shown in Figure 4. The unit utilizes a 4-cell (12V), 100Ah LiFePO4 battery as the storage element. The modules are connected in parallel to the 200V dc bus and controlled by droop or hierarchical command through wireless Modbus communication protocol.

Furthermore, in year 8, a BMS (battery management system) is integrated to the Gen-III DESD. Figure 5 shows the charge and discharge characteristic under different charge and discharge current. The state of charge (SOC) is monitored by the voltage and current sensors built in the converter. A coulomb counting strategy is used to calculate the SOC. The converter can stop charging or discharging automatically once the battery is fully charged or discharged.



Fig. 3. Prototype of the GaN HEMT based converter.

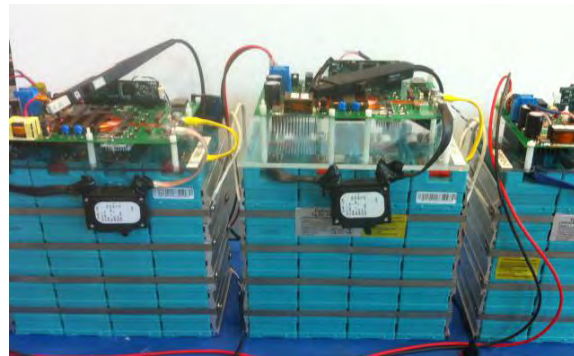
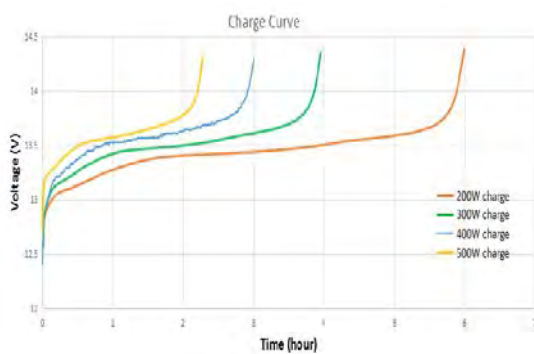
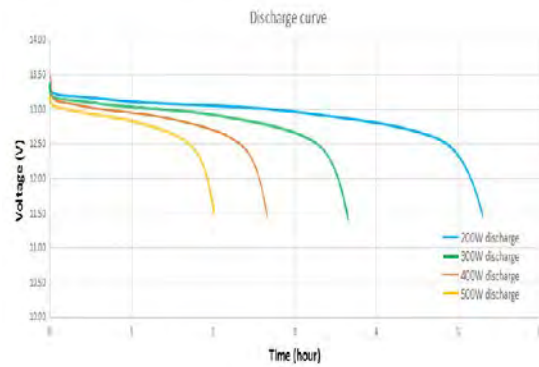


Fig. 4. Three DESD modules in parallel.



(a)



(b)

Fig. 5. Charge (a) and discharge (b) curve of one DESD.

Additionally, in order to address some of the concerns by the SVT, a higher power level DESD development effort was initiated in year 8. The concept is to use a partial power bidirectional buck-boost converter and an extra battery to be placed in between the DC bus and the high voltage battery pack. The prototype is shown in Figure 6. The converter is based on 100V GaN HEMTs. Some preliminary experimental results in light load are shown in Figure 7. We expect to eventually delivery a high power (10 kW) DESD to the GEH testbed by end of Year 8 or beginning of Year 9.

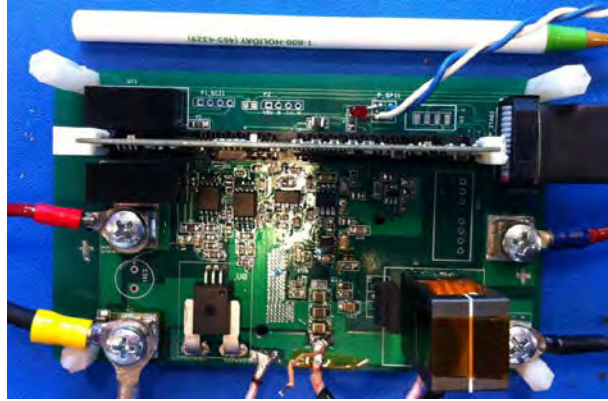


Fig. 6. Prototype of proposed converter for high voltage energy storage device

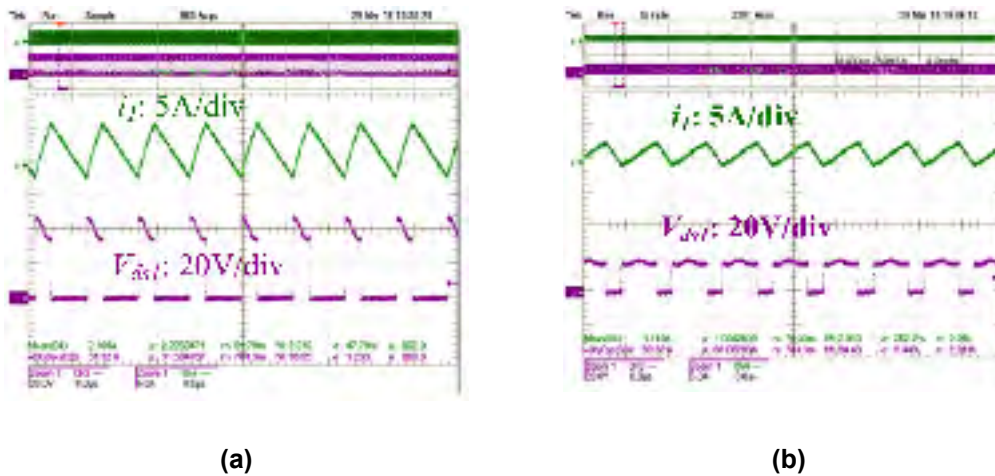


Fig. 7. Preliminary test waveform: (a) 12V-to-30V 1A discharge; (b) 12V-to-6V 1A discharge.

5. Other Relevant Work Being Conducted Within and Outside of the ERC and how this project is different

There are considerable internal and external efforts aimed at developing cost-effective and efficient DESD type systems. From the converter point of view, however, few products in the market exist that deliver similar capabilities. ETH has published two bi-directional dc-dc converter efforts with power ratings of 2kW and 10kW. Akagi's team in Japan has also developed a 200V 2.6 kJ prototype of an energy storage system with supercapacitors. Enphase Energy has a line of microinverter products of 270–350W in residential PV applications. They are also investigating a dc-dc strategy.

Our focus has been on improving the efficiency, reducing the cost and modularizing the storage system. According to Figure 1, our developments described here are competitive with other approaches in both efficiency and power density. They are particularly compatible with the FREEDM Plug and Play vision via the SST interfaced DC microgrid. The team closely monitors the competing approaches being pursued. One ongoing sponsored project focuses on the isolated current-fed dual active bridge (DAB) DC-DC converter for photovoltaic (PV) application on the DC distribution system.

5. Plans for Next Five Years

Higher power DESD with outstanding efficiency will be developed and demonstrated at the beginning of Year 9. Furthermore, an AC interfaced DESD will also be developed. BMS and communication will be fully integrated to reach a higher technology readiness level. DESD reliability will be analyzed. The developed DESD will also be delivered and tested in the GEH and HIL testbeds, hence enabling the Center to document the system level benefits.

6. Member Company Benefits

The modular DESD concept has a patent application pending (application No. 13/600,280) and the technology has also been licensed to a member company. The high-density converter design has been presented to industry members in the last few years. Many papers were also published in IEEE journals and conferences to enable broader knowledge dissemination.

7. Commercialization Impact

In general, high-density and high-efficiency bidirectional DC/DC converters will have significant commercial value to industry companies in the storage space. In the Gen-III DESD, the improved converter efficiency contributes directly to the round-trip efficiency of the DESD. 98% efficiency is also the highest reported in isolated bidirectional DC-DC converters with a rated power smaller than 10kW. The improved power level (1 kW) allows 1C charge and discharge rate of the Li-ion battery. The improved reliability also enables the technology to be closer to commercial application. The high power DESD currently under development will also improve our ability to collaborate with industry since higher power (>1 kW) DESD is needed in real world applications.

10. Recent Publications

- [1] Fei Xue, Ruiyang Yu, Wensong Yu, Alex Q. Huang, Yu Du, "A Novel Bi-directional DC-DC Converter for Distributed Energy Storage Device" IEEE APEC 2015
- [2] Fei Xue; Ruiyang Yu; Wensong Yu; Huang, A.Q., "Distributed energy storage device based on a novel bidirectional Dc-Dc converter with 650V GaN transistors," in Power Electronics for Distributed Generation Systems (PEDG), 2015 IEEE 6th International Symposium on , vol., no., pp.1-6, 22-25 June 2015
- [3] Fei Xue; Yuling Zhao; Ruiyang Yu; Wensong Yu; Huang, A.Q., "Stationary energy storage system based on modular high voltage battery modules," *DC Microgrids (ICDCM), 2015 IEEE First International Conference on* , vol., no., pp.153a,153f, 7-10 June 2015
- [4] Fei Xue; Ruiyang Yu; Wensong Yu; Huang, A.Q., "GaN transistor based Bi-directional DC-DC converter for stationary energy storage device for 400V DC microgrid," *DC Microgrids (ICDCM), 2015 IEEE First International Conference on* , vol., no., pp.153g,153l, 7-10 June 2015
- [5] Fei Xue, Ruiyang Yu and Alex Q. Huang "Loss Analysis of a GaN and Si Devices Mixed Isolated Bidirectional DC-DC Converter" published at APEC 2016

Y8.ET5.2: Safety Testing of Li-ion Batteries

Team Members

Project Leader:	Jim P. Zheng
Faculty:	Mark Weatherspoon and Eric Kalu
Students:	Omonayo Bolufawi

1. Project Goals

Lithium-ion batteries (LIBs) have been chosen by FREEDM as the energy storage cells in the DESD system to be integrated with the GEH Testbed. The LIBs are widely used as a power source in portable electrical and electric vehicle products. While the rate of failures associated with their use is small, several well-publicized incidents related to the failure of lithium-ion batteries in actual use (including fires and explosions) have raised concerns about their overall safety. In 2015 the NSF SVT raised concern that “The ongoing work related to DESD subsystems needs to emphasize the integration of battery systems and safety issues.” In this task, we propose to conduct safety tests of Li-ion battery cells.

2. Role in Support of Strategic Plan

To address some of the safety risks associated with the use of LIBs, a number of standards and testing protocols have been developed to provide Enabling Technology level (Distributed Energy Storage Device Development, Dr. Srdjan Lukic) and then to the Demonstration Testbed level (Green Energy Hub, Dr. David Lubkeman) with guidance on how to more safely construct and use LIBs.

3. Fundamental Research, Technological Barriers and Methodologies

The large amount of test and analysis on LIB cell safety issues have been done by LIB manufacturers; however, it is important to provide independent safety testing support for FREEDM needs since the LIB performance depends on the chemistry of the LIB and operating conditions.

4. Achievements

Results of Lithium Cobalt Oxide (LCO) Battery Nail Penetration Test

There was a sudden spike in temperature (about 400 °C) after few seconds of penetration, which leads to thermal runaway and finally explodes and caught fire. The temperature began to decrease after maintaining a high constant temperature for about 10 sec. It was observed that the temperature increases exponentially and decreases partly linear.

The rated voltage of LCO at 100% state of charge (SOC) dropped at a very fast rate. It also takes about 10 sec for the voltage to drop from 4.1 to 0 V. The battery's rapid reaction to the abuse condition was due to its poor thermal stability. LCO has been proven to have a very poor thermal stability following its crystalline structure. The results of these tests are presented in Figures 1-3.

Results of Lithium Iron Phosphate (LFP) Nail Penetration Test

The noticeable response of the LFP during this test was 20 °C rise in its operating temperature. (up to 54 °C). Figure 4 shows the temperature of the battery with respect to time of the LFP.

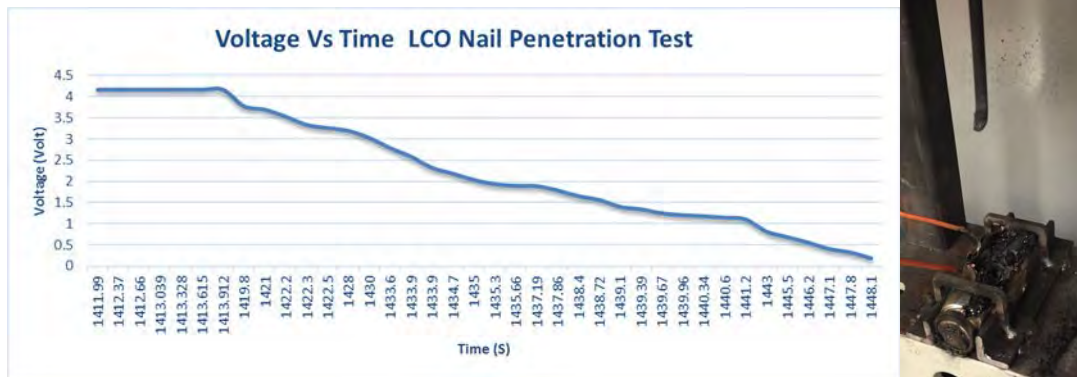


Fig. 1. Voltage profile as a function of time from a LCO battery.

There was a sudden drop in voltage with respect to time over a few seconds.



Fig. 2. A photo of the LCO 18650 battery after a nail penetration test.

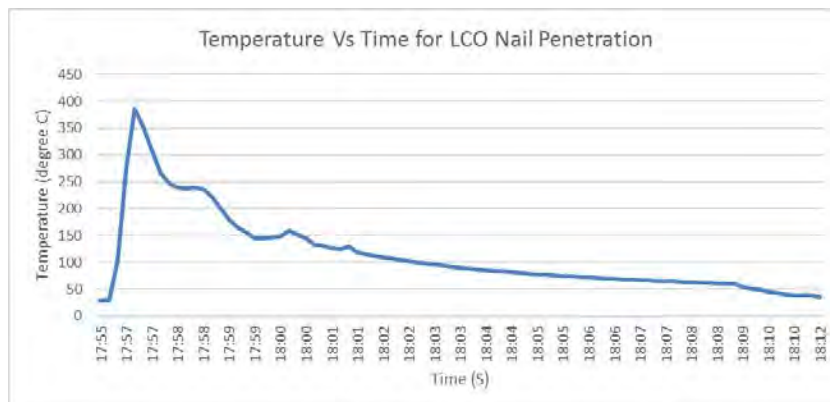


Fig. 3. Temperature profile as a function of time during a nail penetration test.

Short Circuit Test of LFP Batteries:

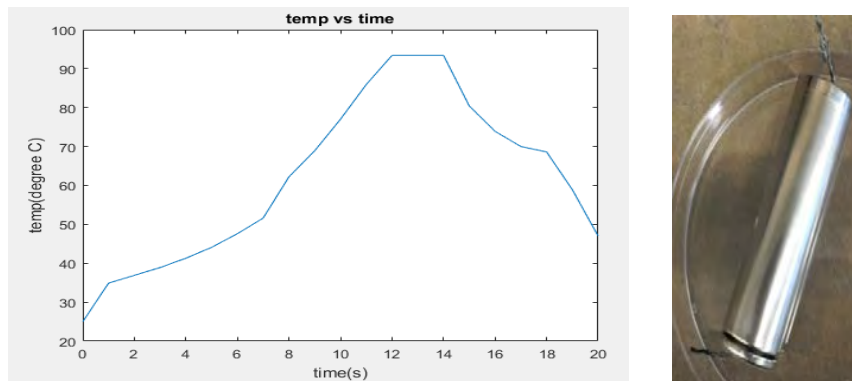


Fig. 4. Temperature profile of a 18650 LFP battery under short circuit.

Crush Test of a LFP Battery

The LFP battery is relatively safe when crushed. The only damage was the compression of the cell due to the applied pressure which led to a small spill of electrolyte. The temperature profile is shown in Figure 5 below;

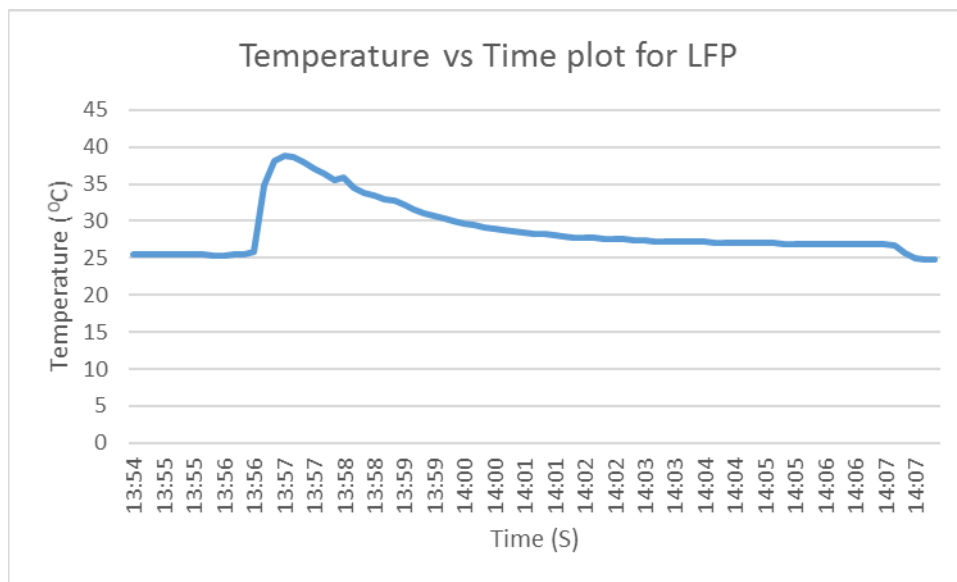


Fig. 5. A temperature profile as a function of time of a LFP battery during a crush test.



Fig. 6. A photo of a 18650 LFP battery after a crush test.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

General Capacitor engineers have closely worked with faculty and students to provide independent safety testing support for their own products.

6. Milestones and Deliverables

Q3/2015 – Purchase battery cells, equipment, and hardware for battery safety tests

Q4/2015 – Complete the design of test method and setup for safety tests

Q1/2016 – Complete electrical and mechanical safety tests

Q2/2016 – Complete environmental safety tests

7. Plans for Next Five Years

- Develop test methods suitable for safety standards;
- Assess Li-ion battery cells' ability to withstand certain types of abuse. We intend to assess specific risks from electrical, mechanical, and environmental conditions which can occur in the real world, including external short circuit tests (a direct connection between the anode and cathode terminals), Over charge testing (an over-charging current rate and charging time), crush tests (a specified crushing force applied by two flat plates, e.g. 12 kN), needle penetration tests (a steel needle placed across the cell), and heating tests (a specified application of an elevated temperature for a period of time, e.g. 150 °C).

8. Member Company Benefits

General Capacitor LLC, a FREEDM spin-off Li-ion capacitor (LIC) company is also interested to develop LIC safety testing methods, which should be similar to that for testing of LIBs.

Y8.ET5.3: Battery Degradation Model for Real-Time Levelized Cost Calculation

Team Members

Project Leader:	Srdjan Lukic
Faculty:	Srdjan Lukic
Students:	Yuhua Du, Rishabh Jain

1. Project Goals

The objective of this task is develop (or adopt from literature) a model that estimates the battery degradation as the function of the DESD use profile. The off-line degradation model supports system cost-benefit studies while the on-line implementation resides on the DESD ARM board (BeagleBoneBlack), and supports the IEM application. The on-line model will be implemented on the newly-developed AC DESD platform, which uses the new Lithium Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$ or LTO) batteries. The on-line battery degradation model will expand the capabilities of the standardized DESD communication and control platform developed in past years, which already contains safety (voltage, current and temperature monitoring) and battery management functionalities. Therefore, the main goals of the project are (1) redesign the FREEDM AC DESD unit to use SCiB batteries and associated battery management and protection features, and (2) develop and implement an on-line battery degradation model that determines the instantaneous cost of use of the DESD.

2. Role in Support of Strategic Plan

The proposed work addresses two issues brought up by the SVT. First, we will use the LTO chemistry, which the team determined in the past years to be best suited for the FREEDM application from in terms of performance and safety. Toshiba LTO batteries boast a long cycle life, are less volatile than other Li-ion chemistries (such as the Boeing 787 Dreamliner batteries that caught fire, which used a lithium cobalt oxide chemistry), and integrate the latest state of the art battery monitoring and protection functions. Second, the development work on the battery degradation modeling aims to address SVT concerns that the effects of battery use and the resulting battery degradation are not considered in the cost-benefit analysis, and in developing strategies for optimal DESD dispatch.

3. Fundamental Research, Technological Barriers and Methodologies

The vision of FREEDM to have a very high renewable penetration while maintaining extremely high power quality and availability, is enabled by the availability of the DESD. The work in this project aims to address the optimal sizing question for the FREEDM DESD. Since the DESD use profile is a strong function of the distributed generation and load mix, optimal storage sizing is very case-specific. Many studies have dealt with solving this sizing problem, given a known load and generation mix, while trying to minimize a given cost or maximize revenue. The FREEDM cost-benefit team is doing this in their cost-benefit analysis. In this work, we try to give these studies more fidelity by considering the battery degradation as it serves the application. Given the battery capacity loss and resistance growth as the battery degrades, the battery has to be sized to serve the application over the entire service life. In this work we determine the changes in battery performance over the battery life, evaluating the resulting performance, losses, and eventual failure. The battery degradation model will be introduced in the next section.

4. Achievements

High Efficiency AC DESD: This year the team has embarked on developing and deploying a new AC DESD which integrates the Toshiba LTO batteries as the energy storage system. This work demonstrates recent DESD integration efforts including control, communication, and protection functionalities developed in past years. The resulting system topology is shown in Fig. 1. The new system employs a commercialized three-leg SiC MOSFET module, where one leg is used as a boost converter, while the other two legs are controlled as a full-bridge inverter. The boost converter boosts the battery nominal voltage of 135V to 200V required by the full-bridge inverter, which delivers 120Vac to the grid.

In the new AC DESD implementation, the team makes use of the standardized DESD communication and control platform, shown in Fig. 1. At the lowest level, a TI TMS320F28335 digital signal processor (DSP) implements control loops for the power electronics, which actuate the real and reactive power commands from the DGI. The DSP communicates via the MODBUS protocol to the local Beagle Bone Black ARM Board, which links to the FREEDM distributed grid intelligence (DGI) via the MQTT protocol. The DSP receives power and relay status commands from the DGI via the ARM Board and reports the actuated power and relay status. The Toshiba battery modules have an integrated battery management system (BMS). The BMS measures the battery voltage, current, temperature; estimates the battery state-of-charge (SOC); and communicates this information to the local ARM board using CAN communication. The BMS monitors all five LTO battery modules, and autonomously controls two additional relays if a fault condition is detected (overvoltage, overcurrent, temperature rise, or leakage current). The ARM board collects the information from the battery and the DSP and uses this information to implement higher-level applications, such as calculating round trip efficiencies, and running the on-line battery degradation model.

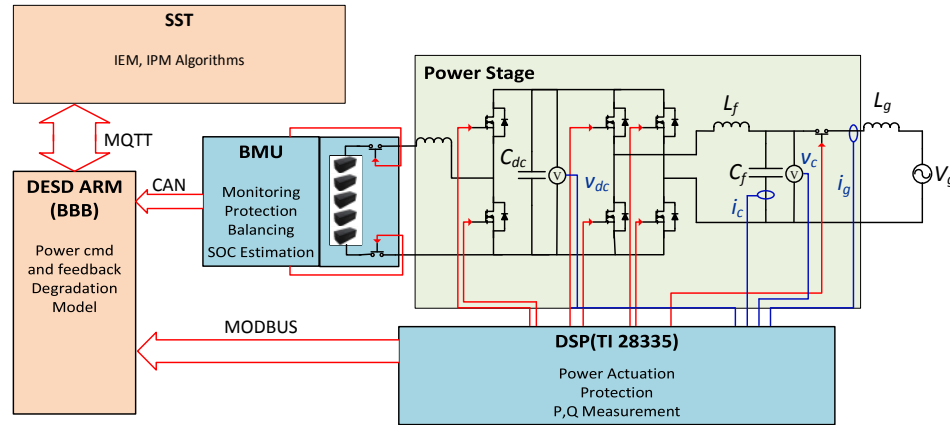


Fig. 1. DESD System Configuration

Battery Degradation Model: The team has adopted a semi-empirical model developed by researchers at National Renewable Energy laboratory (NREL) and described in [1]. This semi-empirical model determines the battery resistance increase and battery capacity loss as a function of calendar and cycling life.

$$R = a_0 + a_1 t_{life}^{1/2} + a_2 t_{life} \quad (1)$$

$$Q_{sites} = c_0 - c_2 t_{life} \quad (2)$$

$$Q_{Li} = b_0 - b_1 t_{life}^{1/2} \quad (3)$$

$$Q = \min(Q_{Li}, Q_{sites}) \quad (4)$$

In (1)-(4), R refers to the battery's internal resistance, Q is the capacity at time t , Q_{Li} represents the capacity loss due to calendar life degradation, Q_{sites} represents the cycling capacity loss, and a_0 , b_0 , and c_0 are chemistry-specific constants. Variables a_1 , a_2 , b_1 , c_2 are determined as follows:

$$a_1 = \frac{a_{1,ref}}{\Delta t_{cyc}} \int e^{\frac{-E_{a,a1}}{R_{ug}} \left(\frac{1}{T(t)} - \frac{1}{T_{ref}} \right)} \cdot e^{\frac{\alpha_{a1} F}{R_{ug}} \left(\frac{V_{oc}(t)}{T(t)} - \frac{V_{ref}}{T_{ref}} \right)} \cdot \left(1 + \frac{\max(\Delta DOD_i)}{(\Delta DOD_{ref})} \right)^{\beta_{a1}} \cdot dt \quad (2)$$

$$a_2 = \left(\frac{a_{2,ref}}{\Delta t_{cyc}} \int e^{\frac{-E_{a,a2}}{R_{ug}} \left(\frac{1}{T(t)} - \frac{1}{T_{ref}} \right)} \cdot e^{\frac{\alpha_{a2} F}{R_{ug}} \left(\frac{V_{oc}(t)}{T(t)} - \frac{V_{ref}}{T_{ref}} \right)} dt \right) \cdot \frac{1}{\Delta t_{cyc}} \sum_i \left[N_i \cdot \left(\frac{\max(\Delta DOD_i)}{(\Delta DOD_{ref})} \right)^{\beta_{a2}} \right] \quad (3)$$

$$b_1 = \frac{b_{1,ref}}{\Delta t_{cyc}} \int e^{\frac{-E_{a,b1}}{R_{ug}} \left(\frac{1}{T(t)} - \frac{1}{T_{ref}} \right)} \cdot e^{\frac{\alpha_{b1} F}{R_{ug}} \left(\frac{V_{oc}(t)}{T(t)} - \frac{V_{ref}}{T_{ref}} \right)} \cdot \left(1 + \frac{\max(\Delta DOD_i)}{(\Delta DOD_{ref})} \right)^{\beta_{b1}} \cdot dt \quad (4)$$

$$c_2 = \left(\frac{c_{2,ref}}{\Delta t_{cyc}} \int e^{\frac{-E_{a,c2}}{R_{ug}} \left(\frac{1}{T(t)} - \frac{1}{T_{ref}} \right)} \cdot e^{\frac{\alpha_{c2} F}{R_{ug}} \left(\frac{V_{oc}(t)}{T(t)} - \frac{V_{ref}}{T_{ref}} \right)} \cdot dt \right) \cdot \frac{1}{\Delta t_{cyc}} \sum_i \left[N_i \cdot \left(\frac{\max(\Delta DOD_i)}{(\Delta DOD_{ref})} \right)^{\beta_{c2}} \right] \quad (5)$$

Where the constant terms:

$$p = \{a_{1,ref}, a_{2,ref}, b_{1,ref}, c_{2,ref}, E_{a,a1}, E_{a,a2}, E_{a,b1}, E_{a,c2}, \alpha_{a,a1}, \alpha_{a,a2}, \alpha_{a,b1}, \alpha_{a,c2}, \beta_{a,a1}, \beta_{a,a2}, \beta_{a,b1}, \beta_{a,c2}\} \quad (6)$$

are fitted to experimental results. In our initial evaluation, the model is developed to represent the degradation of the NCA chemistry from [2]. The NCA chemistry is selected due to the fact that the chemistry is mature, well-understood, and that substantial experimental data is available in the literature.

Equations (2) to (9) together present the lifetime prediction (degradation) model. The model uses a Rainflow algorithm [3] to assess the battery stress due to cycling. The Rainflow algorithm is used to break up a complex depth of discharge history into individual macro- and micro-cycles, ΔDOD_i . The algorithm also tracks whether each cycle was a full or a single-ended charge/discharge cycle and stores this information as N_i . N_i equals to 1.0 for a full cycle and 0.5 for a single-end cycle.

To model the battery behavior, we use a simple equivalent circuit model, shown in Figure 2(a). In this model, the voltage source V_0 represents the open circuit voltage (OCV) of the battery, and Q_c represents the battery capacity. R_{in} represents the total cell resistance and can be considered as a function of both cell aging and battery SoC. This resistance model is a simplification of the well-established battery capacity fade model of lithium-ion cells [4], which considers the battery impedance as a resistor R_1 in series with a parallel R_2C branch of resistance R_2 . The resistance term R_1 refers to the ohmic resistance and R_2C presents all the faradic non-linear components, with its parameters varying with the battery SOC and age. In steady state, the battery impedance can be represented as $R_{in} = R_1 + R_2$. In degradation model, the dynamic response of the cell is intentionally ignored. The relation of V_{oc} to SOC, and R_1 are intrinsic to the cell, while R_2 and Q_c vary as the battery degrades. To model the changes in temperature during the charge-discharge cycles of the ESS we use a simple thermal model:

$$q_{heat} = I^2 R_{in} = \frac{\theta_{battery} - \theta_{ambient}}{R_{SA}} + C \cdot \frac{d\theta_{battery}}{dt} \quad (7)$$

q_{heat} represents the heat generated by battery; $\theta_{battery}$ and $\theta_{ambient}$ represent battery temperature and ambient temperature respectively; R_{in} is the internal resistance; R_{SA} is the thermal resistance of

the battery casing; C is the thermal capacity of the battery. Referring to [5], the thermal model parameters for an 18650 cell are set to $R_{SA} = 2 \text{ K/W}$ and $C = 670 \text{ J/K}$. Fig. 2(b) shows the equivalent circuit diagram.

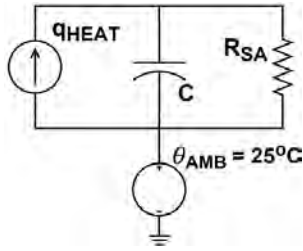


Fig. 2a. Equivalent Circuit Battery Model

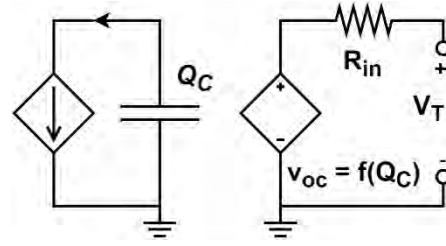


Fig. 2b. Equivalent Thermal Model

Use of Degradation model for cost-benefit analysis: The degradation model is used in FREEDM system cost-benefit studies, as well as in developing control strategies for DESD dispatch. The battery degradation model allows for estimating the battery capacity loss caused by serving an application. This information is then used to calculate the DESD levelized costs over the system life. As system cost-benefit studies consider the power requirements on the battery, the degradation model in conjunction with the equivalent circuit battery model is used to determine the actual battery current, which will be substantially affected by the battery voltage swings, thus providing a higher fidelity battery current estimation. By explicitly calculating the battery current, a higher fidelity estimate of the battery SOC can be obtained, thus avoiding unrealistic SOC excursions in serving the application – an issue that becomes more pronounced as the battery capacity reduces, and the equivalent resistance increases. Explicit knowledge of battery internal resistance allows for battery round-trip efficiency estimation, which is considered in determining the timing of battery replacement, or battery derating in the DESD application. Work still needs to be done in considering this information in developing optimal DESD control strategies. At this stage, our goal is to provide relevant battery behavior data to teams developing the DESD control strategies.

On-line implementation of the degradation model: Our on-line implementation of the degradation model is made up of two components: first is the run-time mathematical implementation of the model described in (1)-(9) and the associated rainflow algorithm that converts the captured voltage and current data into micro-and macro cycles that can be fed to the model. The implemented model also estimates the battery resistance as a function of the state of charge, and the battery capacity loss in real-time, and independently of the degradation model. The resistance information is used for higher-fidelity round-trip efficiency estimation, while the capacity information is used for the validation of the degradation model. The data collected via the described model will also be used as a training set for further tuning of the degradation model.

Real-time pricing of DESD-supplied power: The on-line degradation model and the associated round-trip efficiency calculation will be used to determine the real-time pricing of supplying power from the DESD. We envision that a service request $S=f(P, E, t)$ is sent to DESD where P is the constant or time-varying power demand, E is the total energy demand and t is service time. The cost of providing the grid-support service from the DESD will then be calculated as:

$$C_{service} = C_{deg} + C_{soc-balance} + C_{loss} + C_{markup} \quad (8)$$

In (11), C_{deg} represents the projected degradation of the battery capacity as a ratio of the total expected battery throughput, multiplied by the replacement cost. $C_{soc-balance}$ represents the cost of returning the battery back to its initial SoC, $soc_{initial}$, after providing the grid-support service. To provide the request, the final SoC, soc_{final} , can be estimated. If $soc_{final} > soc_{initial}$, the DESD can sell

the extra energy at favorable time back to the market. The projected soc_{final} , and the projected future battery use profile determines the value and the sign of $C_{soc-balance}$. If $soc_{final} < soc_{initial}$, the DESD has to purchase the energy from the market at a spot market price to replenish the battery back to the target SoC of $soc_{initial}$. The term C_{loss} considers the inverter and battery round trip efficiency explicitly, while the last term represents the desired profit the DESD owner expects per service request.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

The degradation model used in this work was developed by researchers at NREL. We will build on the work done by these entities to complete our goals.

6. Milestones and Deliverables

This year, the team focused on integrating center-developed DESDs into the GEH and HIL testbeds. This completes the migration of technology from the enabling plane to the demonstration plane. To that end, the team demonstrated a unified messaging protocol for the DESD to deliver the necessary information to the DGI to optimally use these resources. The team also adopted degradation model from the literature and implemented the algorithm to run in real-time on an ARM platform.

7. Plans for Next Five Years

The team will continue the integration and standardization of commercial and center developed DESDs using the described integration platform. The work done this year shows that the center is able to quickly integrate new DESDs, which will allow for commercial and second party DESDs to be integrated into the GEH. The degradation modeling work will continue, with the ultimate goal of providing real-time cost estimation of using the DESD to support the FREEDM System. Having this real-time cost data will allow for system-level cost or efficiency optimization in real-time, thus allowing DESD optimal dispatch in the context of the defined cost function.

8. Member Company Benefits

The LTO batteries used by the center are developed by a member company, Toshiba. The company has provided battery test data and has helped the center procure the batteries. Another member company Pos-En is using the same LTO battery modules in their products, and joint development on battery integration has benefited both institutions.

9. References

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Core Projects
Fundamental Science

Y8.FS1.1: SiC Power Devices for SST and FID Applications

Team Members

Project Leader: Dr. Jayant Baliga

Faculty: Dr. Alex Huang, Dr. Woongje Sung

Students: Yifan Jiang

1. Project Goals

Design and fabrication of high temperature 10kV SiC MPS rectifiers for solid-state transformer application. Determination of high temperature operating capability of 10kV SiC Power MOSFETs.

2. Role in Support of Strategic Plan

Our Year 8 goal is aligned to the road map for developing devices that have better high temperature performance for the solid-state transformer and fault-interruption device applications within the FREEDM green energy hub.

3. Fundamental Research, Technological Barriers and Methodologies

A major technological barrier is the lack of sufficiently high quality semiconductor fabrication equipment in the NNF NCSU cleanroom. We have to often make use of the Duke University cleanroom. We have to sometimes ask for assistance from outside companies but this is not always supported making it difficult to meet our milestones.

4. Achievements

MPS Rectifiers: We have proposed a novel SiC MPS (Merged-PiN-Schottky) Rectifier to improve the trade-off between on-state and turn-off switching losses [1]. This improves the efficiency of the solid-state transformer (SST). The MPS rectifiers were successfully fabricated in Year 6 and demonstrated to have much superior trade-off curves at room temperature compared to available PiN and JBS rectifiers in the industry. High temperature characterization of devices was done in Years 7 and 8.

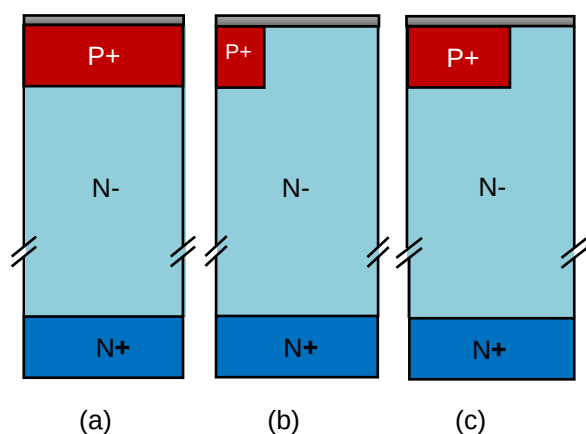


Fig. 1. (a) PiN; (b) JBS; (c) MPS Rectifier Structures

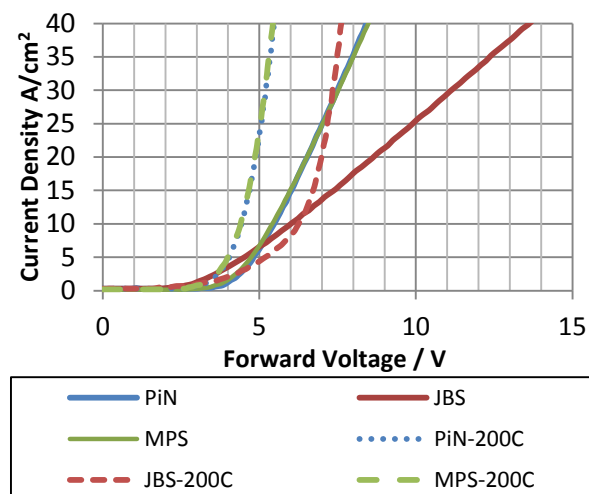


Fig. 2. On-State characteristics of Rectifiers.

Figure 1 shows the cross section view of the SiC PiN, JBS and MPS rectifiers. The structure of JBS and MPS rectifiers looks similar in that they both have P+ regions to form a potential barrier under the Schottky contact during reverse bias to reduce the electric field resulting in smaller leakage current. The difference between these two structures is that for the JBS rectifier, the P+/N junction does not turn on in the on-state resulting in a high on-state voltage drop. The MPS rectifier is designed with a narrow Schottky contact region so that the P+/N- junction is turned on to reduce the on-state voltage drop [1]. The results of our numerical simulations are shown in Fig. 2. The on-state voltage drop for the 10kV MPS rectifier (dashed green line) is identical to the PiN rectifier (dashed blue line) and becomes much smaller than that of the JBS rectifier (dashed red line) at 200°C. The JBS rectifier starts to behave like an MPS rectifier at 200°C.

Figure 3 shows the extracted reverse recovery charge for 10kV SiC MPS and PiN rectifiers from 27 to 200°C obtained by our numerical simulations. The performance of the MPS rectifier becomes even more superior to the PiN rectifier at elevated temperatures. Figure 4 shows the trade-off curve between on-state voltage drop and reverse recovery charge with temperature as a parametric variable. The trade-off curve for the MPS rectifier becomes even better compared with the PiN rectifier when the temperature increases. Fig 5 shows the leakage current at room temperature and 125°C for JBS, PiN and MPS rectifiers. MPS rectifiers have low leakage current like PiN rectifiers. Our work demonstrates for the first time that the MPS rectifier is an ideal choice for diodes operating at elevated junction temperatures.

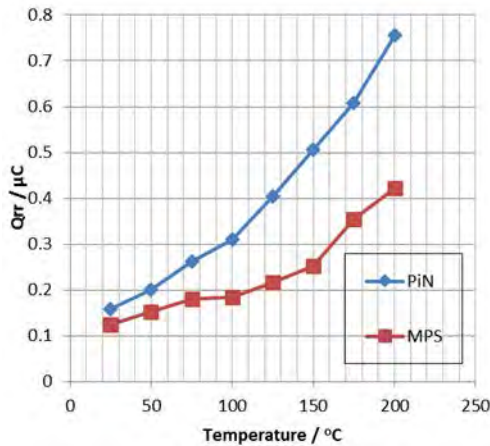


Fig. 3. The Reverse Recovery Charge versus Temperature for PiN and JBS

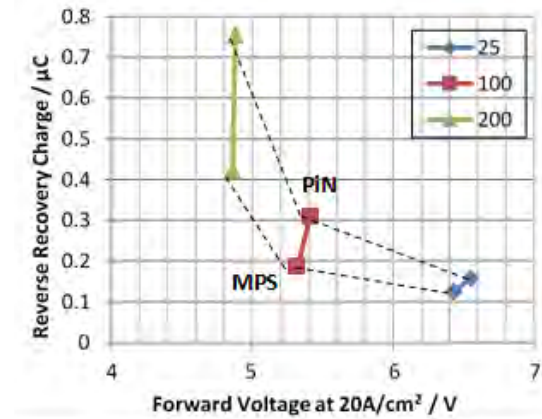


Fig. 4. The Trade-off Curve for SiC PiN and MPS diode at different temperature (°C)

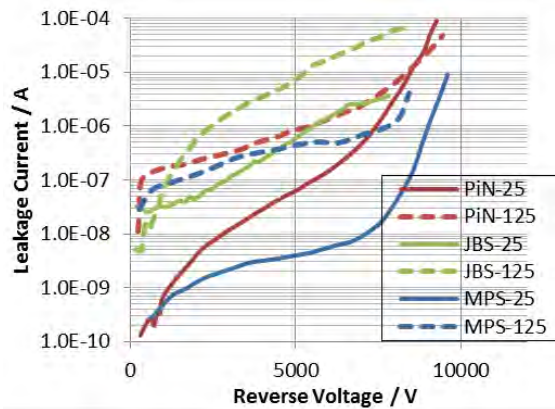


Fig. 5. The Reverse Leakage Current for SiC PiN, JBS and MPS diodes.

Our measurements on the MPS rectifiers have demonstrated that the main issue with respect to the high temperature operation is the large leakage current during reverse blocking. This can lead to thermal runaway. Consequently, we have designed SiC MPS rectifiers with reduced leakage current at high temperature in Year 8 by using a Schottky metal with larger barrier height. A larger Schottky barrier height was achieved by replacing nickel with platinum or gold. Figure 6a and 6b show the simulation results obtained for the on-state characteristics at room temperature and 200°C, respectively. It was found that metals with different metal-semiconductor barrier heights have very little impact on the on-state I-V characteristics of MPS rectifiers while reducing leakage current by 3-5 orders of magnitude at room temperature and 200 °C.

Based on our analysis, high barrier metals such as Pt and Au will be used to fabricate MPS rectifiers in Year 8. For the edge termination design, non-equally spaced floating field rings are used because rings can be made at the same time as the main P+/N junction is formed by ion implantation and activation anneal. The mask and process flow were designed based on a linear device cell structure. The process will utilize 7 masks. The chip layout is shown in Figure 7. The label of different dies shown in the layout is the width of the Schottky region (W_s). W_p is the width of the P+ region.

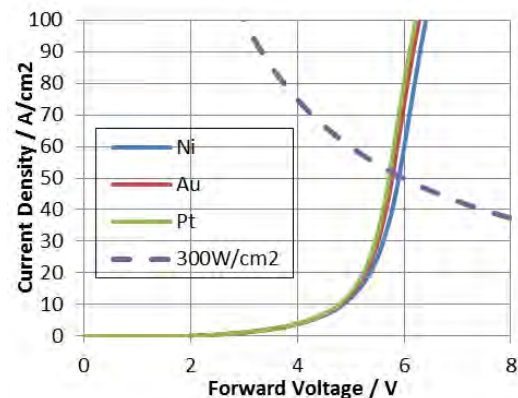


Fig. 6a. Simulated on-state characteristics of MPS diodes with three kinds of metal as Schottky contacts (room temperature)

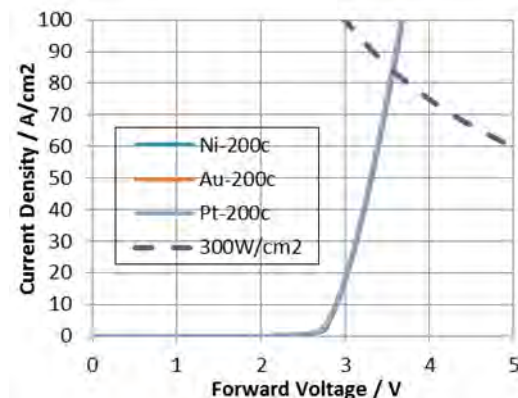


Fig. 6b. Simulated on-state characteristics of MPS diodes with three kinds of metal as Schottky contacts (200°C)

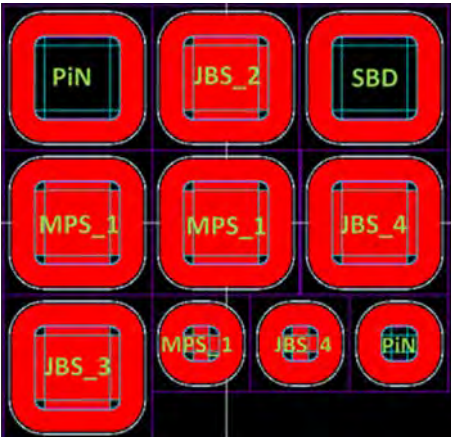


Fig. 7. Device layout

PiN	PiN Diode
SBD	Schottky Barrier Diode
MPS_1	Ws=1μm, Wp=3μm
JBS_2	Ws=2μm, Wp=3μm
JBS_3	Ws=3μm, Wp=3μm
JBS_4	Ws=4μm, Wp=3μm

SiC Power MOSFETs: The characterization of commercially available 1.2 kV SiC power MOSFETs was first performed to establish the measurement procedures to be used for 10kV devices. The I-V curves (including breakdown characteristics, output characteristics and transfer characteristics) were measured

as a function of temperature. The input capacitance C_{iss} , output capacitance C_{oss} , reverse transfer capacitance C_{rss} and gate charge Q_g were measured by using specially designed PCB boards.

The measured off-state characteristics are shown in Fig. 8. The leakage current increases with temperature but is acceptable even at 250°C. The output characteristics are shown in Fig. 9 and 10 at 150 and 225°C. The on-resistance increases from 0.14 to 0.20 ohms. The transfer characteristics of are shown in Fig. 11. The threshold voltage reduces from 1.8V at 25°C to 1.0 volts at 225°C, but is still acceptable for circuit applications.

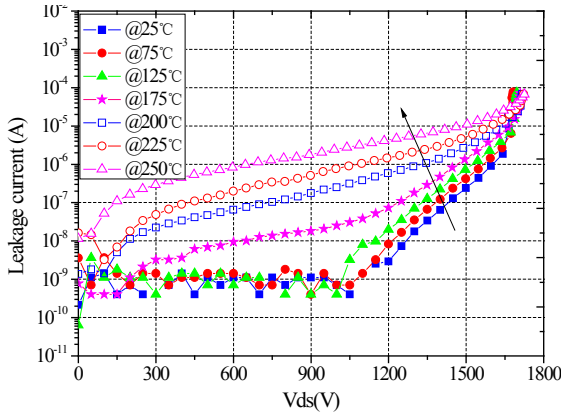


Fig. 8. The off-state characteristics at different temperatures.

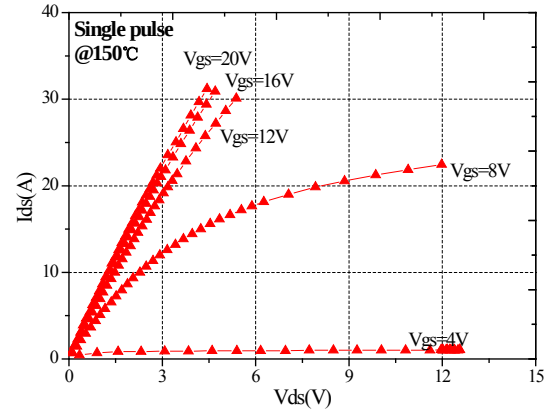


Fig. 9. The output characteristics at 150°C.

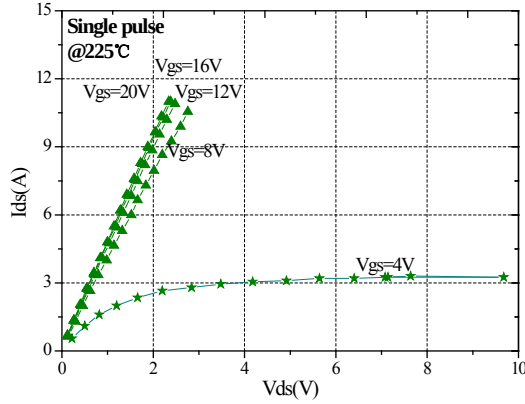


Fig. 10. The output characteristics at 225°C

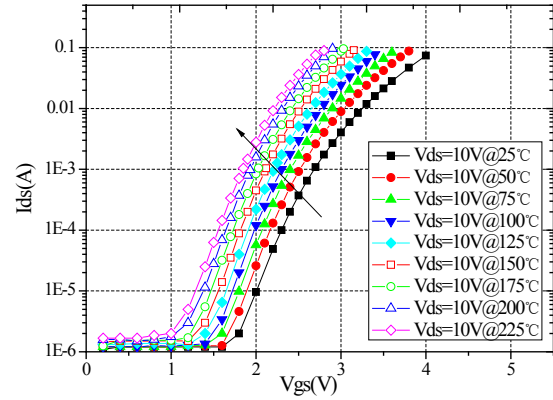


Fig. 11. Transfer characteristics at different temperatures

The measured capacitance characteristics are shown in Fig. 12. As expected from device physics [3], they do not change with temperature.

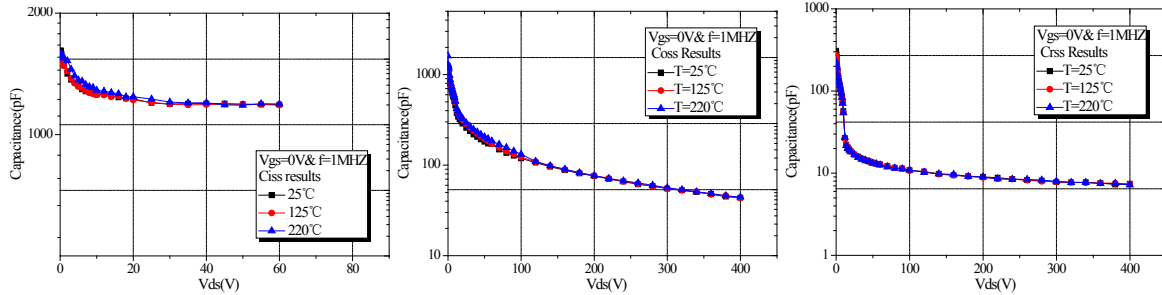


Fig. 12. Device capacitances at different temperatures.

The measured gate charge characteristics are shown in Fig. 13. The gate charge (extracted from the time scale) does not change with temperature as expected from device physics [3]. The vertical shift in the curves is due to a reduction of the threshold voltage.

Having validated the testing procedures, we are now performing characterization of 10kV SiC power MOSFETs. The results will be reported at the site visit.

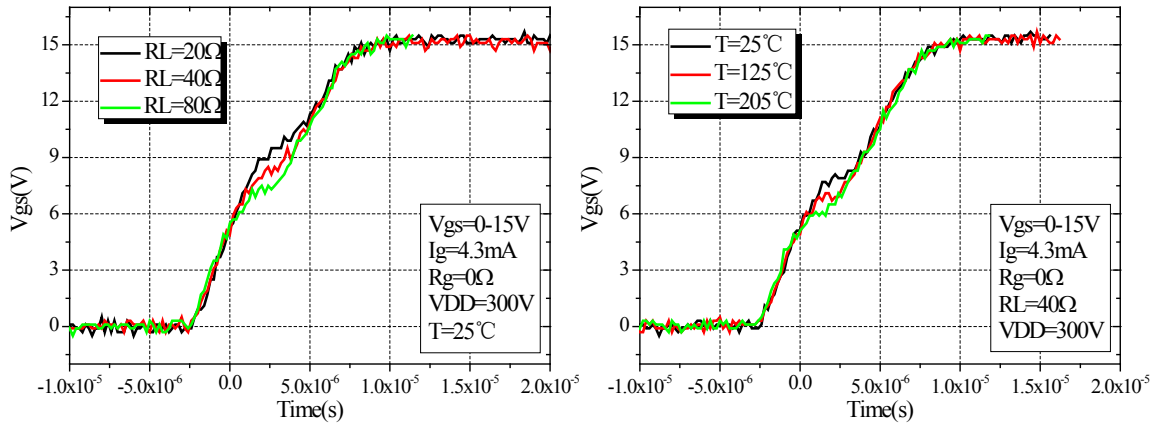


Fig. 13. Measured Gate Charge curves.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

To the Center's knowledge, no other research activity is being directed towards making 10kV 4H-SiC MPS rectifiers and 10 kV SiC power MOSFETs with high temperature capability.

6. Milestones and Deliverables

In year 8, the 10kV SiC MPS rectifiers were fabricated and characterized as a function of temperature. The characteristics of 10kV SiC power MOSFETs were obtained as a function of temperature.

7. Plans for Next Five Years

Contingent on availability of funds, the PSD group will continue developing SiC high voltage devices, including rectifiers and transistors, for SST and FID applications.

8. Member Company Benefits

This project will allow member companies to assess if high voltage SiC MPS rectifiers are attractive commercial products. Members will be able to assess the benefits of high temperature operation in terms of reduced packaging cost or reduced chip cost.

9. References

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Y8.FS1.2: GaN Low Voltage Power Device Development

Team Members

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Postdoc: In Hwan Ji

1. Project Goals

The overall objective of the GaN power device project is to fabricate and demonstrate normally-off Metal-Oxide-Semiconductor (MOS) GaN/AlGaN High Electron Mobility Transistor (HEMTs) power devices for the solid state transformer (SST) and distributed storage devices (DESD) having 600V of blocking voltage characteristics and 50-Ampere current capability with a specific on resistance of 1-2 mohm-cm². The specific goals for this year are:

- Fabricate 1200V 5-10A depletion mode power HFETs and MOSHFETs
- Fabricate 1200V 5-10A enhancement mode power HFETs and MOSHFETs
- Deliver a packaged 1200V GaN MOSHFET operating at 150°C
- Optimize the gate stack and passivation dielectric for reliable and stable power GaN devices
- Evaluate device reliability at elevated temperatures up to 150°C

2. Role in Support of Strategic Plan

The proposed FREEDM 20KVA solid state transformer (SST) converts a high voltage (7kV) input to a low voltage (120V) output at a switching frequency of 10 kHz. The secondary side of the SST needs medium voltage (600V), high current (100A) power devices. In order to achieve extremely high SST efficiencies (>97%), power loss should be minimized. For this purpose wide-bandgap GaN-based power devices will be implemented due to the superior physical properties of the GaN materials relative to Si. This project is critical to enabling SST and directly supports the strategic plan of the SST and DESD thrusts.

3. Fundamental Research, Technological Barriers and Methodologies

Due to the basic epi material availability, today's GaN power devices are fabricated using a lateral device structure. Lateral GaN HFET devices have very low parasitic capacitance; therefore, are very suitable for high-speed applications. In terms of conduction losses, the GaN device is about two times worse than vertical devices due to larger device cell sizes, lateral current flowing pattern (heat concentrated with the top 1um of a 500um wafer) and poor thermal performance when compared with the SiC MOSFET. Therefore, a large die size is needed to reach high current levels in a single die. This has been a major challenge facing the GaN research team in the last few years. In the industry, solutions to this problem include 1) using multiple metallization to reduce cell size; 2) use flip-chip packaging to remove heat directly from the surface of the die. Supported by state-of-the-art fabrication facilities, industry have been successful in scaling the die size, and today devices with R_{on} smaller than 20 mohm/ are commercially available. The acceleration in industry manufacturing is unprecedented. Although NCSU has one of the best university based cleanroom facilities, it is difficult to achieve high current devices with good blocking capability. In addition to the processing challenges, there are also challenges related to the substrate material quality due to large material variations expected when the die size increases.

To address the above issues, we are shifting our strategy to the following two aspects: 1) focusing on medium current level devices such as 5A and using packaging technology to parallel devices to reach higher current devices; 2) focusing on higher blocking voltage (1200V) devices.

4. Achievements

4.1 Large Current 600V Device Fabrication

With a revised mask design and an optimized ALD dielectrics, the team has successfully fabricated a medium current (5A) device. Higher (>30A) current is then achieved at the packaging level by paralleling six devices. Figure 1 (a) shows the cross-sectional schematic of the fabricated device where ALD SiO_2 was used as a gate dielectric and ALD HfAlO was used as a passivation layer. The packaged module with six devices in parallel has 80 mm of total gate width and can conduct 30A current at $V_{ds} = 1\text{V}$ ($V_{gs}=0\text{V}$) with the calculated $R_{on,sp}$ value of $3\text{ m}\Omega\text{-cm}^2$. However, these devices did not support high voltage due to problems with surface passivation.

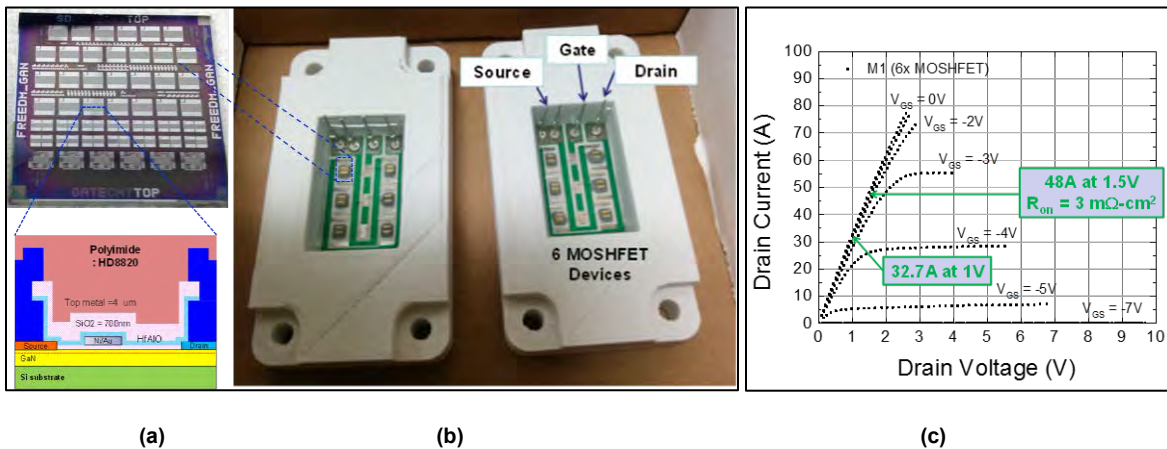


Fig. 1. (a) Cross-sectional schematic of fabricated device and a microscopic image of the fabricated chip, (b) microscopic image of parallelized module package, and (c) I_{ds} - V_{ds} characteristics of packaged module

4.2 High Voltage (1200V) GaN HFET Development:

Previously we studied the impact of various passivation dielectrics on leakage current and concluded that a better passivation is needed to achieve lower leakage current. In year 8, a new passivation based on ALD SiO_2 + Polyimide as passivation film stack were proposed and studied. The focus is on reducing the leakage current and to study the feasibility of reaching much high breakdown voltages. With these improved passivation films and an improved layout design that avoids edge-related premature breakdown, we have successfully demonstrated that $BV > 1200\text{V}$ can be achieved using GaN-on-Si wafers available to the research team. The test results are shown in Fig.2. In Fig.2a, several low current devices ($W=50\mu\text{m}$) have successfully demonstrated $>1200\text{V}$ blocking capability. In Fig.2b, higher current devices ($W=80\text{mm}$) were tested and their blocking voltage were all below 200V. So it remains a major challenge in achieving high voltage and high current at the same time. This is not a fundamental device issue but a processing and material uniformity issue. Therefore, future work will continue with a focus on medium current devices ($W=10\text{-}15\text{mm}$).

4.3 Magnesium Ion Implant to form lateral P-N Junction

This year we have also studied the Magnesium ion implant and annealing process to implement p-GaN layer as a device function layer. A lateral GaN P-N junction diode was successfully fabricated on an AlGaN/GaN-on-Silicon substrate by implanting Mg at 500°C , and annealing at 1350°C for 60 sec. The device demonstrates a breakdown voltage of 135V ($I_{off}=1\mu\text{A}$) and a forward current density 191

mA/cm² at 50V when characterized at 200°C. Further investigation is needed to reduce the p-GaN and p-type contact resistivity. A paper to report this result has been accepted by CS MANTECH 2016.

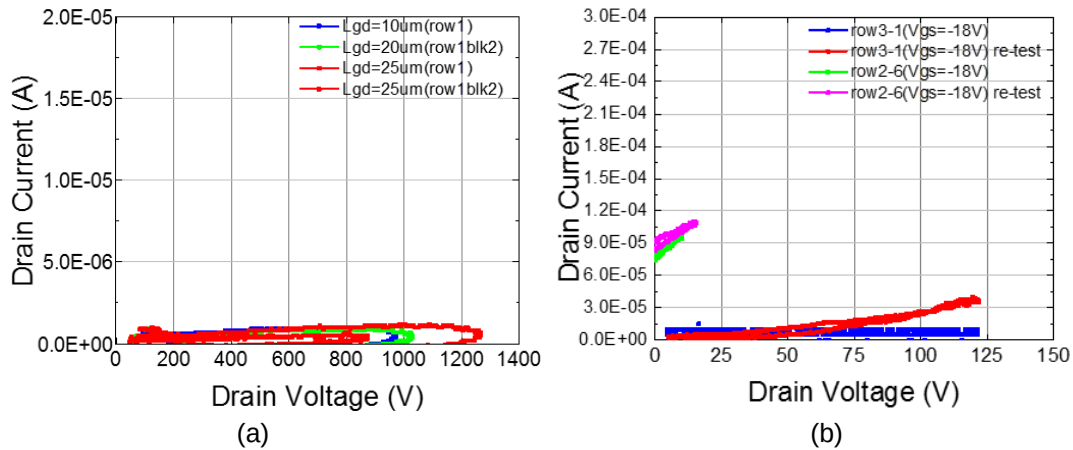


Fig. 2. Breakdown voltage evaluation (a) W = 50μm b) high current device with gate width W= 80mm

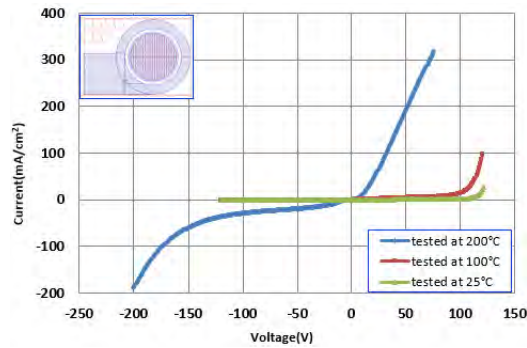


Fig. 3. Circular P-N junction diode I-V curve test at different temperatures

5. Other Relevant Work Being Conducted Within and Outside of the ERC

At present, 650V GaN e-mode HEMT devices with high current (from 7A to 60A) ratings are commercially available from a number of companies, e.g. GaN Systems. The Naval Research Lab has successfully fabricated low resistivity p-GaN layer ($\rho=830\text{mohm-cm}$) by Magnesium implantation and a sophisticated annealing process.

6. Milestones and Deliverables

1200V/5A GaN HFET devices.

7. Plans for Next Five Years

There are significant challenges in fabricating large current devices in our NCSU NNF processing facility. The current plan includes additional research on developing 1200V GaN HFET with lower current capability. Parallel operation of these 1200V devices could be an alternative pathway to increase the current rating. The team also plans to study vertical power devices at 1200V or higher blocking levels due to the availability of GaN epi wafer on GaN substrate. There is very little academic research currently conducted on vertical GaN power devices with more than 1200V breakdown voltage capability. Innovative edge termination designs to accommodate low activation rates for p-type GaN implant layer will be our first major contribution.

8. References (Published after last report)

- [1] Ji, In-Hwan; Lee, Bongmook; Wang, Sizhen; Misra, Veena; Huang, Alex Q., "A new AlGa_N/Ga_N power HFET employing partial deep trench drain structure for high voltage application," in Wide Bandgap Power Devices and Applications (WiPDA), 2015 IEEE 3rd Workshop on , vol., no., pp.147-149, 2-4 Nov. 2015

Y8.FS1.3: Packaging Research and Demonstration

Team Members

Project Leader:	Dr. Douglas C Hopkins
Faculty:	Dr. Douglas C Hopkins
Students:	Haotao Ke

1. Project Goals

High Temperature packaging development for SST 1.2kV* GaN & 15kV SiC applications

2. Role in Support of Strategic Plan

The outcomes in high temperature power electronics to develop and test devices and circuits will raise the visibility of FREEDM as the leading power electronics center from device to packaging to application. FREEDM will become sustainable and draw members to utilize the special resources in high temperature power electronics design and test.

3. Fundamental Research, Technological Barriers and Methodologies

This task supports the testing of the WBG devices developed within the other Y8.FS1 tasks (i.e. 1.2kV* GaN & 15kV SiC), by providing a physical package that supports high power testing at high temperatures ($\leq 200^{\circ}\text{C}$). Packaging is characterized and parasitic parameters quantified to be deducted from final device-in-package test results. The greatest challenge is developing compatible materials and processes to produce a test package usable at 200°C and 15kV.

4. Achievements

A power module test package suitable for 200°C testing of 10kV SiC Diodes. The module was tested, characterized and verified without inclusion of a switching device. A 9kV SiC diode design was also tested and results conclusively showed operational device characteristics devoid of package influence.



Fig. 1. Tested 10kV SiC package with thermistor and two SiC diodes

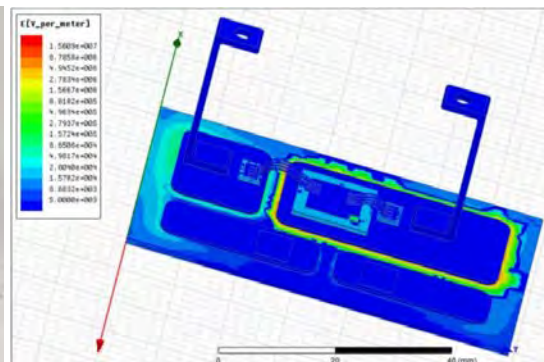


Fig. 2. Simulation of the electric field for SST 10kV operation.

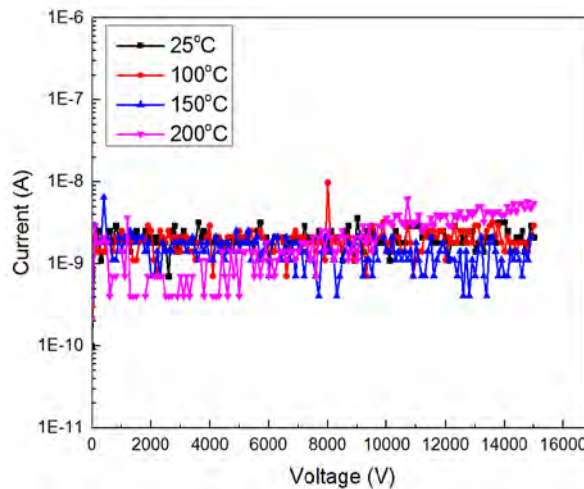


Fig. 3. Blocking voltage test result for package without device

5. Other Relevant Work Being Conducted Within and Outside of the ERC

- High Power 1.2kV SiC 'Six Pack' Power Module Decomposition
- High Density Inverter Packaging Development for 55kW Electric Vehicle
- Direct Cooled High Density SiC-based Air Cooled Inverter
- True-3D Power Electronics Module
- Ultra-Thin Ceramic substrates for 1.2kV SiC Planar Power Modules
- Ultra High Density 12V:1.2V, 100W GaN VRM

6. Milestones and Deliverables

- Q4 (12/31/2015) – Identified and assessed materials, established design for hi-T,hi-f test system
 - Delivered high temperature (250°C) and high frequency ($\leq 50\text{kHz}$) 10kV test module with characterization.
- Q1 (3/31/2016) – Demonstrated design through simulation of a low-frequency 1200V, 100A power module.
 - Delivered an 'air cooled' module and true-3D module* (through simulation) (* under patent disclosure)

7. Plans for Next Five Years

- Secure continuation of funding for sustainability of the PREES Laboratory through corporate sponsorships and service center support

8. Member Company Benefits

- Advanced WBG device characterizations suitable for full system simulations from device through power circuits

9. References

- [1] A. J. Morgan, A De, S Bhattacharya, D. C. Hopkins, "A Robust, Composite Packaging Approach for a High Voltage 6.5kV IGBT and Series Diode," 48th IMAPS Int'l Symp. on Microelectronics, Orland, FL Oct 28-30, 2015
- [2] A De, S Bhattacharya, A. J. Morgan, D. C. Hopkins, "Design Considerations of Packaging a High Voltage Current Switch," ASME 2015 Int'l Technical Conf on Packaging and Integration of Electronic and Photonic Microsystems (and ASME 2015 12th Int'l Conf on Nanochannels, Microchannels, and Minichannels - InterPACKICNMM2015, July 6-9, 2015, San Francisco, CA

- [3] W. Sung, A. Q. Huang, B. J. Baliga, I. Ji, H. Ke and D. C. Hopkins, "The First Demonstration of Symmetric Blocking SiC Gate Turn-Off(GTO) Thyristor," W. Sung, A. Q. Huang, B. J. Baliga, I. Ji, H. Ke and D. C. Hopkins, Proc. 27th Int'l Sym on Power Semiconductor Devices & ICs, Hongkong, 2015

Y8.FS2.1: Distributed Control Methods for Intelligent Power Management with Moving Equilibria

Team Members

Project Leader: Dr. Iqbal Husain

Faculty Members: Dr. Aranya Chakrabortty (NCSU)

Graduate Students: Alireza Milani (NCSU), Md Tanvir Arafat Khan (NCSU)

1. Project Goals

The objective of this project is to develop a comprehensive state-variable model of the FREEDM system for feasibility, stability and dynamic performance analysis, followed by controller designs. The specific goals for this year are to:

- Perform comprehensive feasibility analysis of FREEDM system
- Develop the operational bounds for different operating conditions
- Develop intelligent power and energy management functionalities based on feasibility bounds
- Develop power sharing methods in the multi-SST configuration

2. Role in Support of Strategic Plan

The role of this SMC project is to produce a convincing framework for the design and analysis of all necessary controls in the system, including feasibility, stability, power, energy, and fault managements and enable validation of the control algorithms. The FREEDM system IPM control (voltage and frequency regulation) is implemented in a distributed manner given the small time constants of the power electronics components in the system. The IEM algorithms serve as the set-points for the FREEDM devices for energy management. Integration of control with protection allows the FREEDM System to transform the legacy distribution system with centralized control and decoupled protection to a resilient distributed power and energy managed system.

3. Fundamental Research, Educational, or Technological Advancement Barriers and Methodologies Used to Address Them

The FREEDM system is an engineered, non-linear, hybrid, multivariable system, and hence, has its challenges for identifying suitable analysis techniques. Much of the existing autonomous and distributed control in power systems relies on temporal and spatial decoupling among the phenomena being controlled. A FREEDM system is bound to be affected by the faster switching surge dynamics to slower frequency control both qualitatively (novel dynamics) and quantitatively (many more components). The stability analysis of a large FREEDM system involving many fast responding power electronic based devices, and distributed and varying loads, generation and storage thus remains a challenge for the system controls research. A similar situation exists in microgrid research.

The fundamental research carried out in this project is to produce a convincing framework for the design and analysis of all necessary controls in the system, including stability, power, energy, and fault management. In the FREEDM controls framework, each controller has a local component and a global component. The local controller is designed for faster response time without communications to address IPM functionalities, while the global controller operates under specified communications requirements to address IEM requirements.

4. Achievements in Previous Three Years with an Emphasis on the Current Year

The research in controls in previous years was focused on developing the local controls for power management of FREEDM devices, such as the SSTs and DESDs, and energy and fault management algorithms on simulated FREEDM systems. A Year 7 task completed collecting the local controllers developed in prior years into a platform based controls framework, and developing a comprehensive FREEDM system model. This SMC thrust project focused on performing the feasibility analysis in Year 8 based on the comprehensive model developed in Year 7. The resulting feasibility bounds are then utilized to determine the operational ranges based on the different loading conditions and then methods are proposed to expand the operational range. Derived results are also utilized for the development of power sharing methods in multi SST systems to maintain the feasibility of the total system.

4.1 Feasibility Analysis of FREEDM System

The 70th-order nonlinear differential-algebraic state-space model of a single-SST FREEDM power distribution system developed in the Year 7 provides the opportunity to derive analytical relationships between physical parameters and a feasible operational range. In the Year 7 report, the pair (u_3, I_{DAB}) has been identified to be critical for determining the equilibrium of the nonlinear FREEDM model where I_{DAB} represents the net current flowing through the dual active bridge(DAB) and u_3 is the d -axis grid voltage. The equilibria analysis served as a motivation to derive an analytical equation relating the feasible range of operation of the system with the system parameters. This relationship could provide the opportunity to extend the feasibility study for the full SST model and then utilize the results to design a better controller that handles feasibility and stability together. Feasibility analysis of the FREEDM system is also essential to answer the maximum net power capability that the system can handle. Once the feasibility bounds are known, the system parameters can be designed accordingly to provide the required power flow and energy exchange flexibility. The average model that was developed in Year 7 for the SST is utilized for the feasibility study on each stage of the SST (which are rectifier, DAB, and inverter) and the range of permissible total load that each part can handle (assuming infinite generation) has been found. Dynamic model and duty cycle constraints for each SST subsystem can be written as (1) and (2), respectively where α_1 and α_2 denote the load data and system parameters, respectively. For a given set of (α_1, α_2) , the operating point of the system $(\bar{x})$ can be found by setting $\dot{x} = 0$.

$$\dot{x} = f(x, \alpha_1, \alpha_2) \quad (1)$$

$$g(x, \alpha_1, \alpha_2) \leq 0 \quad (2)$$

The rectifier is the front-end segment of the SST and it has three physical states along with three states from the designed PI controllers. In the steady state, the dynamic model of the rectifier can be summarized as two circle equations that define the feasibility of the rectifier, given in (3) and (4). The

$$\begin{aligned} (x_1 + \frac{u_3}{2a_2})^2 + (x_2 + \frac{u_4}{2a_2})^2 \\ = \frac{u_3^2 + u_4^2}{4a_2^2} - \frac{2P}{a_2} \end{aligned} \quad (3)$$

$$(x_1 + \frac{a_2 u_3 + a_1 u_4 u_2}{a_2^2 + a_1^2 u_2^2})^2 + (x_2 + \frac{a_2 u_4 - a_1 u_3 u_2}{a_2^2 + a_1^2 u_2^2})^2 \leq \frac{r_1^2}{a_2^2 + a_1^2 u_2^2} \quad (4)$$

feasibility ranges for the DAB and Inverter stages of SST are also derived utilizing the physical and controller states. By proper choice of DAB and inverter parameters, the front-end rectifier will be the most dominant part of the SST system in terms of feasibility. Fig. 1 shows the feasibility circles for the front-end rectifier of SST Gen II, when the total load flowing through the rectifier is 50kW. The shadowed circle represents the duty cycle constraint and the other circle shows the feasibility bound. Any point on the marked line can be a solution for the system. Therefore, in order to guarantee feasibility, the two circles should always have at least one intersection point. Two circles will overlap if the distance between their centers (A) is either less than the sum of their radii (R_1 and R_2) or it is more than the absolute value of the difference between their radii. Therefore, based on their radii and center distance, the maximum positive and negative feasible power of the rectifier can be found as shown in Table 1. If the required power flowing through the rectifier is not in the range, i.e., two circles do not have any interconnection point, changes in rectifier DC output voltage (r_1) would increase the radius of the duty cycle circle, and thereby, possibly make that required power a feasible power. This would result in a minimum r_1 as shown in Fig. 2.

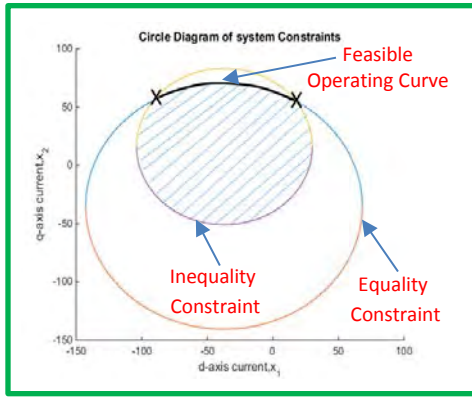


Fig. 1. Feasibility Circles for SST Rectifier at $P = 50kW$.

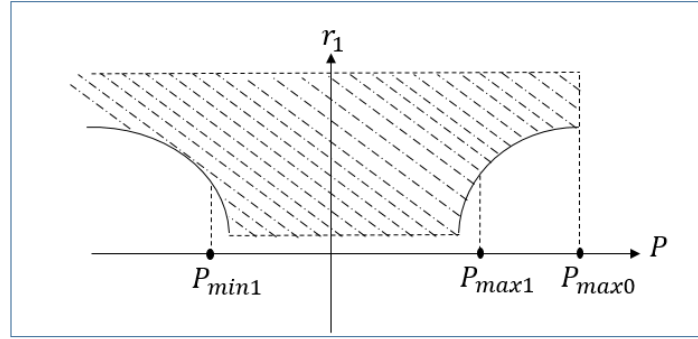


Fig. 2. Rectifier Feasibility Expansion by Changing Rectifier Output DC Voltage Reference.

	Max positive power	Max negative power	
$A \leq R_1 \leq R_2$	P_{max1}	inf	$P_{max} = \frac{u_3^2 + u_4^2}{8a_2}$ $P_{max1} = \frac{\frac{u_3^2 + u_4^2}{4a_2^2} - \left(\sqrt{\frac{u_3^2 + u_4^2}{4a_2^2}} - \sqrt{\frac{r_1^2}{a_2^2 + a_1^2 u_2^2}} \right)^2}{\frac{2}{a_2}}$ $P_{min1} = \frac{\frac{u_3^2 + u_4^2}{4a_2^2} - \left(\sqrt{\frac{u_3^2 + u_4^2}{4a_2^2}} + \sqrt{\frac{r_1^2}{a_2^2 + a_1^2 u_2^2}} \right)^2}{\frac{2}{a_2}}$
$A \leq R_2 \leq R_1$	P_{max}	P_{min1}	
$R_1 \leq A \leq R_2$	P_{max1}	inf	
$R_1 \leq R_2 \leq A$	P_{max1}	inf	
$R_2 \leq A \leq R_1$	P_{max1}	P_{min1}	
$R_2 \leq R_1 \leq A$	P_{max1}	P_{min1}	

Table. 1 Maximum Feasible Power for Different Operating Conditions of Rectifier

For power levels between “max power” and “min power”, r_1 is chosen such that the circles intersect (there always exists a minimum r_1 that guarantees feasibility in this interval). The dotted line in the figure that specifies the maximum allowable value for r_1 is based on SST rating. System equations are further analyzed to develop the node voltage constraints of an individual SST so that the feasibility can be maintained. This development is particularly important for multi-SST system where voltage constraints have to be satisfied considering the coupling effect.

When multiple SST systems are connected together, a power flow algorithm is required to find the input current (and input node voltage) of each SST. However, it should be assured that the commands developed by this algorithm would maintain the feasibility of the system, therefore, the power flow algorithm should consider the voltage constraints on each SST system developed for the single-SST system. In other words, in an n -SST distribution system, aside from the convergence of the power flow solution, there are “ n ” voltage constraints that should be satisfied. It should be noted that the solution of the power flow, i.e., the input voltages of each SST in the system is dependent on the net power of all the SSTs in the system (coupling effect of SST loads on their input voltage). Besides maintaining the voltage constraint, feasibility has to be maintained when there is a change in the load of any of the SSTs. Algorithms are then developed to guarantee feasibility of the whole system as the next step of research. Several algorithms can be developed to maintain the feasibility of the system when there is a change in the power of a SST. In this section, two different methods have been proposed to address the feasibility question above. Both of these methods are based on power sharing among neighboring SSTs.

a. Method 1 (Power Sharing with Constant Input Current)

In order to avoid the complexity of running power flow when there is a change in power of an SST, other SSTs can help the SST in need by reducing their net power while keeping their input current command the same as before. Net power of the neighboring SSTs has to satisfy the maximum power constraints with their updated input voltages. This would result in a second order polynomial as given in (5) relating the change of d -axis current of SST_i to the system parameters and its current operating point.

$$\left(a_2 + \sum_{k=1}^i R_k\right) \Delta x_{1i}^2 + \left\{2a_2 x_{1i} + u_{3i} + \sum_{k=1}^i R_k x_{1i} + \sum_{k=1}^i X_k x_{2i}\right\} \Delta x_{1i} + 2\Delta P_i = 0 \quad (5)$$

Therefore, based on the discriminant for this equation, the ΔP_{max} can be found as:

$$\Delta P_i \leq \frac{\{2a_2 x_{1i} + u_{3i} + \sum_{k=1}^i R_k x_{1i} + \sum_{k=1}^i X_k x_{2i}\}^2}{8(a_2 + \sum_{k=1}^i R_k)} \quad (6)$$

Updated SST input voltages should be such that the net power of each SST is less than its max capability, moreover, rectifier output DC voltage for each SST should be updated to guarantee feasibility for each individual SST.

b. Method 2 (Power Sharing with Constant Node Voltage)

If the change in power of an SST is such that method 1 cannot make the system feasible, an alternative approach can be used. In this method, with a change in power of SST_i , the input voltage of SST_j ($j \neq i$) will be kept constant by changing their input current commands which leads to the second order polynomial given in (6) relating the change of d -axis current of SST_i to the system parameters and its current operating point.

$$D_1 \Delta x_{1i}^2 (a_2 + D_1) + \Delta x_{1i} (2a_2 x_{1i} + u_{3i} + x_{1i} D_1 + x_{2i} E_1) + 2\Delta P_i = 0 \quad (7)$$

Therefore, based on the discriminant for this equation, the ΔP_{max} for method 2 can be found as follows:

$$\Delta P_i \leq \frac{(2a_2x_{1i} + u_{3i} + x_{1i}D_1 + x_{2i}E_1)^2}{8(a_2 + D_1)} \quad (8)$$

Since in this mode of operation, the input current of SSTs change to keep their input voltages constant (except for SST_i), the new operating current commands have to be calculated. With a change in SST_i power, the objective is to keep the input voltage of other SSTs constant, i.e., $\Delta V_m = 0$ ($m = 1:n, m \neq i$). This results in a change in the current of the other SSTs in the system which are governed by the following relationships:

$$\Delta I_j = 0 \quad (j \geq i + 2) \quad (9)$$

$$\Delta I_j = - \sum_{k=j+1}^{i+1} \Delta I_k \quad (j \leq i - 1) \quad (10)$$

$$\Delta I_{i+1} = - \frac{Z_i}{Z_i + Z_{i+1}} \Delta I_i \quad (11)$$

Typically, two main controller layers are associated with the FREEDM system. These layers are IPM (intelligent power management) and IEM (intelligent energy management). The IPM unit is responsible for regulating the input current of each SST system such that the system operates within feasible and stable regions. The IEM unit is responsible for providing set-points at fixed intervals (for example, every 20 minutes) based on the distributed renewable energy resources (DRER) and distributed energy storage devices (DESD) available in the system. These set-points are chosen based on weather forecast data, economic constraints, and feedback from power levels of energy cells in the system. However, the net power of energy cells at any instant of time may not match the predicted power from the IEM and the current that is flowing into the DC bus gets changed due to the change in power, and the input current reference of the SST (flowing from the grid) also needs to get adjusted according to that. The IPM controller has to match those excess or shortfall power requirements by updating the set-points of the system instantaneously. Therefore, the IPM needs to override the IEM command whenever no local control (such as droop control) can make the system work using its previous set-point. Load changes in a FREEDM system can be divided into three categories based on controller action, as shown in Fig. 3. Unpredicted load changes within a small noise band are considered *Case 0*. In this case, the system will continue running by using internal control methods like droop control or change in DESD output, and hence, no update in input reference commands of SST is needed. Unpredicted big changes in the system are considered *Case 1*. In this case, one of the two proposed power sharing methods will maintain the feasibility of the system. Predicted big changes in the load of the system are defined as *Case 2* where IEM will generate reference commands for the system that guarantee feasibility of the entire system. Simulation results of applying the two methods proposed earlier to a three SST system is studied. Fig. 4(a) shows the simulation results of applying method one to the three SST system. The top figures show the net power flowing through each SST and the bottom figures show the input voltage and current of

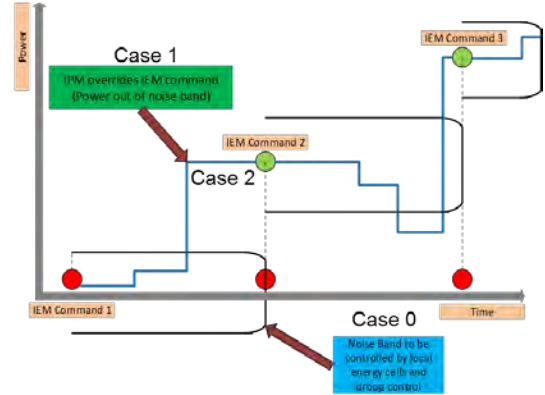


Fig. 3. Load change categories in a FREEDM system and IEM/IPM interaction.

each SST. As it can be seen, SST_2 and SST_3 have adjusted their input power by increasing their DESD usage to help keep the system feasible. Fig. 4(b) shows the simulation results of applying method two to the same system. As it can be seen in this case, the input currents of SSTs have changed but their input voltage has remained constant. Both of the methods have been successful in keeping the system feasible.

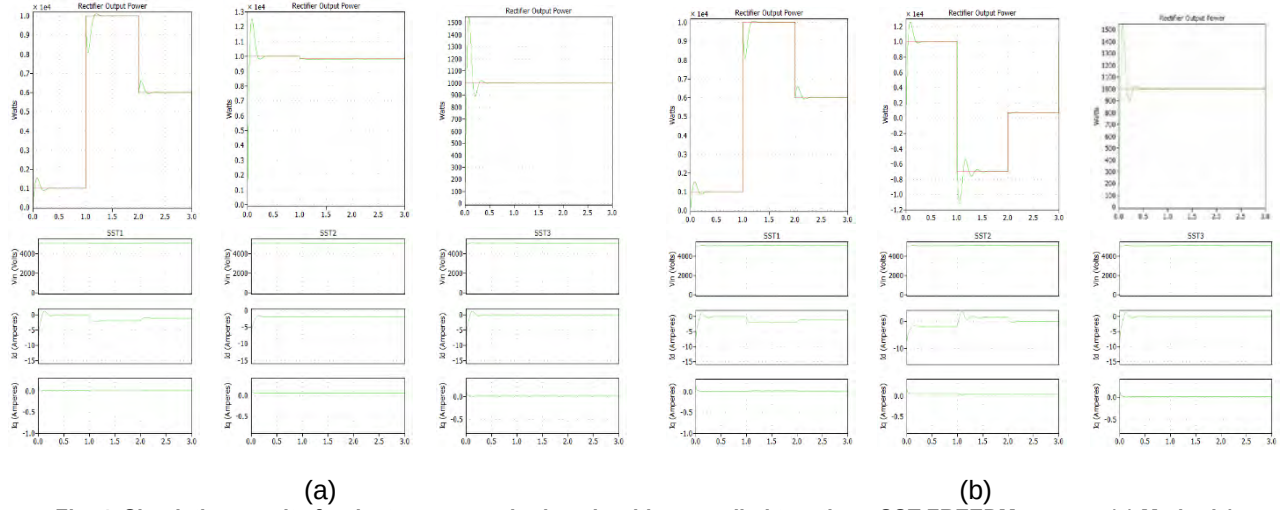


Fig. 4. Simulation results for the two power sharing algorithms applied to a three-SST FREEDM system: (a) Method 1: Constant Input Current (b) Method 2: Constant node voltage.

This research takes an SST as an example of the set-point based energy routers to derive its physical model, and then, utilize the model to identify the bounds that have been imposed by the non-linearity of this power transformer and its duty cycle constraints. The SST's front-end rectifier output voltage reference is found to be the deciding factor in extending the feasibility bounds of the system. Also, when multiple SST systems are connected in a tree configuration, power sharing algorithms are proposed to maintain the feasibility of the system when there is a change in the load of any of the SSTs. Control layers of FREEDM system have been analyzed (IEM and IPM) and their interaction based on different levels of load change in the system has been defined. The next step is to design robust controllers which would guarantee stability and good performance of the system with the changes in the loads in the system while maintaining all the constraints developed throughout this research.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

With respect to fundamental controls research outside the ERC, the activities are fairly limited to serve the needs to fulfill the FREEDM vision. There are activities in terms of power electronics controls of microgrid devices or at a much higher systems level such as in Professor Iravani's group at University of Toronto, Canada and Professor Gurrero's group at Aalborg University in Denmark. However, there is no activity for scaled systems with solid state transformer interfaced microgrids. This provides the FREEDM group a unique opportunity to make fundamental advances in distributed controls for power distribution systems.

6. Milestones and Deliverables

The deliverables from this SMC research task are:

- Comprehensive feasibility analysis of the FREEDM system
- Operational bounds for FREEDM system during various operating conditions.
- Droop curve of the rectifier output DC voltage
- Power sharing algorithms for multi-SST system in tree configuration
- IPM and IEM control functionalities based on feasibility study

7. Plans for Next Year and Five Years

The following activities are planned for the next three years in the SMC sub-thrust with respect to fundamental controls activities:

- Closed-Loop (Contextual) Model Development and Control Design
 - ✓ Implement the proposed power sharing methods with the development of IPM and IEM algorithms for power and energy routing among SSTs
 - ✓ Co-design for IPM and IEM functionalities based on feasibility and stability performance
 - ✓ Design robust non-linear control to maintain stability
 - ✓ Verify the proposed controller experimentally in HIL testbed

8. International Collaboration

The NCSU team collaborates with Prof. Romeo Ortega and his PhD student Daniele Zonetti in Centrale-Supelec, France. The controls team in Centrale-Supelec is conducting stability analysis using a port-Hamiltonian representation of the FREEDM system. Daniele spent a weeks in summer 2015, and communication continued between the two teams throughout Year 8.

9. References

- [1] D. G. Shah and M. L. Crow, "Stability Design Criteria for Distribution Systems With Solid-State Transformers," in *IEEE Transactions on Power Delivery*, vol. 29, no. 6, pp. 2588-2595, Dec. 2014.

Y8.FS2.2: Modeling and controller design for SST with plug and play features under high DG penetration

Team Members

Project Leader:	Dr. Iqbal Husain
Faculty:	Dr. Raja Ayyanar
Students:	Ziwei Yu, Yingying Tang

1. Project Goals

Develop suitable models of SST for different levels of stability studies and controller designs
Develop methods for simulation and validation of SSTs and high penetration of PV inverters in power systems analysis tools

2. Role in Support of Strategic Plan

Validated analytical and simulation models of SST suitable for different types of analytical, stability and performance studies are critical for several thrusts and testbeds in the FREEDM center. Methods for dynamic study of high penetration of inverters and SSTs in standard distribution analysis tools enable the development and verification of different control strategies.

3. Fundamental Research, Technological Barriers and Methodologies

Develop a detailed analytical model of the Gen-II SST being developed at FREEDM Center

- Develop differential and algebraic equations for both the power stage circuit and controllers implemented in the DSP
- Use average model for the power stage circuit due to the high switching frequency
- Represent the controllers as continuous domain state-space representations, use 2nd order Padé approximation for high order calculations.
- Validate model through time domain simulation comparing with detailed SST switching model

Develop simplified SST models suitable for system level studies and controller designs

- Study a small distribution system with detailed SST model and identify dominant and minor system behaviors
- Develop a complete analytical model for the studied distribution system, solve the time-varying working point problem existing in AC systems
- Study the time constants and weight of system modes based on eigenvalue analysis
- Develop reduced-order models of SST based on the results of previous steps
- Validate developed models through time-domain simulation

Implement user-defined model for PV inverters for dynamic study in OpenDSS

- Dynamic Linked Libraries (DLLs) are created for the user-defined models of the three-phase and single-phase PV inverters. Embarcadero Delphi has been used for the creation of DLLs.
- PV inverter filters, PV controller (current controller) and Phase-locked Loop (PLL) are written as state-space equations in the DLL.
- Initialization, integration, exporting and update steps are written in Object Pascal (Delphi) programming language, and used to interface DLL and OpenDSS during dynamic simulations

To study the time constants of the system modes introduced by the SST, a SST is modeled together with a 4-bus distribution system as shown in Figure 2. The detailed analytical model is derived for the system including the distribution network. To solve the problem of time varying steady-state working points when the system model is linearized, a DC type model of the system based on dq transformation is proposed. As shown in Figure 3, the dq frame model of the single-phase system is derived by applying the dq transformation on the $\alpha\beta$ frame model. The β phase model is derived based on a fictitious system where the state-space equations are duplicated from the real system, but with orthogonal system inputs.

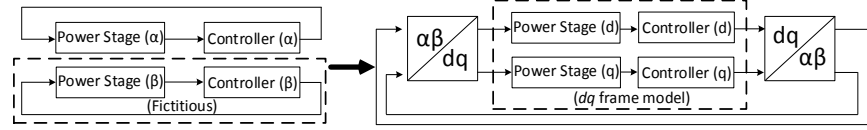


Fig. 3. Proposed DQ frame model by adding a fictitious system

The proposed model is validated through time domain simulation in PLECS. As shown in Figure 4, a step change is applied to the load attached to the SST low voltage AC terminal at 1s. The green curves are the results from the original stationary frame model, the red curves are the results from the derived dq frame model. The dq frame model results are DC quantities, corresponding sinusoidal results such as the current results in Figure 4, can be recovered based on the phase angle of the dq reference frame.

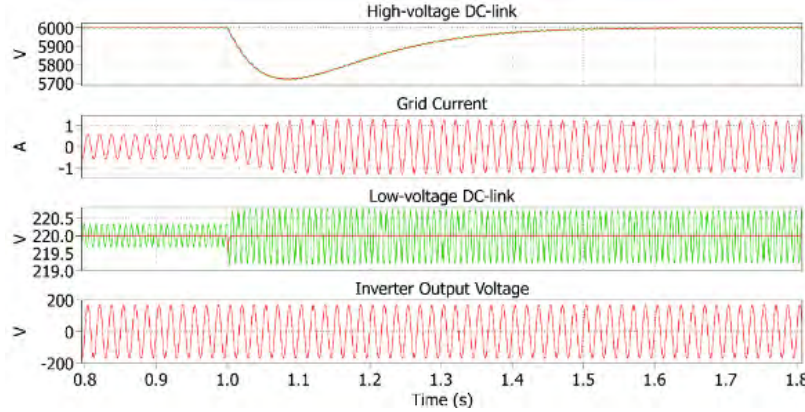


Fig. 4. Simulation validation of the proposed DQ frame model with the original stationary frame model

Eigenvalue analysis of the 4-bus distribution system

The linearized model of the 4-bus system is derived based on the proposed DC type model for eigenvalue analysis. The resulting A matrix has a size of 59 by 59 and its eigenvalue plot is shown in Figure 5. The eigenvalue sensitivity and participation factor are also calculated to identify the location of the sources of system modes in the circuit and controller. Table 1 shows the participation factor of each state corresponding to the eigenvalue $-7e8+j3.77e2$.

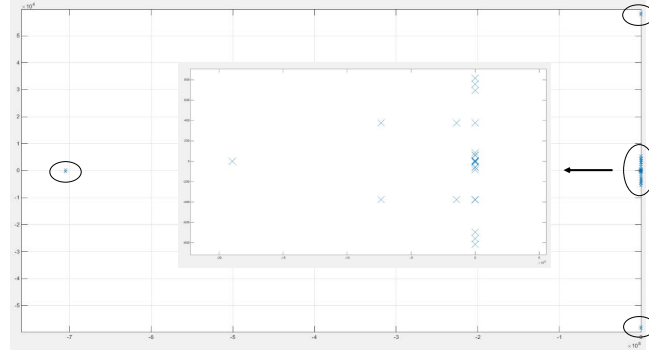


Fig. 5. Eigenvalue plot of the 4-bus system

State Index	Participation Factor	State Index	Participation Factor	State Index	Participation Factor
3 (i_{23d})	0.3605	1 (i_{12d})	0.122	6	0
4 (i_{23q})	0.3605	12 (i_{L1d})	0.0175	5	0
2 (i_{12q})	0.122	13 (i_{L1q})	0.0175	...	...

Table 1 Participation factors corresponding to one of the eigenvalues (-7e8+j3.77e2)

Dynamic study in OpenDSS with user-defined models for of PV inverters and SSTs

In order to extend the capability of OpenDSS that merely performs snapshot analysis and quasi-static analysis for PV inverters, Embarcadero Delphi is used to develop the Dynamic Linked Library (DLL) of the PV user-defined model for dynamic studies. Based on the dq transformation introduced in the last section, the analytical models of the PV inverter, including the filter, current controller and PLL are designed and written as state-space equations into the DLL. During the dynamic simulations, the written PV functions are implemented through the interaction between the DLL and OpenDSS. Figure 6 shows the interactions between the PV inverter DLL, and the network model in OpenDSS.

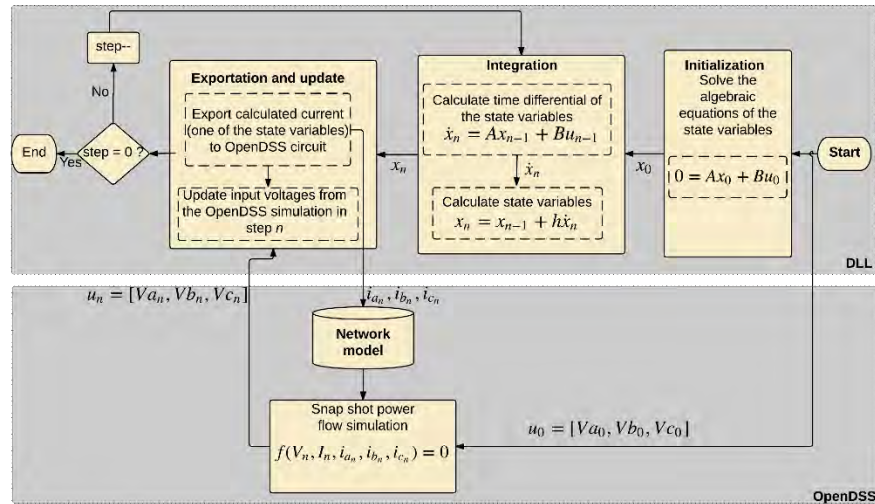


Fig. 6. Algorithm of interaction between the DLL and OpenDSS during dynamic study

The DLL for three-phase PV inverters as well as single-phase inverters have been created and verified with PLECS results first in a three-bus system. A positive-sequence PV inverter model is built in a separate DLL to illustrate the advantage of proposed PV modeling method. The use of DLL largely shortens the simulation time of the dynamic study, by solving the PV inverter model as differential equations, and the circuit without the PV inverters as algebraic equations. Figure 7 shows instantaneous currents from the PV models in OpenDSS simulation, as well as those obtained from the detailed simulation in PLECS. The PV output current obtained by using the proposed modeling method overlaps those obtained via detailed simulation in PLECS. In contrast, the output current waveforms are markedly different from the PLECS output when the positive-sequence PV model is used in OpenDSS, due to the balanced assumptions of the model.

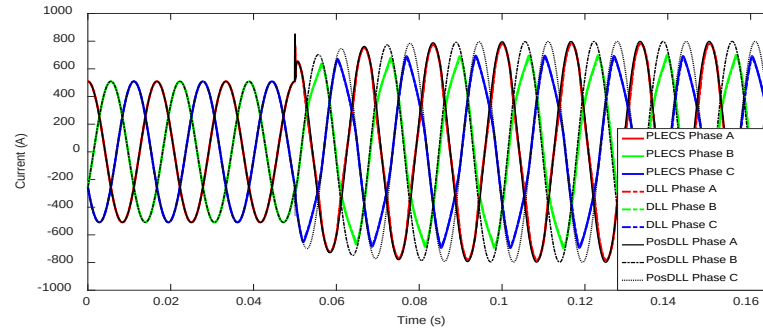


Fig. 7. Simulated PV inverter output current in PLECS, DLL, and positive sequence DLL for a single-phase fault

The IEEE 123-bus system has also been used to test the performance of the microgrid operation. Three PV systems are installed respectively at bus 1, bus 7 and bus 47. The ratings of the three CIGs are 525 kW respectively. The three PV units have the same droop settings. At 1 s, the breaker near the substation is opened. The real power supplied by the PV inverters is plotted in Figure 8 (b). Before the breaker opens, the three PV units are supplying power based on their ratings. After the breaker opens, the lost generation due to the lack of the main grid is picked up by the PV units based on the droop characteristics. With the selected droop coefficients and power ratings, the PVs share the total loads equally. This work is currently being extended to include to develop a DLL of detailed SSTs and to study large-scale distribution systems with multiple SSTs.

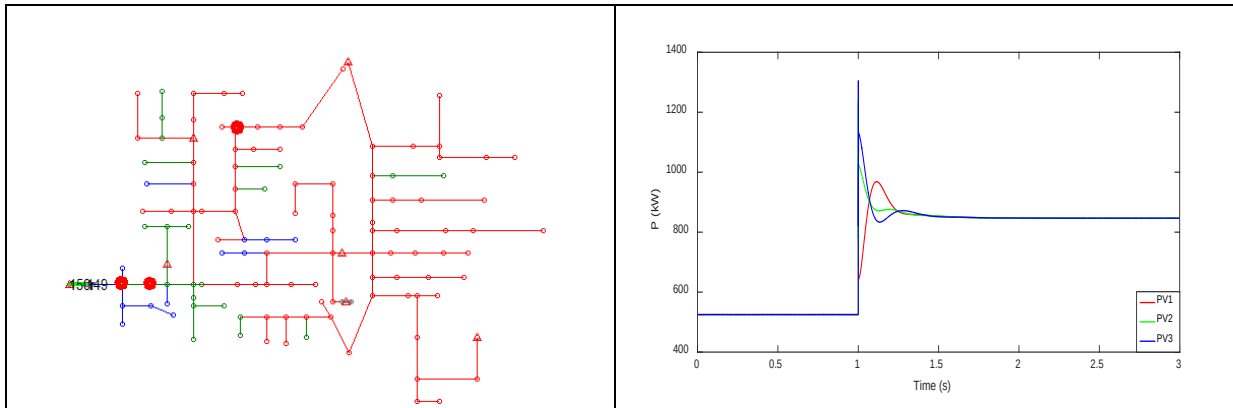


Fig. 8. (a) Locations of the PV units in 123-bus test feeder (b) Active power outputs from the three PVs before and after islanding in the 123-bus microgrid

5. Other Relevant Work Being Conducted Within and Outside of the ERC

Other relevant work includes modeling and analysis of three-phase inverter based microgrids. Analytical models have been derived, and particular oscillatory modes introduced by the network circuit and inverter controls are established through eigenvalue analysis. In terms of dynamic study of large power systems, three-phase unbalanced dynamic models of synchronous machines have been built in GridLAB-D. The dynamic models were validated and studied in microgrids.

6. Milestones and Deliverables

Q3 (9/30/2015) – Development of large scale distribution system model in OpenDSS with high DG penetration

Q4 (12/31/2015) – Complete development of robust controller suitable for high DG operation and complete specifics of plug and play features (taken up as part of SST sub-thrust)

Q1 (3/31/2016) – Complete validation of SST model with Gen-II and Gen-III SST hardware results; complete validation of robust controllers in DAE and phasor domain analysis for several use cases

Q2 (6/30/2016) –Complete modeling of non-FREEDM smart distribution devices and include in the OpenDSS base model

7. Plans for Next Five Years

1. Support Green Energy Hub testbed demonstration through detailed SST models, robust controllers and plug & play design
2. Inputs to the development of FREEDM Architecture
3. Validation of robust control concepts and developed FREEDM Architecture in dynamic simulations of large-scale distribution systems

8. Member Company Benefits: Access to validated analytical models and methods for dynamic study of large scale power systems with high penetration of smart PV inverters and SSTs.

9. References

- [1] Ziwei Yu, R. Ayyanar, I. Husain, "A detailed analytical model of solid state transformer," Energy Conversion Congress and Exposition (ECCE), 2015 IEEE, pp. 723-729, Sept. 2015

Y8.FS2.3: Distributed Model Predictive Control based for Intelligent Energy Management of the FREEDM System

Team Members

Project Leader:	Dr. Chris S. Edrington
Students:	Sanaz Paran, Farzad Ferdowsi
Staff:	Dr. Touria El-Mezyani

1. Project Goals

Power scheduling of multiple storage devices and renewable energy resources in microgrids is crucial for reliable and optimal operation. Conventionally, this problem has been solved with a centralized methodology which has access to all the information. This type of controller has limitations in computation and communication. The primary objective of this research is to manage the energy from the energy management layer via distributed model predictive controllers to reduce the operational cost of AC microgrids. This allows for optimal power reference signals to be generated for all energy resources based on the system's demand, constraints, and objective function.

Model predictive control (MPC) is applied for the purpose of optimal distributed energy management since it allows the control action (output) in the current time-step to be optimized while taking into account the future time-steps. With the proposed distributed energy management controllers, the computation and communication burdens are reduced in comparison to a centralized controller. The proposed distributed method is validated for a candidate FREEDM system via MATLAB simulation.

2. Role in Support of Strategic Plan

This work supports the strategic plan set forth by FREEDM by addressing the systems level control of a FREEDM system. FREEDM systems, characterized by cyber-physical systems enabled via a high penetration of power electronics devices can take advantage of the advanced distributed control this work proposes to provide optimal energy resource allocation.

3. Fundamental Research, Technological Barriers and Methodologies

The proposed MPC-based IEM design of the FREEDM system is composed of three components:

- A model of the system. The DESD model is used to predict the future evolution of the state of charge (SOC). Other models are also considered such as DRER and load.
- A performance index over a finite horizon. The operational cost is minimized subject to constraints imposed by the system model, restrictions on control inputs and system state at each sampling time to obtain a trajectory of future power references.
- A receding horizon scheme. This scheme introduces the notion of feedback into the control system to compensate for disturbances and modeling errors.

The distributed control architecture is specified for a candidate two-node system, in which two SSTs are interconnected in the high AC voltage side. The architecture is shown in Figure 1 representing the distributed IEM scheme, where each IEM communicates with other IEMs to exchange the DESDs energy information. Historical data, physical system constraints, and market information are received

from a supervisory control and data acquisition (SCADA) system. Based on this information and the objective function, the optimization problem is formulated for an IEM by considering the system performance, load demand, and possible economic performance. The optimization problem is solved to maintain the global objectives, which are the energy demand and economic benefits. The solution of the optimization problem is the required power commands sent to the intelligent power management (IPM), which performs the power control tasks such as current control and voltage control on each SST.

In Figure 2, the FREEDM system is described with DRER, DESD, load, utility (grid), and energy market. Two SSTs are controlled with MPCs which exchange information about the DESD state. In the following, energy and power flows between devices in each SST node are defined in order to describe all of the possible information: E_{BL}, P_{BL} : energy, power from DESD to load; E_{RB}, P_{RB} : energy, power from DRER to DESD; E_{GB}, P_{GB} : energy, power from grid to DESD; E_{GL}, P_{GL} : energy, power from grid to load; E_{RG}, P_{RG} : energy, power from DRER to grid; E_{RL}, P_{RL} : energy, power from DRER to load.

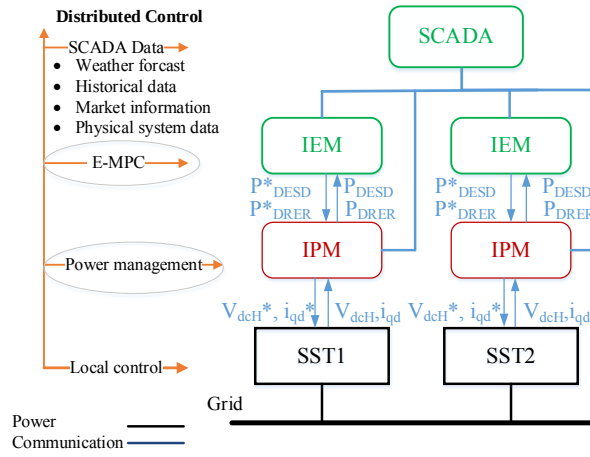


Fig. 1. Distributed IEM for a two – node system

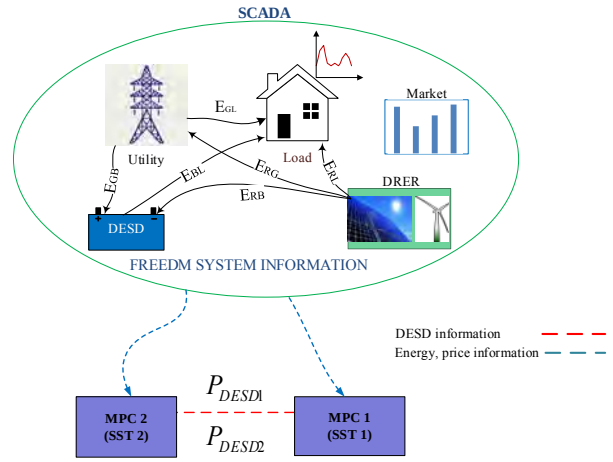


Fig. 2. Distributed MPC architecture for the FREEDM system

The general formula for defining the energy vector is represented in (1). The neighbors of a node i are presented with j , $j \in N, j \neq i$, and N is the number of SST nodes. In the proposed formulation, the power references (controller outputs) in the two-node system are calculated using the information obtained from the IEMs. The principal input information are defined by energy vectors as shown in (2) and (3). Equation (2) defines energy of node 1 and the possible energy exchange from node 2 to node 1. Equation (3) demonstrates energy of node 2 and the possible energy exchange from node 1 to node 2.

The discrete-time state space models of energy storage of nodes 1 and 2 are formulated in (4) and (5) based on the definition of the energy variables $U_{k1,2}$ and the initial energy ($x_{DESD,k}$). The energy of loads and DRERs are defined in (6) to (9). B_{Load1} and B_{Load2} are the analytical models of $Load_1$ and $Load_2$ which are connected to SST_1 and SST_2 , respectively. B_{DRER1} and B_{DRER2} are the analytical models of $DRER_1$ and $DRER_2$, respectively. The DRER consists of E_{RB} (charging the DESD), E_{RL} (supplying the load), and E_{RG} (sending and selling energy back to the grid).

$$U_{ki} = [E_{GiBi} \ E_{RiBi} \ E_{BiLi} \ E_{GiLi} \ E_{RiLi} \ E_{RiGi} \ E_{GjBi} \ E_{RjBi} \ E_{BjLi} \ E_{GjLi} \ E_{RjLi} \ E_{RjGi}]$$

$$i \in N \ j \in N \text{ and } j \neq i \quad (1)$$

$$U_{k1} = [E_{G1B1} \ E_{R1B1} \ E_{B1L1} \ E_{G1L1} \ E_{R1L1} \ E_{R1G1} \ E_{G2B1} \ E_{R2B1} \ E_{B2L1} \ E_{G2L1} \ E_{R2L1} \ E_{R2G1}] \quad (2)$$

$$U_{k2} = [E_{G2B2} \ E_{R2B2} \ E_{B2L2} \ E_{G2L2} \ E_{R2L2} \ E_{R2G2} \ E_{G1B2} \ E_{R1B2} \ E_{B1L2} \ E_{G1L2} \ E_{R1L2} \ E_{R1G2}] \quad (3)$$

$$x_{DESD1,k+1} = x_{DESD1,k} +$$

$$[1 \ 1 \ -1 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]^T U_{k1} = x_{DESD1,k} + B_{DESD1} U_{k1} \quad (4)$$

$$x_{DESD2,k+1} = x_{DESD2,k} +$$

$$[0 \ 1 \ -1 \ 0 \ 0 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]^T U_{k2} = x_{DESD2,k} + B_{DESD2} U_{k2} \quad (5)$$

$$E_{Load1,k} = [0 \ 0 \ 1 \ 1 \ 1 \ 0 \ 0 \ 0 \ 1 \ 0 \ 1 \ 0]^T U_{k1} = B_{Load1} U_{k1} \quad (6)$$

$$E_{Load2,k} = [0 \ 0 \ 1 \ 0 \ 1 \ 0 \ 0 \ 0 \ 1 \ 1 \ 1 \ 0]^T U_{k2} = B_{Load2} U_{k2} \quad (7)$$

$$E_{DRER1,k} = [0 \ 1 \ 0 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T U_{k1} = B_{DRER1} U_{k1} \quad (8)$$

$$E_{DRER2,k} = [0 \ 1 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T U_{k2} = B_{DRER2} U_{k2} \quad (9)$$

The proposed approach is validated for a microgrid configuration which consists of two SSTs. Each SST includes a storage device (DESD), a DRER (PV), and a load. The physical system constraints, energy market information, and DRER data are obtained from SCADA. The MPC-based IEM controllers receive this information along with the other information such as DESD energy and load energy requirement (E_{DESD}, E_{load}). The objective of the distributed IEM is that the devices collaboratively coordinate with each other and find the optimal power schedules for the next 12 hours (N_p). Therefore, the MPC controllers are solved and generate the power references for the DESD and DRER ($P_{DESD1,2}^*, P_{DRER1,2}^*$) which are sent to the IPM controllers. MPC_1 and MPC_2 exchange the information about the DESD energy. The outputs of the IPM are d - q axis reference currents (I_q^*, I_d^*), which are sent to the SST local controllers. Several parameters of the system are depicted in Table I. The sampling time of the SCADA data sent to the IEM is one hour. However, the real-time optimization takes much less time (58.9 s for 4096 iterations) to generate the power references (outputs of the MPC) for the IPM layer. The solution to the optimal control problem is found in an iterative optimization procedure.

The online data for the load, DRER profiles, and online energy market price are shown in Figure 3 and Figure 4, respectively. Figure 5 represents the power schedule for $DESD_1$ and $DESD_2$ (outputs of the MPC algorithm) that include the power from $DESD$ to loads ($Load_{1,2}$), DRERs ($DRER_{1,2}$) to $DESD$, and grid to $DESD$. When P_{B1} (in Figure 5) is positive the DESD is charging, and when P_{B1} is negative, the DESD is discharging based on the minimization of the cost function. When the price is high (time steps 7 to 9), DESD discharges to the maximum value to support the demand and avoid high operational cost. The IEM purposes for SSTs are the power balance between generation ($DRER_{1,2}$, $DESD_{1,2}$, and grid) and consumption ($Load_{1,2}$) and also minimization of the power flow from the grid.

Parameters	Value
Prediction horizon	12
Sample Time	1 h
Lower Bound	[-10; 0; 0; 0; 0; 0; -10; 0; 0; 0; 0; 0] kWh
Upper Bound	[10; 10; 10; 10; 20; 20; 10; 10; 10; 10; 20; 20] kWh
Minimum SOC	2 kWh
Maximum SOC	40 kWh
w_1	0.6
w_2	0.4

Table I. Parameters Initialization

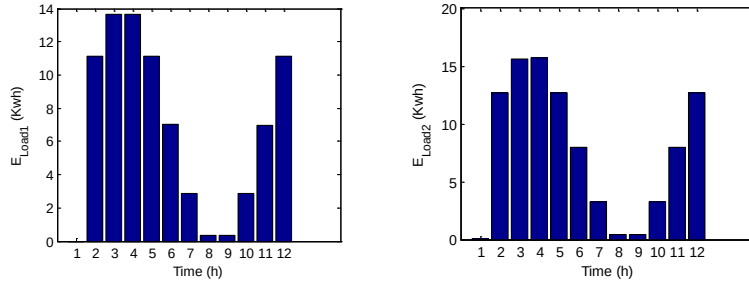


Fig. 3. Load profile

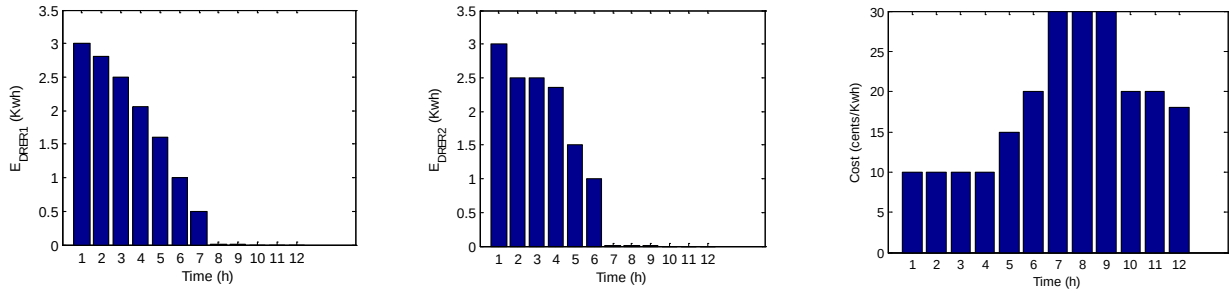


Fig. 4. DRER profiles and energy market price (c_k)

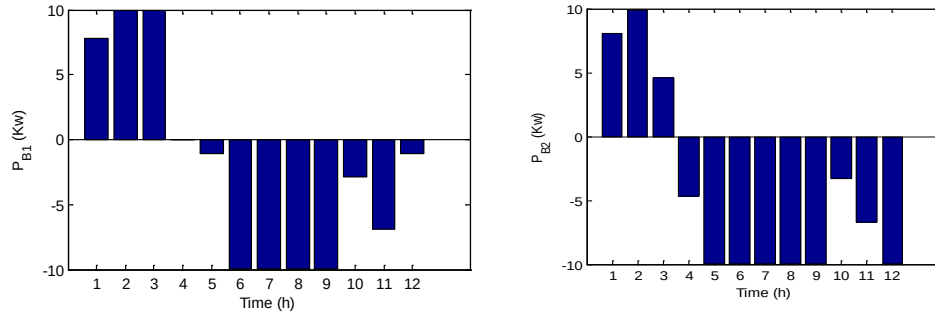


Fig. 5. The power schedules for DESD₁ and DESD₂

4. Achievements

In this work, the application of control technologies and practices to improve reliability, efficiency, and security of the smart grid are investigated. We applied the model predictive control method to the IEM layer of the FREEDM system in order to dynamically optimize the power references and operational cost. The optimal power reference signals are generated for all energy resources based on the system's interest. The main advantages of the proposed distributed IEM are as follow:

- The integration of sensing, communications, and control technologies with distributed devices in smart grids improves reliability and efficiency.
- Implementation of the MPC controllers in the IEM level is a new method which is applied to the FREEDM system.
- The computation and communication burden are reduced from the control center.
- The computation time for the distributed method is faster than the centralized method.

There is some future work that can be done in this area such as:

- The usage of game theory is an appealing candidate for implementing a distributed communication in the future work.
- The line losses can be considered as one of the physical constraints of the system.
- Infrastructure cost is another objective function that can be considered in the smart grids.
- Uncertainties in system parameters such as the load demand and the renewable generation forecast can be considered.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

The group led by Dr. Edrington at Florida State University is addressing via MPC-based energy and power management, controls for all electric ship systems with a high penetration of advanced weaponry and sensors in a DC grid structure.

6. Milestones and Deliverables

- **Oct. 2015** – Defined the IEM control architecture and constraints for the FREEDM system, and formulated the distributed MPC scheme
- **Dec. 2015** – Completed all modeling and subsequent instantiation of multiple nodes system (GEH target candidate)
- **Feb. 2016** – Investigate the IEM controller in a real-time environment by utilizing NI myRIO and identify related communications issues
- **May 2016** – Apply the controller in the IEM level to a candidate cyber-physical system (GEH) in coordination with the SMC group

7. Plans for Next Five Years

The plans over the next 5 years are to bring the research to a level where it is commercially viable and deployable for future microgrid applications. The algorithms developed by Florida State University have been disclosed to the university with intent to file a patent application.

8. Member Company Benefits

Companies who have interest will be able to license the technology. This cutting edge research will yield advantages to companies who develop controls and/or power systems in that it should provide for a more resilient and optimal power system.

9. Major references

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Y8.FS2.4: Real Time Stability Analysis Utilizing Nonlinear Time Series Analysis and Embedding Phase Space Techniques

Team Members

Project Leader:	Dr. Iqbal Husain
Faculty:	Dr. Chris S. Edrington
Students:	Farzad Ferdowsi, Sanaz Paran
Staff:	Dr. Touria El-mezyani

1. Project Goals

Recently, power electronic devices provide excellent features in contemporary distribution networks such as load regulation and power factor adjustment. On the other hand, these devices exhibit non-linear characteristics due to the semiconductor devices along with non-linear control loops. Therefore, current distribution networks are more prone to instability issues. In different sets of literature, well-known linear based tools are widely utilized to assess stability in power systems. These methods can only be applied to linear systems; therefore, non-linear systems have to be linearized prior to utilizing linear-based techniques. The main disadvantage of this process is missing the information related to the non-linear behavior when the non-linear model is linearized. As a result, inaccurate information might be extracted.

In this study, a non-linear technique which is based on non-linear time-series analysis is utilized to assess the stability, it can also be utilized in real-time applications. Technically, time-series data sets are extracted from terminal measurements which can be voltage, current or power. By embedding the extracted data into the phase-space construction, the system's behavior can be visualized which makes a useful understanding of the system's dynamical characteristics.

By utilizing a complexity metric, the complexity of the dynamic behavior of the system can be quantified which helps in detecting deviations from the normal behavior. As the complexity based approach is highly dependent on data characteristics, selecting optimum parameters associated with the complexity technique is discussed in this study.

Since the quantification of the complexity does not provide any information about the stability directly, the Lyapunov exponents are employed as a non-linear criterion for the stability assessment. Lyapunov exponents determine the system's sensitivity to initial conditions. In this study, the real-time stability assessment will be conducted in two sequential steps: (i) computation of complexity metric to evaluate the complexity of information and the dynamic changes of the system's behavior due to instability, faults, and disturbances, (ii) computation of Lyapunov metric to check if the change in the system's behavior is related to instability problems. The second step is initiated when a deviation from the regular behavior is detected by the complexity metric. In order to validate the proposed technique, a single phase solid state transformer which is used in distribution systems is analyzed as a case study. Results show that the proposed technique is able to determine the level of stability while the system is working. The project goals are summarized below:

- Visualization of the System's dynamic behavior
- Developing a metric to represent the system's irregularity

- Quantification of the system's complexity
- Real time stability evaluation utilizing Lyapunov exponents

2. Role in Support of Strategic Plan

The research in this work being led by Dr. Edrington at Florida State University paves the way for a more resilient and reliable FREEDM system, which directly supports the mission and goals of FREEDM. This effort, addresses the fundamental work of utilizing non-linear tools to address a non-linear power system in-situ via development of algorithms that provide this assessment in real-time.

3. Fundamental Research, Technological Barriers and Methodologies

3.1. Quantification of system's dynamic utilizing the approximate entropy metric

In order to quantify the system's complexity, the approximate entropy as a general metric is first developed in real time representing the irregularities in the system. The approximate entropy represents a logarithmic likelihood that two points that are close within a distance r in an m -dimensional space remain close in an $m+1$ dimensional space. Considering a specific time resolution, one can create a set of data by taking samples of a signal. In the next step, embedded vectors have to be derived from each window.

Afterward, points which are close enough in the phase space have to be detected based on the filtering level r . Based on the definition of entropy, the logarithmic likelihood has to be calculated for a data set which is embedded into an m -dimensional phase space. In the last step, one needs to calculate the distance between the same points when they are embedded into a phase-space with a higher dimension. Then the approximate entropy is determined.

The complexity in this study is computed utilizing the entropy profile by considering both order and disorder in the system. The entropy represents the disorder. Obviously, the system is not all disordered. Therefore, both order and disorder have to be considered. Therefore, the complexity is defined as the product of disorder (entropy) and order ($1 - \text{entropy}$).

3.2. Stability Assessment utilizing Lyapunov Exponents

Lyapunov exponents quantify the average exponential separation between phase space trajectories which are close to each other. In other words, it quantifies the sensitivity of the system to the initial condition. Let δX_0 denote the initial separation between two points in the phase space. Quantitatively, two trajectories diverge at a rate given by equation (7) where λ shows the Lyapunov exponent. Both δX_0 and $\delta X(t)$ represents the Euclidean distances between the points in the phase space.

$$|\delta X(t)| = e^{\lambda t} |\delta X_0| \quad (7)$$

Figure 1 illustrates the evolution of an m -dimensional system in real time. As discussed earlier, what has to be calculated is the divergence from the reference trajectory when initial points with an infinitesimally small distance from the reference point are evolved.

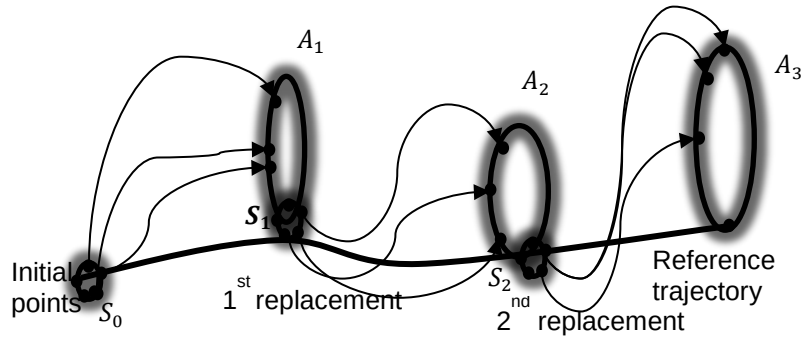


Fig. 1. Schematic evolution of an m-dimensional system

4. Achievements

A single phase SST is considered as the case study implemented in MATLAB/SIMULINK. There might be various disturbances when the system is operating, which can make the system unstable. From the practicality point of view, changes in the load play an important role in the non-linear dynamics in the system. In this study, some scenarios are studied to assess the stability of the system utilizing only data sets collected from the terminal measurement (voltage/current).

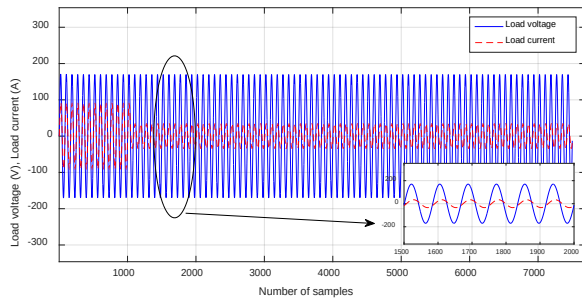


Fig. 2. Load voltage and current waveforms in the normal loading condition

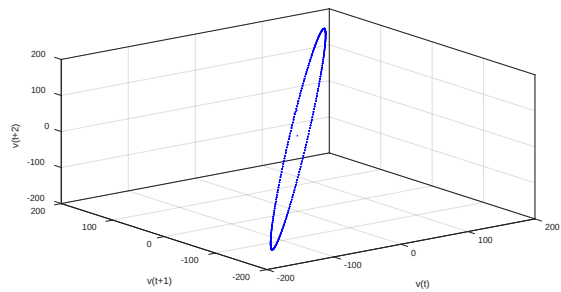


Fig. 3. Phase space portrait of the load voltage

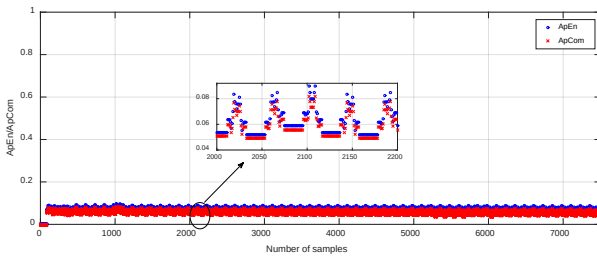


Fig. 4. Real-time approximate entropy and complexity in the load voltage

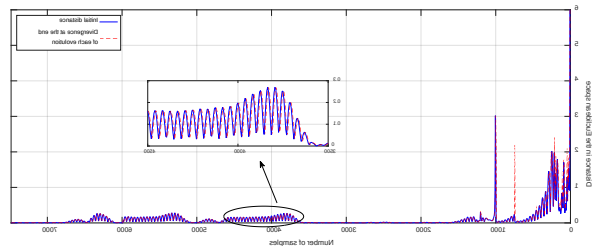


Fig. 5. Fiducial and diverged trajectories for the load voltage in the normal loading condition

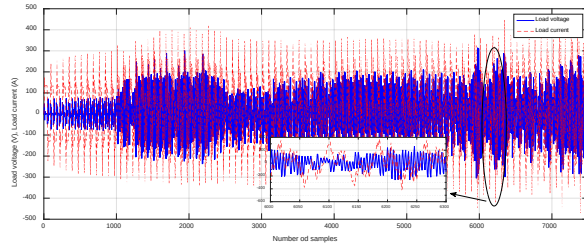


Fig. 6. Load voltage and current waveforms in the high loading condition

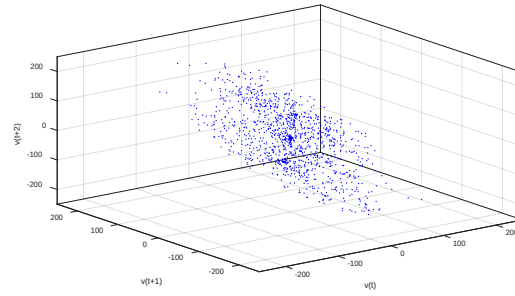


Fig. 7. Phase space portrait of the load voltage

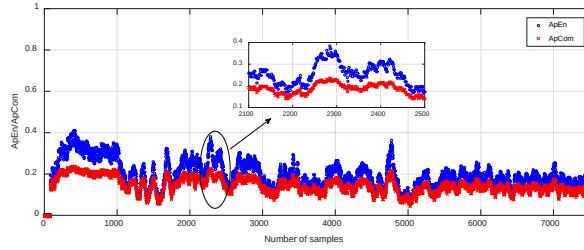


Fig. 8. Real-time approximate entropy and complexity in the load voltage

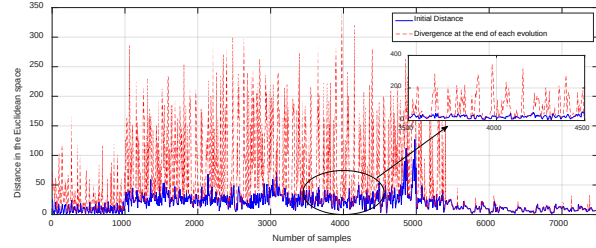


Fig. 9. Fiducial and diverged trajectories for the load voltage in the high loading condition

4.1. Normal loading condition

In the first scenario, the system operates in the normal condition. The load is considered as an R-L load with $R= 4.45 \, \Omega$ and $L= 5.81 \, mH$. The voltage and current profiles at the load side are shown in Fig. 2. It should be noted that the first 0.3 seconds has to be disregarded due to the high voltage side startup transient. As shown in the figure, the voltage and current profiles are in sinusoidal form and the controller has been able to keep the voltage regulated at 120 V rms.

Fig. 3 illustrates the 3-dimensional phase space portrait of the system's voltage. In fact, phase space portraits describe the system's behavior by visualization. In order to detect the irregularity in the load voltage, ApEn and ApCom profiles are calculated. Real-time approximate entropy and complexity in the load voltage are both depicted in Fig. 4. As shown in the figure, neither ApEn nor ApCom change considerably with the time. In addition, the amount of ApEn/ApCom provides a clear understanding of the level of irregularity in the system especially when compared with other scenarios.

In order to calculate the maximal Lyapunov exponent in real time one needs to obtain the divergence between trajectories initiated from nearby points for a specific amount of evolution and then repeat the procedure with the new replacement of initial points. This approach allows the application of real-time analysis in the stability assessment. Fig. 5 indicates the two trajectories (i.e. fiducial and diverged trajectories) for the normal loading condition. As Shown in the figure, the deviation in the initial points has not led to a considerable divergence between trajectories.

4.2. High loading condition

In the second scenario, the R-L load connected to the low voltage side AC decreased to $R= 0.015 \, \Omega$ and $L= 0.27 \, mH$. The number of samples and the sampling time are the same as the normal case to make a reasonable comparison. Results are shown in Figures 6-9.

5. Other Relevant Work Being Conducted Within and Outside of the ERC

We have related work in advanced controls for maritime systems as well as FREEDM systems.

6. Milestones and Deliverables

- Oct. 2015 – A rudimentary stage of mathematical development of the stability metric.
- Dec. 2015 – Apply the developed stability metric to the real-time stability analysis of a single SST and coupled SST systems under different loading conditions.
- Feb. 2016 – Investigate the uses of the stability information and the dynamic changes of the system in different operating modes (plug-and-play conditions) as feedback information to the control of dynamic changes in the system.
- May 2016 – Extend the proposed stability method for the system at the component level to a higher level, which is the system stability.

7. Plans for Next Five Years

This work has been disclosed to Florida State University. The plan is to work to make this work more commercially viable so that it is integrated holistically into the overall power and energy management of microgrid structures.

8. Member Company Benefits

Member companies who invest in the effort will be able to license the capability that Florida State University is developing, placing them at the forefront of resilient and adaptive microgrid control.

9. Major references

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Y8.FS2.5: Modeling, analysis and control of distribution networks based on solid-state transformers

Thrust: System Theory Modeling and Controls

Project leader: Dr. Romeo Ortega (L2S Centrale Supélec)

Faculty: Dr. Iqbal Husain (NCSU).

Students: Daniele Zonetti, Rafael Cisneros Montoya (L2S Centrale-Supélec).

1 Project goals & Role in support of the strategic plan

The main objective of this project is to face with the challenges and the open questions related to the operation of the FREEDM system, as defined in [4]. In particular, the implications of the introduction of solid-state transformers (SSTs) in substitution of conventional transformers in the existing distribution networks are investigated. Based on this analysis, the project moves around two fundamental guidelines:

- revisit and question usefulness and validity of system's architectures and control strategies—which are usually employed in traditional distribution networks—in the expected scenario, where some, if not all, conventional transformers are replaced by SSTs. The underlying objective is to determine, if any, their intrinsic limitations, as well as possible scope for their improvement.
- based on advanced methods in nonlinear systems and control theory, investigate alternative system architectures and control strategies for the system. With the intention to bridge the gap between theory and practice, one of the main concerns is to establish connections between existing engineering solutions, usually derived via ad hoc considerations, and the solutions stemming from theoretical analysis.

Major efforts are focused on a rigorous, mathematically-founded, stability analysis and control design for the elements composing the FREEDM system, which shed some light on the unstable behaviors recently observed in simulations [7]. Fundamental research is developed around three fundamental axes, which are described in the next section.

2 Fundamental research, barriers and methodologies

2.1 Analysis of vector control & passivity-based control design of SSTs

For the modeling of the single SST we refer to the averaged model introduced in [6], where a multiple dq representation, is employed. The HV side is expressed in a frame rotating at frequency ω_h , while the LV side is expressed in a frame rotating at frequency ω_ℓ . The model of the SST is thus given by:

$$\begin{aligned} L_h \mathbb{I}_2 \dot{i}_h &= (J_2 L_h \omega_h - R_h \mathbb{I}_2) i_h - v_{Ch} \cdot d_h + v_H, & C_\ell \mathbb{I}_2 \dot{v}_{C\ell} &= i_\ell \cdot d_\ell - G_\ell v_{C\ell} + v_{Ch} \cdot d_0 - i_C \\ L_\ell \mathbb{I}_2 \dot{i}_\ell &= (J_2 L_\ell \omega_\ell - R_\ell \mathbb{I}_2) i_\ell - v_{C\ell} \cdot d_\ell + v_L, & C_h \mathbb{I}_2 \dot{v}_{Ch} &= i_h \cdot d_h - G_h v_{Ch} - v_{C\ell} \cdot d_0, \end{aligned} \quad (2.1)$$

see also Fig. 1, for the physical notation. Since switched electronic devices usually operate at a time-scale much faster than the attached subsystems, it is common to assume that the rates of change of the bus voltages v_H, v_L and of the dc current i_C are extremely slow, from which follows that they can be considered constant. Note that this is possible only for analysis and design of the local (faster, inner) control of the SST, while for higher level of control, like primary control, the assumption is not valid anymore. An SST can be intended as the interconnection of two voltage source converters (VSCs), at their dc side, via an ideal controllable gyrator, see [2]. Hence, it may be questioned if the methods employed for the inner control of VSCs, suitably adapted, can be used for SSTs. A widely diffused control strategy for VSC is vector current control, which is based on an appropriate combination of feedback linearization methods and PI control with respect to the current variables, see [3] for an overview. The controller, adapted to an SST, can be written:

$$\begin{aligned} d_h &= \frac{1}{v_{Ch}} \left[J_2 L_h \omega_h + K_{h,P} y_h + K_h \int y_h(t) dt \right], & d_\ell &= \frac{1}{v_{C\ell}} \left[J_2 L_\ell \omega_\ell + K_{\ell,P} y_\ell + K_\ell \int y_\ell(t) dt \right], \\ d_0 &= \frac{1}{v_{C\ell}} \left[K_{0,P} \tilde{y}_0 + K_0 \int y_0(t) dt \right], & y_h &:= i_h - i_h^*, \quad y_\ell := i_\ell - i_\ell^*, \quad y_0 := v_{C\ell} - v_{C\ell}^*. \end{aligned} \quad (2.2)$$

The controller, whereas stability is guaranteed, allows to track the desired HV and LV currents as well as the desired dc voltage at the LV side. Because of the division by $v_{Ch}, v_{C\ell}$, it is obvious that using this controller implies that the system (2.1) is feedback linearized with respect to the currents and to the dc voltage at the LV side, which are next driven to their setpoints $i_h^*, i_\ell^*, v_{C\ell}^*$ by simple PI controllers. Moreover, HV current setpoints are determined by an outer controller in order to achieve constant active and reactive power profiles. However, nothing is said about convergence of the dc voltage to a stable operating point on the HV side. In [7] the case of a simple vector-controlled VSC was investigated. Using the notion of zero dynamics, it was shown that cranking up the controller gains yield an unstable behavior of the uncontrolled variable. Since the controller (2.2) is based on the same control strategy, it may be questioned if the same problem arises. Hence, we perform the same analysis, which leads to the following proposition and corollary. The mathematical proof, here omitted for lack of space, is similar to the one given in [9], while corollary follows by Theorem X in [5]. Both will be provided in a future journal publication.

Proposition 2.1. *Consider the system (2.1), together with the output $y := \text{col}(y_h, y_\ell, y_0)$, which is the output employed by the controller (2.2). Then the associated zero dynamics is locally asymptotically stable and its trajectories are bounded.*

Corollary 2.2. *Consider the system (2.1), in closed-loop with the controller (2.2). Then the system is locally asymptotically stable and trajectories are bounded.*

It is proved that vector control ensures local asymptotic stability and boundedness of trajectories of the closed-loop system because the same properties hold for the correspondent zero dynamics. Interestingly, it can be shown that stability is ensured by the control of the dc voltage at the LV side of the SST. If this control action is removed, as for the case of standard VSC, the associated zero dynamics is not stable anymore. This fact shows the great benefits of the SST enhanced controllability which, through the additional control of the dc voltage, enables the system to operate safely, in contrast with the alternative AC/DC/AC architectures. Unfortunately, the analysis of the zero dynamics shows that, although local stability is ensured, smallest eigenvalues are placed very near the real positive axes. Hence it is expected that vector control is limited in performances. Motivated by these performance limitations, we next propose an alternative design for the inner-loop control, which exploit the passivity properties of the SST. For sake of brevity, we only provide a brief sketch of the procedure for deriving the controller. The interested reader is referred to [9], where a similar procedure is applied to VSC, for more details. The rigorous mathematical proof for the specific case of the STT will be instead reported in a future journal publication (see Section 3). For the design, it is first shown that the system (2.1) can be rewritten in the following compact (nearly port-Hamiltonian) form:

$$Q\dot{x} = (J_0 - R)x + \sum_i J_i x d_i + B\bar{u}, \quad (2.3)$$

where: $x := \text{col}(i_h, v_{Ch}, v_{C\ell}, i_\ell) \in \mathbb{R}^5$ is the state, $d := \text{col}(d_i) \in \mathbb{R}^5$ is the duty ratio vector, $\bar{u}$ is the constant voltage sources vector, Q, R are positive definite matrices, J_0, J_i are skew-symmetric matrices. The error system with respect to the desired equilibrium point x^* can be rewritten as:

$$Q\dot{\tilde{x}} = (J_0 - R)\tilde{x} + \sum_i J_i \tilde{x} d_i^* + \sum_i J_i x^* \tilde{d}_i + \sum_i J_i \tilde{x} \tilde{d}_i, \quad \tilde{x} = x - x^*, \quad \tilde{d}_i := d_i - d_i^*, \quad (2.4)$$

where x^* and d_i^* are respectively the desired equilibrium point and the correspondent equilibrium controls. Based on this formulation, it is then possible to determine a passive output for the error system. Since it is well-known that passive systems can be stabilized using simple PI controllers [5], the establishment of a passive output is instrumental for the prove of stability. To determine the passive output let define the energy function:

$$\mathcal{H} = \frac{1}{2} \tilde{x}^\top Q \tilde{x}, \quad \Rightarrow \quad \dot{\mathcal{H}} = -\tilde{x}^\top R \tilde{x} + \tilde{x}^\top \sum_i J_i x^* \tilde{d}_i \leq \tilde{x}^\top \sum_i J_i x^* \tilde{d}_i,$$

from which it is easy to see that the input-output pair $(\tilde{d}, y_P)$ is passive, with $y_P := \text{col}(J_i x^* \tilde{d}_i)$, $\tilde{d} := \text{col}(\tilde{d}_i)$. It is possible then to formulate the following proposition.

Proposition 2.3. *Consider the system (2.1), in closed-loop with a PI controller based on the output $y_P := \text{col}(y_{P,h}, y_{P,\ell}, y_{P,0})$, with*

$$y_{P,h} := v_{Ch}^* i_h - i_h^* v_{Ch}, \quad y_{P,\ell} := v_{C\ell}^* i_\ell - i_\ell^* v_{C\ell}, \quad y_{P,0} := v_{C\ell}^* v_{Ch} - v_{Ch}^* v_{C\ell}.$$

Then the equilibrium point $(i_h^*, v_{Ch}^*, i_\ell^*, v_{C\ell}^*)$ is globally asymptotically stable for any positive controller gain.

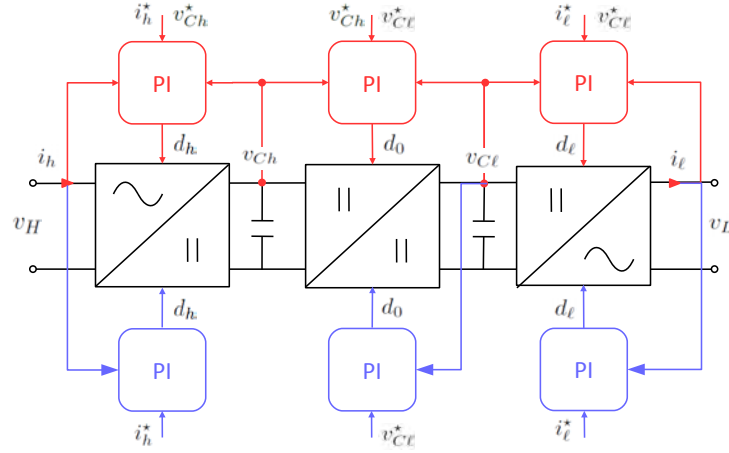


Figure 1: Block schemes of the standard PI controller (blue) and passivity-based PI controller (red).

The proof of the proposition, as already said, is a straightforward consequence of the existence of a passive output for the error system. More details on this topic can be found in [3]. Realistic simulations need to be carried out to compare the passivity-based controller with standard vector controllers.

2.2 FREEDM system modeling & power preserving interconnection laws

The FREEDM system consists in the meshed interconnection of a certain number of LV distribution networks, interfaced to the HV network, via conventional transformers or SSTs, see Fig. 2. It can be viewed as an unweighted directed graph $\mathcal{G}^\dagger(\mathcal{V}, \mathcal{E})$ where distribution networks, RL transmission lines and HV bus capacitors correspond to edges and buses correspond to nodes (vertices). All buses associate a potential and there are three type of buses: *distribution buses*, to which a distribution network is connected through a HV capacitor, *transmission buses*, to which no distribution networks nor capacitors are attached; a *reference bus*, a bus with respect to which all potentials are measured. The reference bus is assumed to be at ground potential. The distribution and reference buses are boundary buses, while the transmission buses are interior

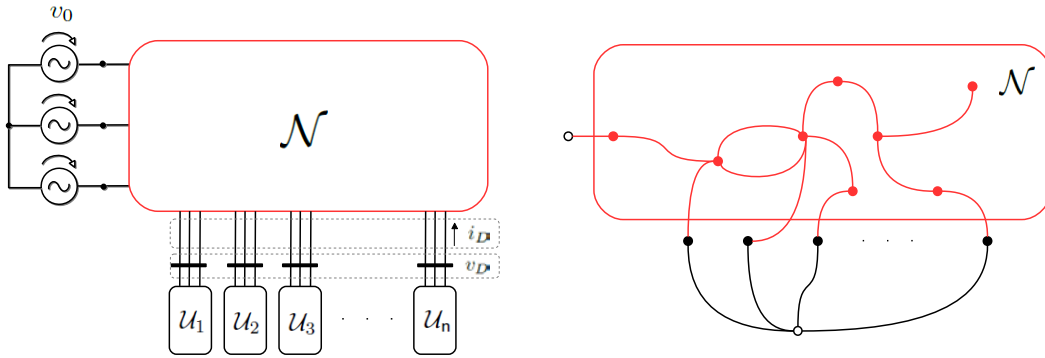


Figure 2: [Left] Schematic circuit of n distribution networks (units $\mathcal{U}_i$) interfaced to the main HV network ($\mathcal{N}$), attached to an infinite bus (purely sinusoidal voltage source v_0). [Right] Correspondent three-phase graph representation.

buses. Because it is always possible to eliminate these interior buses through a process, that is called Kron-reduction [8], we assume that there are no interior buses. If n is the number of distribution buses, then the total number of buses (nodes) is $n + 1$. Without loss of generality we assume that the set of nodes $\mathcal{V}$ can be partitioned into two ordered subsets called $\mathcal{V}_D$ and the one-element set $\mathcal{V}_0$, associated to distribution nodes and the reference node respectively. We call $V_n \in \mathbb{R}^{n+1}$ the vector of node potentials. Let t the number of

transmission edges — associated to transmission units — that connect distribution buses. Since, there is a *distribution* and a *HV capacitor edge* between every distribution bus and the reference bus, there are in total $m = 2n + t$ edges. Without loss of generality we assume that the set of edges $\mathcal{E}$ can be partitioned into three ordered subsets called $\mathcal{E}_D$, $\mathcal{E}_H$, $\mathcal{E}_T$ associated to distribution, HV capacitor and transmission edges respectively. We call $(V_e, I_e) \in \mathbb{R}^m \times \mathbb{R}^m$ the vectors pair associated to edge voltages and currents respectively. The topology of the system is thus fully described by the directed graph $\mathcal{G}^\dagger$ to which are associated the vectors V_n , V_e , I_e and the following *single-phase* incidence matrix

$$\mathcal{M} = \begin{bmatrix} \mathbb{I}_n & \mathbb{I}_n & \mathcal{N} \\ -\mathbf{1}_n^\top & -\mathbf{1}_n^\top & 0 \end{bmatrix} \in \mathbb{R}^{(n+1) \times m}, \quad (2.5)$$

The submatrix $\mathcal{N} \in \mathbb{R}^{n \times t}$, represents the incidence matrix of the sub-graph $\mathcal{G}_{net}^\dagger$, that is obtained by eliminating the reference node and edges that are connected to it. The incidence matrix $\mathcal{N}$ thus captures the topology of the HV network. Note that the description of the topology holds *modulo 3*, since the system is a balanced-three phase system. Power preserving interconnections, which are dictated by Kirckkhoff's currents and voltages laws (KCL, KVL) are indeed fully determined by the incidence matrix and node and edge vectors. Let consider the reference node $\mathcal{V}_0$ to be at ground potential and define the node and edge vectors:

$$V_n := \begin{bmatrix} v_n \\ 0 \end{bmatrix} \in \mathbb{R}^{3n+1}, \quad V_e := \begin{bmatrix} v_D \\ v_H \\ v_T \end{bmatrix} \in \mathbb{R}^{3m}, \quad I_e := \begin{bmatrix} i_D \\ i_H \\ i_T \end{bmatrix} \in \mathbb{R}^{3m}, \quad (2.6)$$

where the subindex D , H and T indicate distribution, HV capacitor and transmission edges variables. KCLs and KVLs are given by:

$$(\mathcal{M} \otimes \mathbb{I}_3)I_e = 0, \quad V_e = (\mathcal{M} \otimes \mathbb{I}_3)^\top V_n, \quad (2.7)$$

where the notation $\otimes \mathbb{I}_3$ indicates that KCLs and KVLs hold on the three-phase system structure. Then we obtain:

$$[KCL]: i_D + i_H + (\mathcal{N} \otimes \mathbb{I}_3)i_T = 0, \quad [KVL]: v_T = (\mathcal{N}^\top \otimes \mathbb{I}_3)v_D, \quad v_D = v_H \quad (2.8)$$

Based on a dq -frame description of the RL transmission lines fed by a sinusoidal voltage source v_0 and of the HV bus capacitors, the three-phase interconnection laws are mapped into two-phase interconnection laws and the system can be written as:

$$\begin{aligned} (L_T \otimes \mathbb{I}_2)\dot{i}_{T,dq} &= (J_{2t}L_T\omega - R_T \otimes \mathbb{I}_2)i_{T,dq} + (e_1 \otimes \mathbb{I}_2)v_{dq,0} + \underbrace{(\mathcal{N}^\top \otimes \mathbb{I}_2)v_{H,dq}}_{v_{T,dq}} \\ (C \otimes \mathbb{I}_2)\underbrace{\dot{v}_{D,dq}}_{v_{H,dq}} &= (J_{2n}C\omega - G \otimes \mathbb{I}_2)v_{H,dq} - \underbrace{(\mathcal{N} \otimes \mathbb{I}_2)i_{T,dq} - i_{D,dq}}_{i_{H,dq}}, \end{aligned} \quad (2.9)$$

where the notation $\otimes \mathbb{I}_2$ indicate that matrices are dq two-phases matrices, v_D , i_D correspond to the HV bus voltages and currents injected by the LV distribution networks, which are determined by the attached distribution subsystem $\mathcal{U}_i$ interfaced via conventional transformers or SSTs.

2.3 Steady-state analysis of the HV network equipped with SSTs (in progress)

It has been recently observed in simulations that the introduction of SSTs in conventional power systems may induce some oscillating, erratic behaviors of the state variables. Understanding the reasons for this behavior is of major importance. Since SSTs are usually controlled in order to achieve a constant power profile at the HV side, a straightforward implication is that whereas standard LV transformers are substituted by SSTs, the distribution networks can be approximated by constant power devices (P-models), the values of which are determined by the power setpoints provided by the power-loop to the inner-loop controllers. The power injected at each distribution bus can be expressed in dq variables as

$$P_i^* = V_{Dd,i}I_{Dd,i} + V_{Dq,i}I_{Dq,i}, \quad Q_i^* = V_{Dd,i}I_{Dq,i} - V_{Dq,i}I_{Dd,i}. \quad (2.10)$$

where P_i^* , Q_i^* correspond to the active and reactive setpoints provided to the inner controller of the SST. Hence the model of n distribution networks, interfaced to the HV network through internally controlled SSTs, is simply given by the system (2.9), constrained to (2.10), with $i \in [1, n]$. On the other hand, if we assume that the distribution network is not equipped with an SST, this can be modeled by a dominantly ZI-model (constant current, constant impedance models). Starting from the obtained model, which is clearly

nonlinear because of the constraints (2.10), it is possible to show that in general the system may not admit an equilibrium point, thus explaining the erratic behaviors observed in simulations. To see this, it suffices to see that equilibria are determined by setting the left-hand of (2.9) to zero, constrained by (2.10). After some manipulations, it is possible to determine the following steady-state relation:

$$i_{D,dq}^* = Y(\mathcal{N})v_{D,dq}^* + Kv_{dq,0}, \quad (2.11)$$

where $Y(\mathcal{N})$ is a suitably defined dq -admittance matrix, and K an input matrix. Note that the admittance matrix clearly depends from the topology of the network, that is determined by the incidence matrix $\mathcal{N}$. An appropriate coordinate transformation of the relation (2.11) finally allows to reformulate the problem of existence of solution for the system as the problem of determining whether a set of quadratic equations of the form:

$$P_i^* = \frac{1}{2}(v_{D,dq}^*)^\top \mathcal{A}_{P,i} v_{D,dq}^* + \mathcal{B}_{P,i}^\top v_{D,dq}^*, \quad Q_i^* = \frac{1}{2}(v_{D,dq}^*)^\top \mathcal{A}_{Q,i} v_{D,dq}^* + \mathcal{B}_{Q,i}^\top v_{D,dq}^* \quad (2.12)$$

Using the results obtained in [1], it is possible to show that these quadratic equations have a solution only if an appropriate linear matrix inequality (LMI) is verified. More precisely, we can use the following lemma.

Lemma 2.4. *Consider the set of quadratic equations (2.12). A necessary condition for the existence of a solution is that the following LMI (in variables $t_{P,i}, t_{Q,k}$)*

$$\left[\begin{array}{c} \sum t_{P,i} \mathcal{A}_{P,i} + \sum t_{Q,i} \mathcal{A}_{Q,i} \\ (\sum t_{P,i} \mathcal{B}_{P,i} + \sum t_{Q,k} \mathcal{B}_{Q,k})^\top \end{array} \quad \begin{array}{c} \sum t_{P,i} \mathcal{B}_{P,i} + \sum t_{Q,k} \mathcal{B}_{Q,k} \\ 2 \sum t_{P,i} P_i^* + 2 \sum t_{Q,k} Q_k^* \end{array} \right] > 0 \quad (2.13)$$

is unsolvable for any $t_{P,i}, t_{Q,k} \in \mathbb{R}$.

In conclusion, we have a tool for determining necessary conditions for the existence of a steady-state for the FREEDM system, under the assumption that SSTs are internally controlled in order to achieve a constant active and reactive power profile at the point of the interconnection with the network. It should be noted that the obtained LMI is a function of $\mathcal{A}$'s and $\mathcal{B}$'s, which are in their turn dependent by: the network topology and the impedances of the HV network, *i.e.* the matrix $Y(\mathcal{N})$; the setpoint provided to the inner controller of the SSTs, *i.e.* the active and reactive power references P_i^*, Q_i^* . It is thus of particular interest to investigate how to relax these necessary conditions by appropriate: 1) design of the filters of the SST; 2) location of the SSTs with respect to the overall topology; 3) choice of the power setpoints provided to the SSTs (in particular for reactive power).

3 Achievements, milestones and deliverables

Achievements with respect to the three fundamental axes can be summarized as follows

1. It is proved, with a nonlinear analysis, that the standard vector control strategy adopted for the local control of the SST, ensures local asymptotic stability of the closed-loop system and boundedness of trajectories. This is a unique feature of the SST and should be contrasted with AC/DC/AC converters architecture, which instead may experience instability. Unfortunately, closed-loop eigenvalues are located very near the positive real axes. Hence, performance limitations are expected. It is proposed a new PI controller, based on passivity arguments, as an alternative to standard vector control. Current research is focused on a comparative analysis of the controllers in order to assess their performances.
2. A modular approach for the modeling of a general FREEDM system—based on graph theory—is proposed. The procedure easily allows for *plug & play* of the components and outages modeling by direct modification of the graph edges and nodes. Under reasonable assumptions on the operation of the inner controllers, it is further shown that the system can be reduced to a linear time invariant (LTI) circuit with constant power loads, thus paving the road to an analysis on existence of equilibria and stability.
3. Starting from the reduced model (LTI circuit with constant power loads), necessary conditions for the existence of a steady-state are established. These conditions, which take the form of an LMI, are implicitly related to the physical characteristics of the FREEDM system (topology, dissipation) as well as to the setpoints provided to the local controllers of the SSTs. It is expected then that the validation

of such a result on a realistic benchmark, it will likely allow to understand how location of the SSTs, impedances and controller setpoints affect the stability of the system.

A journal paper, to be addressed to the power system community, is now being drawn up and intended to submit it shortly. Considering that several results have been established, it is likely possible that this will be splitted into two parts: a first part dedicated to analysis and design of local controllers, including a comparative analysis; a second part dedicated to the construction of the reduced model and the related analysis on existence of equilibria.

4 Plans for next years

Current research is being developed around two axes:

1. Performance analysis of local controllers, *i.e.* standard vector and passivity-based control for the SSTs. Tuning of the controller gains to guarantee a larger domain of attraction of the equilibrium point. Integration of the SST and of the local controllers with distributed energy sources and storage (batteries, PV panel, wind turbine).
2. Moving from the necessary conditions established by the LMI, it is of interest to determine “rules” for appropriate: design of the SST filters (in the spirit of [7]), choice of the setpoints of the local controllers of the SSTs, location of the SSTs in the network topology. Based on the same model a local analysis can be carried out, which establish conditions for stability of a given equilibrium point, similarly to [1]. Still an open challenge is the problem of estimate the domain of attraction.
3. Straightforward extension of the analysis on existence of equilibria with respect to the DC bus. In particular, it is of interest to investigate the role played by the primary (voltage droop) control.

References

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Y8.FS2.6: Dynamic Phasor-based Controller Design for Solid State Transformer

Team Members

Project Leader: Dr. A. Stankovic

Faculty: Dr. S. Wagh

1. Project Goals

Control Analysis and Design for SST using dynamic phasors

2. Role in Support of Strategic Plan

System Analysis: Modeling using Dynamic Phasors for 3-stage SST

Controller development: Local controllers design – PI and PR design for 3-stage

Port-controlled Hamiltonian model formation for 3-stage SST components

3. Fundamental Research, Technological Barriers and Methodologies

3.1 Dynamic Phasor based model of SST and microgrid components to identify coupling between various quantities and addressing problems at various frequencies.

3.2 Controller development: Local controllers design – PI and PR design for 3-stages of SST

For analyzing small signal stability of a 3-stage SST, a linearized model of all the 3 individual stages is derived around an operating point. Based on it the control scheme using PI and PR controller for the 3 stages of SST is designed.

3.3 Port-controlled Hamiltonian model formation for 3-stage SST components

For control of a SST, energy shaping and port controlled Hamiltonian (PCH) approach principle is applied. The research offers the use of the bond graph approach to recognize the energy representation of the SST i.e. information of energy generation, storage and transfer. One of the abilities of the port-based models is that the complete model is easy to obtain by means of interconnection rules.

4. Achievements

4.1 Switched model for 3-stage SST configuration

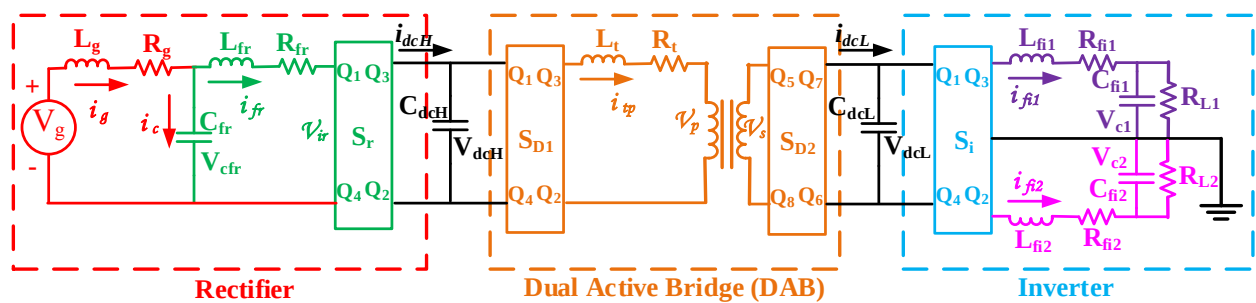
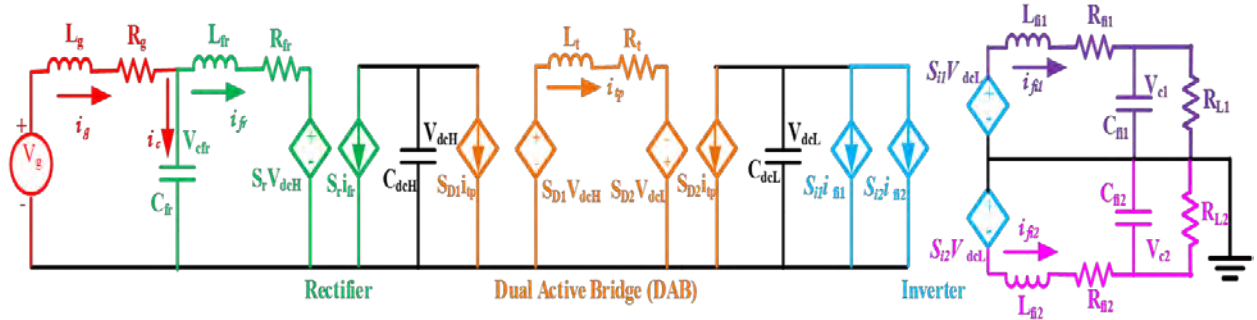


Fig.1. Switched model of 3-stage SST

4.2 Average model for 3-stage SST configuration



$$\dot{x}_{SST} = f(x_{SST}, S_{SST}) ; \text{ where, } S_{SST} - \text{switching functions of SST}$$

4.3 Dynamic phasor model for 3-stage SST

$$\langle \dot{x}_{SST} \rangle = f(\langle x_{SST} \rangle, \langle d_{SST} \rangle, \omega)$$

4.4 Linearized model formation for DP-based model

$$\frac{d}{dt} [\Delta X_{SST}] = [A_{SST}] [\Delta X_{SST}] + [B_{SST}] [\Delta d_{SST}] + [C_{SST}] [\Delta U_{SST}] + [D_{SST}]$$

Where,

$$[\Delta X_{SST}] = \begin{bmatrix} (\Delta i_g)_1^R & (\Delta i_g)_1^I & (\Delta i_{fr})_1^R & (\Delta i_{fr})_1^I & (\Delta V_{cfr})_1^R & (\Delta V_{cfr})_1^I & (\Delta V_{dcH})_0 & (\Delta i_{tp})_1^R & (\Delta i_{tp})_1^I & (\Delta V_{dcL})_0 & (\Delta i_{fi1})_1^R & (\Delta i_{fi1})_1^I & (\Delta V_{cfi1})_1^R & (\Delta V_{cfi1})_1^I \end{bmatrix}$$

$$[\Delta d_{SST}] = [\Delta d_r \quad \Delta d_{D1} \quad \Delta d_{D2} \quad \Delta d_i]$$

4.5 Local controllers design – PI and PR design for 3-stages of SST

The combined model is derived using the individual Rectifier, DAB and Inverter models. The DP model for all the 3 stages is obtained using the average model. For analyzing small signal stability, a linearized model of all the 3 individual stages is derived around an operating point. Based on the linearized model, the control scheme using PI and PR controller for the 3- stages of SST is designed. Fig 1 gives the control scheme for 3-stage SST.

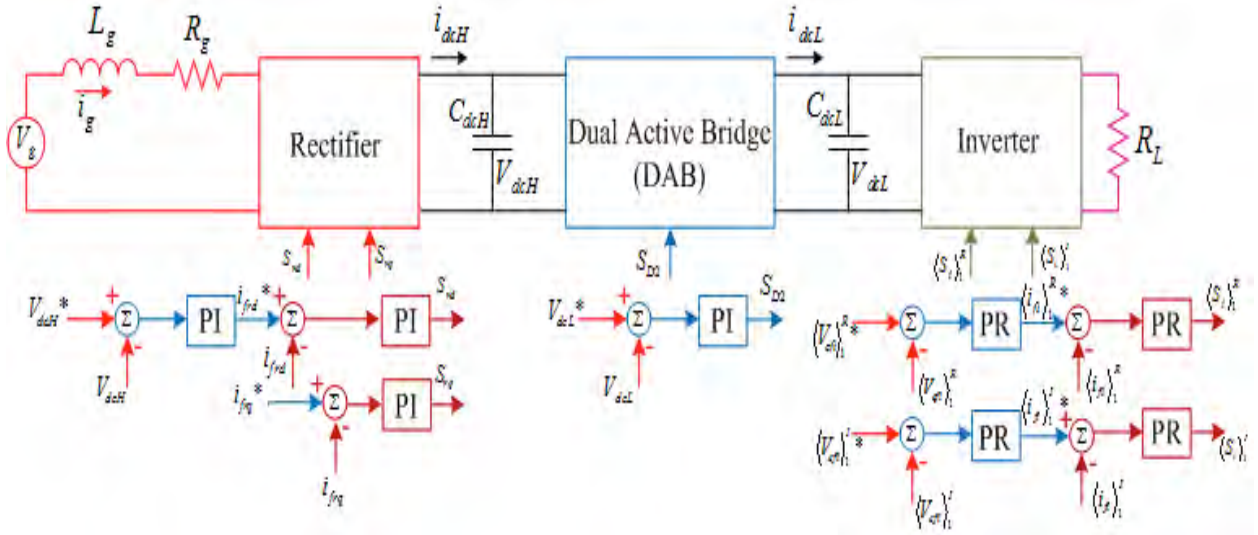


Fig.1. Control Scheme for Combined SST

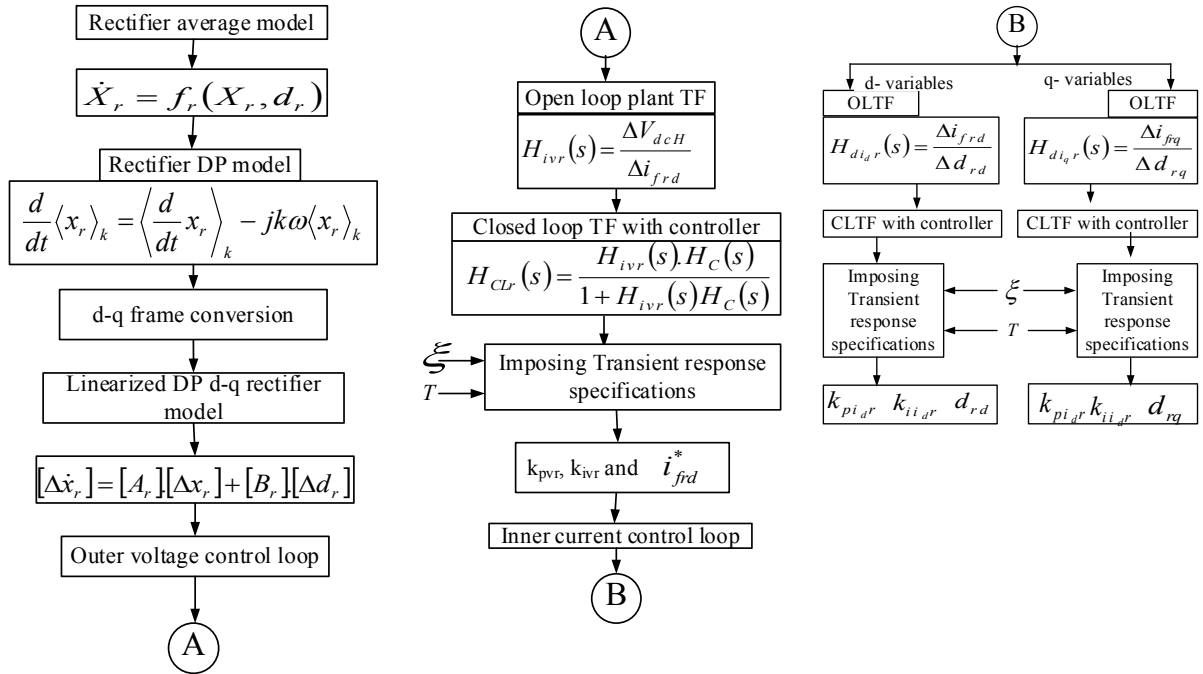
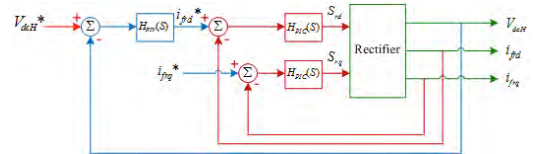
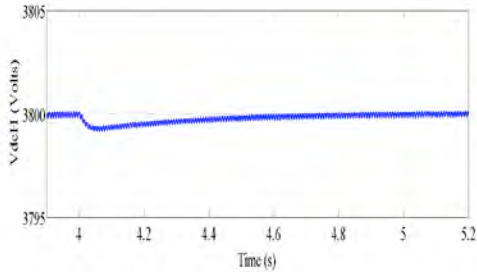


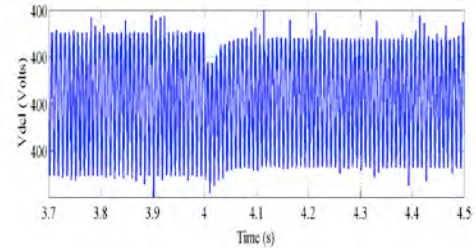
Fig. 2. Flow chart and control scheme for rectifier circuit.

Similar procedure followed for remaining components

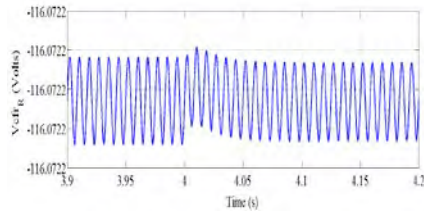




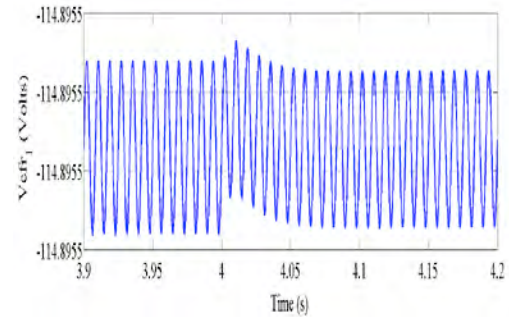
Rectifier output voltage response



DAB output voltage response



Inverter Vcfr_R voltage response



Inverter Vcfr_I voltage response

Fig. 5. Performance of combined SST DP model with controller: Expanded view at 4sec

Conclusions:

The proposed control scheme of SST is based on PI and PR controllers. The goal was to obtain both high dynamic performance and stable operation of SST for input voltage variation. The control problem was formulated for a dynamic phasor model. The control approach was applied to combined and individual stages of SST in simulation. The results are compared with the Average model of the SST. From the closed loop behavior of switched/averaged model and DP based model, it is observed that the DP based control smoothens out ripples in the output voltage. The simulation time required for the DP based model is (much) shorter than the switched/averaged model

4.6 Bond graph approach to Hamiltonian Modeling and Energy Shaping Control of 3 stage SST

Considering the energy transformation aspect of SST, the research uses the bond graph approach to recognize the energy representation of the SST. Bond graph theory is a powerful technique to model a physical system, it allows a description of the system, keeping information about energy generation, storage and transfer and its description permits the integration of sub models easily. It is proven that the power continuous part of bond graphs, the junction structure, can be associated with a Dirac structure and that the equations describing a bond graph model correspond to a port Hamiltonian system. One of the abilities of the port-based models is that the complete model is easy to obtain by means of interconnection rules. The bond graph approach allows building a complex model by interconnecting several subsystems. Through the detailed bond graphs of subsystems of SST i.e.

AC-DC rectifier, DC-DC DAB and DC-AC inverter and of interconnected three stage SST, the equivalent port controlled Hamiltonian (PCH) models for subsystems and the interconnected system are also derived.

For control of the SST, energy shaping and a port controlled Hamiltonian (PCH) approach is applied. First of all, the PCH model of individual model is established in dynamic phasor form. Then according to the target design of the individual system, the desired equilibrium point is obtained. The PCH feedback control method of SST is given in terms of energy shaping theory and the controller is designed through interconnection and damping assignment (IDA). Moreover, a proportional and constant compensation controller is designed to eliminate the steady state error in the DC bus voltage at each stage of SST.

5. Plans for Next Five Years

Dynamic Phasor based modeling of microgrid comprising multiple SSTs

Coordination between different individual SSTs will be analyzed for effective power transfer between the source and the grid as shown in figure 6. Power sharing between different SSTs will continue to be investigated. A dynamic phasor (DP) approach has been proposed for modeling of both DG and SSTs as DP provides advantages such as large bandwidth in frequency domain and reduced computational time.

A ripple may be present in the PV operation due to frequent changes of insolation. Integration of a DP based droop controller with MG will be further investigated. Stability analysis of MG with multi SST operated under droop control technique will be analyzed.

- Dynamic phasor based modeling of fuel cell
- Dynamic phasor based modeling of PV module

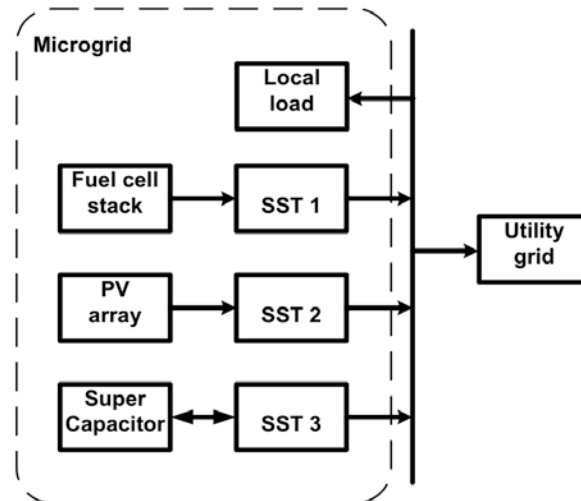


Figure 6: A microgrid with multiple SSTs

6. International Collaborations

Navdeep M. Singh, Electrical Engineering Department, VJTI, Mumbai, India

(PI-Centre of Excellence in complex and Nonlinear Dynamical Systems)

7. References

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Associated Projects

System Demonstration

Project Title: Ocean Energy: Assessment of Energy Storage Aspects Including Control and Grid Connection off the North Carolina Coast

Team Members

Project Leader: Dr. Iqbal Husain (ECE, North Carolina State University)

Faculty: Dr. Alex Huang

Students: Chang Peng (PhD)

Industry Participants: Dr. Bruno Lequesne and Mr. Roger Briggs (E-Motors Consulting)

Funding Agency: Coastal Studies Institute, State of North Carolina

Funding Period: 7/1/2011-6/30/2016

Project Abstract:

The objective of this project is to investigate the challenges associated with the transmission and grid connection of wave energy from an off-shore wave park. DC systems are ideal for offshore wind energy integrations, where the efficiency is higher but the cost can be lower. The showstopper for interconnected DC grids is the fast acting DC circuit breaker. Therefore, different DC interruption technologies are evaluated, and the ultra-fast mechanical switch has been identified as the key component for achieving low-loss high speed operations. A Thomson coil actuator has been adopted to develop a 1 ms mechanical switch for applications at the 15 kV class. The FEA model of the actuator and its drive circuit have been developed using COMSOL Multiphysics as shown in Fig. 1. The model includes electric circuits, electromagnetics, solid mechanics and heat transfer characteristics. In a transient simulation, the model helped the understanding and design of the prototype. The prototype was designed and built for a rating of 630 A, 15 kV and is shown in Fig. 2. The prototype has been tested for both high speed opening operations and low loss conductions. Test results have proved the design to be effective: In opening operations, the switch travels to 1.6 mm within 1 ms, which enables a voltage withstand capability of 32 kV; in steady state conduction, the voltage drop of the contact is about 50 mV at 300 A. The opening delay is only 0.2 ms, which is 100 times shorter than conventional AC circuit breakers; the conduction loss is about 100 times lower than that of the solid state switches. The FEA model has also been validated with the experimental results. Based on this 1 ms mechanical switch, a 2 ms hybrid solid state DC circuit breaker has been developed as well.

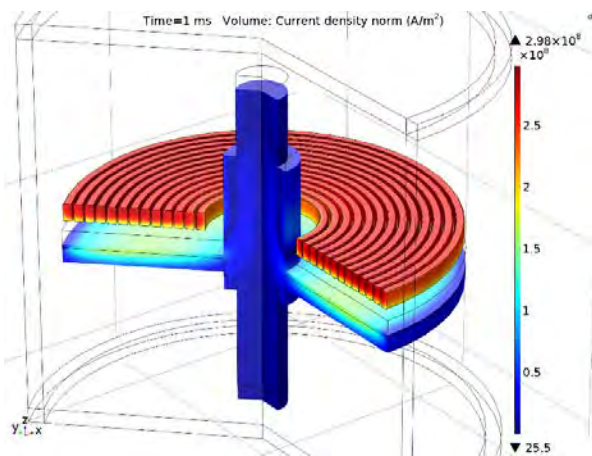


Fig. 1 The FEA model of Thomson coil actuator.

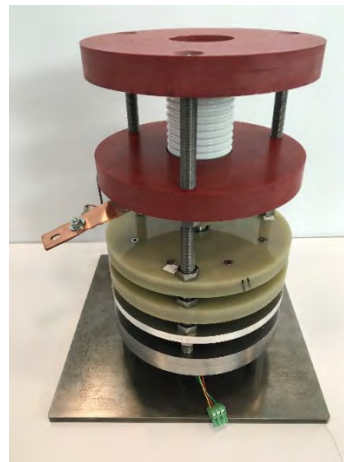


Fig. 2 The prototype.

Project Title: Design and Analysis of Switched Reluctance and Flux Switching Permanent Magnet (FSPM) Machines for Industrial Applications

Team Members

Project Leader: Dr. Iqbal Husain (ECE, North Carolina State University)

Students: Chandan Sikder (PhD)

Industry Participants: Dr. Wen Ouyang (ABB, Inc.)

Funding Agency: ABB, Inc.

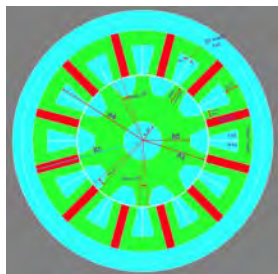
Funding Period: 1/1/2012-8/2016

Project Abstract:

The flux switching permanent magnet (FSPM) machine (also known as flux reversal machine, FRM) is an attractive alternative to induction machines and PM machines in automotive, renewable, other direct drive and industrial applications. FSPM combines the attractive features of both PM machines and switched reluctance machines, but has not been investigated enough to explore its potentials. The cross section of the spoke type 12/10 FSPM machine is shown in Figure 2(a). This structure has been found to be most suitable for industrial applications through the initial research. In the initial period of the project, fundamental research on back-EMF, torque ripple, demagnetization and temperature effect have been carried out. The earlier focuses were on using non rare-earth PM in the stator and achieve maximum torque or power density with design optimization.

A novel idea of rotor pole tip flange or fillet to reduce cogging torque for FSPMs has been developed and analyzed. A complete structural analysis has also been performed with an emphasis to reduce stator vibration and noise for a low-noise machine design. The research on the design and analysis of FSPM for industrial applications was published in the Sept 2015 issue of IEEE Industrial Application Transactions jointly with industrial partner ABB. An analytical model of such stator-PM machines including saturation and torque ripple effect has also been developed.

The designed machine was fabricated and experimentally evaluated at the FREEDM Systems Center. The FEA model and the FSPM parts for fabrication are shown in Figure 1. The field oriented control algorithm for the FSPM was developed and implemented using a TI TMS320F28035 microcontroller. Figure 2(a) shows the dynamometer test stand for experimental evaluation, and the experimental torque output results for three different commands are shown in Figure 2(b).



(a) FEA model of final geometry.

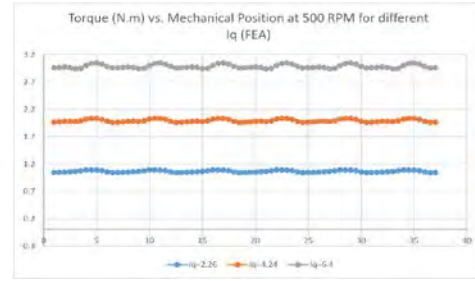


(b) Stator, rotor and other parts of built FSPM.

Figure 1



(a) Test bench with (i) dyno, (ii) torque sensor, and (iii) FSPM (from left to right).



(b) Torque at different current commands (from experiments)

Figure 2

Project Title: Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic

Team Members

Project Leader: Ewan Pritchard (NCSU/MAE)

Students: Di Zhu (PhDME), Eric Green (PhDEE), Landon Mackey (MSEE),
Taha Atif (UGEE)

Staff: Greg Norris, Poria Fajri (Post-Doctoral Researcher)

Funding Agency: Positive Energies/USTDA

Funding Period: 07/15/2015 – MM/DD/2017

Project Abstract

The main objective for this project is to design a Modular Electric Generator (“MEG”) comprised of proven US manufactured products for customer specific applications. The pilot MEG unit will be installed and piloted in Punta Cana, Dominican Republic under CEPM, a privately owned utility. The main purpose of USTDA is to promote and advance US-international trade and US manufacturing. CEPM has been granted a concession area in which it supplies power for its residents and businesses. The MEG will help CEPM keep its concession area by helping them provide power to off-grid communities, increase grid reliability, and to act as a UPS for critical loads. This project is of major importance to our partner companies Positive Energies, Schneider, and Toshiba and represents advancements in FREEDM's industry involvement. Going from concept to fully functioning pilot in just one year, the MEG unit will have immediate industry impact and is poised to be manufactured in high volume in the coming year.

The MEG is designed to be a hybrid system with the ability to accept power inputs from solar, wind, hydro, or the existing on-site power grid. To date, the FREEDM team has done component sizing and architecture selection, solar and wind analysis of the pilot site, detailed system and controls simulation, initial controls design with system operating modes, and assembly of initial storage and charging units complete with system controls. The MEG will improve grid stability and power reliability for unstable electric systems, promote reduction of cost, time, and difficulty of renewable energy integration, and will be a commercially marketable unit easily shipped and used worldwide.

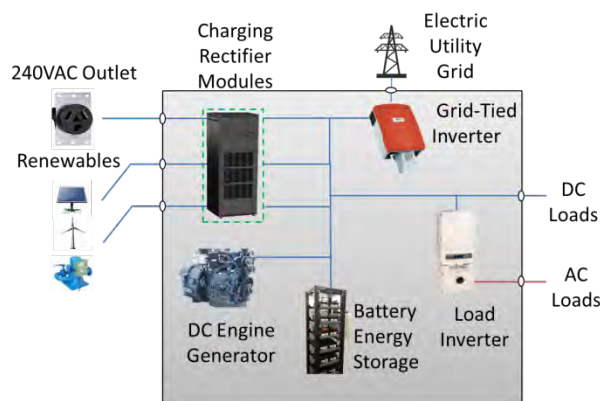


Figure 1: MEG Block Component Layout



Figure 2: Pilot Installation Site in Dominican Republic

Project Title: Electricity Operations Model**Team Members**

Project Leader: Ning LU (NC State University/ECE)

Students: Xinda Ke (EEPhD)

Funding Agency: Pacific Northwest National Lab

Funding Period: 09/01/2015 – 08/31/2016

Project Abstract

Pacific Northwest National Laboratory (PNNL), supported by the Department of Energy's (DOE) Integrated Assessment Research Program, is developing a framework for regional integrated assessment and Earth system modeling, known as RIAM, and applying this framework to different regions of the United States in order to understand the complex dynamics of the climate-energy-water-land nexus.

The RIAM project links regional climate, hydrology, socioeconomics, energy infrastructure, coastal processes, and agriculture and land use models to investigate the multifaceted impacts of climate change, as well as potential adaptation and mitigation strategies being considered by regional stakeholders. The project is highlighting the vulnerability of regional energy systems to heat waves, droughts, coastal storm surges, and other extreme events, with an initial focus on climate change impacts on electricity supply and demand. Another key goal is improving understanding of the benefits and challenges associated with integrated, multiscale modeling and the interdependencies among human and natural systems in the context of climate change.

The Electricity Operations Model, or EOM, simulates the operation of the electric grid at the zonal scale, including inter-zonal transmission constraints. EOM considers the economics of individual power plants and the transmission system's ability to dispatch power to meet hourly loads. The model will be linked to a regional water modeling capabilities to assess the impact of changing water resource quality and quantity on electricity operations, and to a regional climate model to explore how operations are affected by increasing heat waves. The long-term goal is to develop an integrated modeling capability that can simulate the impacts of weather and climate on the electricity system under different future scenarios.

Project Title: Olney Town Center Microgrid Project

Team Members

Project Leader: David Lubkeman (NCSU Team)

Other Faculty: Srdjan Lukic, Ning Lu, Aranya Chakraborty

Industry Participants: Burr Energy LLC (prime), Green Energy Corporation,
FREEDM Systems Center, Schneider Electric, Pepco Holdings Inc.

Funding Agency: Department of Energy

Funding Period: 11/1/2014 – 01/31/2017

Project Abstract

The objective of the Olney Town Center Microgrid project is to research, develop, and model advanced control systems for prospective community microgrids at Olney Town Center, Montgomery County, Md., and Ritchie Station Marketplace in Largo, Md. Also the project will prepare and execute rigorous laboratory testing on the Olney Town Center Microgrid controller. Expected project results include measurable progress toward achieving a range of quantitative goals for the project team; As well as local community stakeholders and the electric power industry.

The project team will achieve these objectives by designing and testing microgrid control systems capable of integrating distributed renewable energy resources, natural gas CHP units, energy storage, and demand-side management technologies in near-real-time optimization schemes to achieve the communities' objectives. The Microgrid Institute will initiate and manage the team's effort through several project phases: Microgrid Controller R&D; System Planning and Design; Test Preparations; Laboratory Testing; and Analysis and Results Reporting.

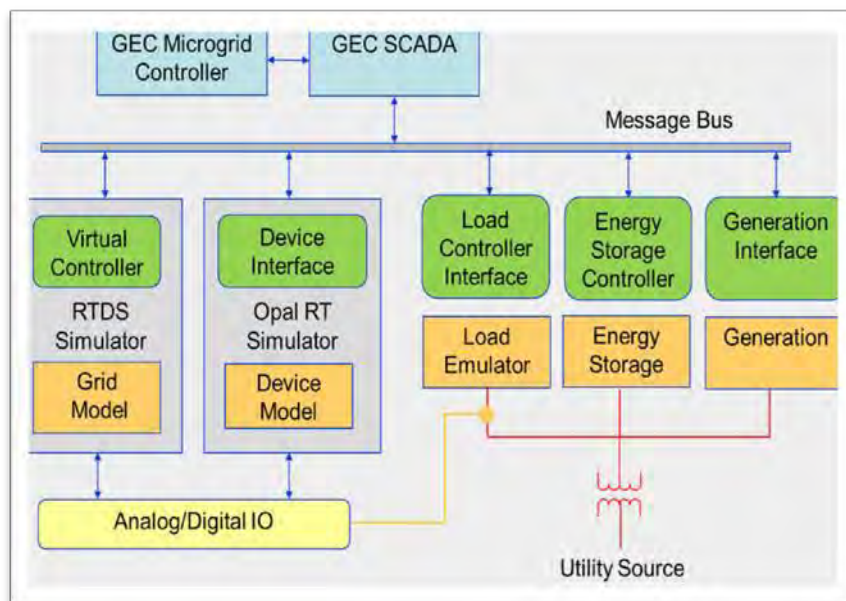


Figure 1: GEH Microgrid Test Facility

Project Title: Permanent Magnet Transverse Flux Electric Machine with Flux Focusing Technique for Direct Drive Applications

Team Members

Project Leader: Dr. Iqbal Husain (ECE, North Carolina State University)

Faculty: Dr. Srdjan Lukic

Students: Adeeb Ahmed (PhD), Zhao Wan (PhD)

Industry Participants: National Renewable Energy Laboratory (NREL)

Funding Agency: National Science Foundation

Funding Period: 9/1/2013-8/31/2016

Project Abstract:

The project aims to develop a high torque density motor, primarily targeted for low speed high torque direct drive applications such as wind turbine or traction. Since transverse flux machines have a reputation for high torque generating capability, this category of electric machines attracts more attention among researchers for high torque density application. Transverse flux machines theoretically exhibit a linear relationship between the number of pole pairs and electromagnetic torque, making it possible to produce extremely high torque by introducing a higher number of pole pairs. Though this relationship deviates in practical application due to increase in leakage flux with increasing number of poles, TFMs are an attractive research topic due to room for innovation and design improvements. Moreover, TFM permits the use of ring winding which helps in reducing end winding size resulting in a lower winding resistance which is also an attractive feature for electric machines.

Currently, extensive study has been performed to improve the machine performance based on certain objective functions. The major objectives include torque ripple minimization, power factor improvement and loss minimization. The primary design was fine tuned to meet certain thresholds in motor performance parameters. The second major task was to incorporate necessary design modifications for easier manufacturing of the prototype. As most TFM structures require a three dimensional flux path requiring the use of a soft magnetic composite (SMC) or a complex lamination structure, modifications were made to enable the use of simple conventional laminations. Two such TFM topologies are proposed: one with an outer rotor double winding, and one with an inner rotor single winding, as illustrated in Figure 1. Instead of relying on rules of thumb for different design set points, finite element based thermal and structural simulations were used to finalize the design before final manufacturing.

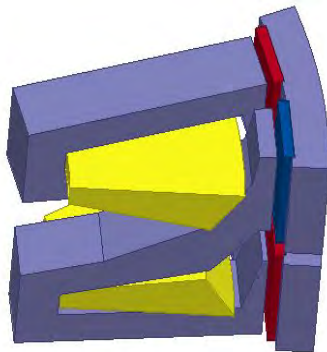
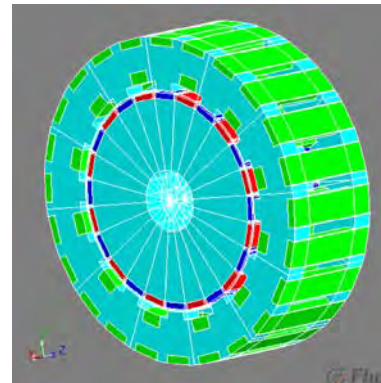


Figure 1: (a) Single-pole view of outer rotor TFM.



(b) Complete model of inner rotor TFM.

Project Title: Power America: SiC Inverter for Electric Vehicle Traction Drive

Team Members:

Project Leader: Dr. Iqbal Husain (NCSU-Electrical & Computer Engineering)

Faculty: Dr. Wensong Yu (NCSU-Electrical & Computer Engineering)
Dr. Douglas C. Hopkins (NCSU / Electrical & Computer Engineering)

Students: Yang Xu (EE PhD), Adam Morgan (EE PhD), Dhrubo Rahman (EE PhD),
Rui Gao (EE PhD), Li Yang (EE PhD)

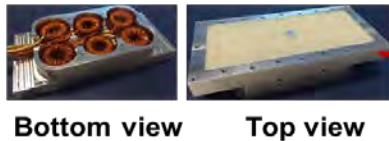
Funding Agency: PowerAmerica Institute (Department of Energy)

Funding Period: 01/01/2015 – 3/31/2016

Project Abstract

Design, fabrication, and testing of a 55kW high power density inverter for an EV traction drive based on SiC technology to enable various levels of functional integration. The system design is guided to accommodate “off-the-shelf” SiC power modules in a planar architecture that aims to improve the efficiency and reduce the size and weight ensuring proper electrical, thermal, and mechanical performance. A bi-directional interleaved DC-DC boost structure and a three-phase voltage source inverter (VSI) have been utilized, with a primary focus on the reduction of passive components fostered by the increased switching frequency of both the boost and inverter stages; 35kHz and 70kHz, respectively. A stacked layer approach has been used for a unique PCB-based busbar, ultra-low profile gate driver, and controller board. This holistic design approach results in a highly compact traction drive inverter with power density of 12.1 kW/L that has lower volume and weight compared to the commercially available state-of-the-art power converter systems for hybrid electric vehicles.

Double-side cooling plate



Cree SiC module

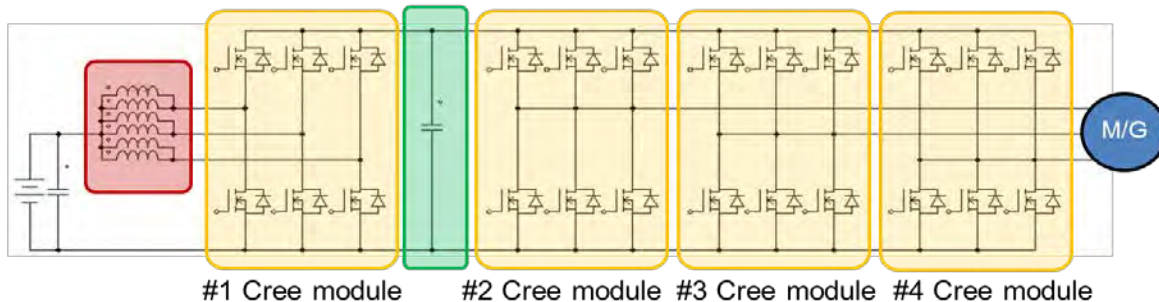


Figure 1: Physical hardware components, system level packaging, and electrical schematic of 55kW inverter.

Project Title: Switched Reluctance Machine and Controller Development for Electric Power Steering

Team Members

Project Leader: Dr. Iqbal Husain (ECE, North Carolina State University)

Students: Helion Dhrimaj (MSc), Zhao Wan (PhD), Adeeb Ahmed (PhD)

Industry Participants: Robert Long (Nexteer Automotive)

Funding Agency: Nexteer Automotive

Funding Period: 10/1/2011-12/31/2015

Project Abstract:

The objective of the overall project is to design and analyze a three-phase switched reluctance machine for electric power steering (EPS), and then to develop and implement the controller on EPS system hardware. A machine and controller was designed and built for the purpose. The work progressed during 2011 to 2014 on electromagnetic, structural FEA with several design variations, control methods and controller development. A predictive current control strategy for torque ripple minimization has been successfully implemented experimentally. The research in 2015 focused on experimental evaluation and analyzing data to aid the next generation design. The experimental results at higher speeds in both motoring and generating mode of operation comply with what have been achieved in simulation.

Some of the experimental results obtained with one SRM could not be replicated in a similar SRM. The cause of this inconsistency is analyzed and the results are described in detail. Torque ripple data was recorded and analyzed in time and frequency domain. Results indicate current phase gain variations, position sensor error, and system resonance due to existing natural frequencies. Parametric analysis of phase resistance, rotor eccentricity, and voltage variation are performed in FEA software and Simulink. Results depict their effects on torque performance for EPS applications. With the aim of improving torque performance, a synchronous reluctance machine (SynRM) has been designed and verified in FEA software. Under similar constraints, the SynRM design reduced torque ripple output to 3.6%.

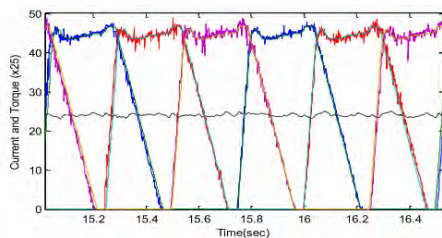


Fig. 1: Phase current with small position error.

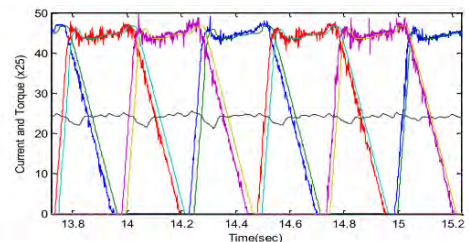


Fig. 2: Phase currents with large position error.



Fig. 3: SynRM design (1/4th of model).

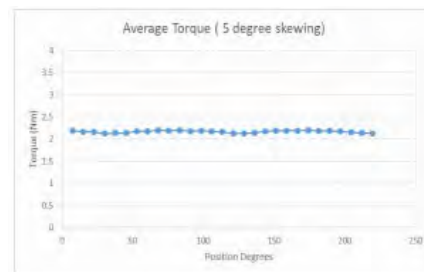


Fig. 4: Torque performance of SynRM.

Project Title: The Solar Endowment - Demonstrating University Leadership in Solar Deployment

Team Members

Project Leader: Jonathan Kimball (ECE/Missouri S&T), Tony Arnold (S&T)

Students: Alicia Pajda (EMSE/S&T)

Funding Agency: Midwest Renewable Energy Association; subaward from a Department of Energy contract

Funding Period: 1/1/2015 – 12/31/16

Project Abstract

The MREA will work with university engineering programs and associated interdisciplinary centers, energy management offices, campus sustainability offices, and local electric utilities to develop a suite of 'shovel ready' solar project plans for consideration by the university governance boards. The plans will be developed by Student Design Teams, building off of past program success with the Solar Decathlon and similar student-led projects, providing graduate-level design and project management experience, offering undergraduate credit and applied engineering experience when applicable, and supporting campus-wide goals such as service to community, carbon emission reductions, and associated campus sustainability charters.

The purpose of the student-led initiative will be to showcase the investment potential of on-site solar energy projects to university governance boards in an effort to generate investment through the university endowment office, advance favorable board policies to govern investments in solar assets, develop a case for giving to solicit continued alumni contributions to support such efforts, and provide a road map for universities across the country to deploy solar energy on their campus.

Project Title: Analysis of Practical Microgrid Stability in the Presence of Random Events**Team Members**

Project Leader: Jonathan W. Kimball (Missouri University of Science and Technology)

Funding Period: 9/1/2015 – 8/31/2016

Project Abstract:

This work is funded by the National Science Foundation under award 1406156, with a start date of August 1, 2014.

Microgrids are power distribution systems that are small where total generation capacity is similar to the total demand. Examples may be found in isolated villages, military bases that may or may not be connected to the surrounding power grid, and vehicles ranging from automobiles to satellites to ships. DC microgrids have also been proposed for residential applications, where a single house would be a complete system, and for telecommunications power systems. Microgrids are an enabling technology for widespread deployment of renewable energy, such as solar and wind systems. This project will apply emerging control theory concepts to microgrid stability analysis. Previous researchers have usually assumed that all loads and sources have some ability to be controlled, but in practical systems, most loads change randomly, and renewable resources are subject to weather variations. The random events could cause the microgrid to become unstable and shut down. Microgrids are essential to the expansion of renewable energy due to the distributed nature of renewable energy generation, and the improved stability analysis from this project is needed to give system operators confidence in their proper operation.

The objective of this project is to analyze AC and DC microgrids using advanced techniques that apply to generic impulsive Markov jump linear systems. A Markov Jump Linear System (MJLS) is a system that jumps instantaneously among a set of linear dynamic systems according to a Markov process. More generically, the transitions in the discrete state could be accompanied by impulses in the continuous-time states, forming an impulsive MJLS. This is a good description for the small-signal characteristics of a microgrid. Unfortunately, generic stability results for an impulsive MJLS are few. In this project, stability results for the subset of impulsive MJLS that appropriately describes microgrids will be derived. Suitable models for both AC and DC microgrids will be derived and analyzed. The results will be parameterized by controller gains and other characteristics that are within the purview of the system designer, so that stability may be guaranteed by design. Both the discrete state, which evolves randomly, and the continuous state, which is deterministic, will be considered simultaneously. The approach will be validated with simulations and experiments. Two example microgrids, one AC and one DC, will be studied to demonstrate the ability to compose an appropriate nonlinear model, to convert it to a set of small-signal models, and to map it into the impulsive MJLS framework. The proposed impulsive MJLS study will be applicable to other dynamic systems, such as networked control systems, that fit a similar framework. Similarly, demonstrating the application of impulsive MJLS methods to microgrids may stimulate research within the power community on other applications that fit a similar structure, such as the load on a voltage regulator module (VRM).

Associated Projects

Enabling Technology

Project Title: Development and Characterization of Li-ion Capacitor Electrodes and Cells

Team Members

Project Leader: Jim P. Zheng (Florida A & M University-Electrical and Computer Engineering)

Funding Agency: Department of Energy

Funding Period: 9/1/2015-8/31/2016

Project Abstract:

The proposed project is based on our recent technical breakthrough on using a mixture of stabilized lithium metal powder and hard carbon as the anode electrode, while activated carbon was used as the cathode. A specific energy of 22 Wh/kg was obtained from a fully packed pouch cell. The capacitor was able to deliver over 60% of the maximum energy at a discharge C-rate of 44C. Through continuous galvanostatic charge/discharge cycling, the capacitance of the Li-ion capacitor degraded less than 3% over 600 cycles.

The proposed research includes (1) evaluation of carbon materials for anode and cathode electrodes in Li-ion capacitors in order to achieve maximum energy density, power density, and cycle life; (2) formulation and testing of electrolytes with high ionic conductivity, wide temperature and electrochemical stability windows which are highly desirable for use in the electrochemical capacitors; and (3) assembly of Li-ion capacitor pouch cells using dye room and facilities and testing of the performance of these cells.



Figure. 1 Li-ion capacitors made by General Capacitor, a FREEDM spin-off company.

Project Title: Enabling High Penetration of Distributed PV through the Optimization of Transmission Voltage Regulation

Team Members

Project Leader: Ning LU (NC State University/ECE)

Students: David Mulcahy/Xiangqi Zhu/Jian Lu (EEPhD)

Funding Agency: DOE SuNLAMP: NCSU subcontract through Pacific Northwest National Lab

Funding Period: 04/01/2016 – 03/31/2019

Project Abstract

PNNL will partner with North Carolina State University (NCSU), GE Global Research, One-Cycle Control Inc. (OCC) and Duke Energy to develop a Coordinated Real-time Sub-Transmission Volt-Var Control Tool (CReST-VCT) to optimize the use of reactive power control devices to stabilize voltage fluctuations caused by intermittent PV outputs. In order to capture the full value of the Volt-Var optimization, we propose to couple this tool to an Optimal Future Sub-Transmission Volt-Var Planning Tool (OFuST-VPT) for short and long term planning. Together, the real-time control and planning tools will remove a major roadblock in the increased use of utility scale and residential PV. The project duration is 36 months.

Project Title: Fabrication of Lithium-Sulfur Pouch Cell Batteries

Team Members

Project Leader: Jim P. Zheng (Florida A & M University-Electrical and Computer Engineering)

Funding Agency: NC State University

Funding Period: 9/1/2015 – 8/31/2016

Project Abstract:

Lithium-sulphur (Li-S) batteries have attracted much attention because of their higher energy density and low cost from the use of sulfur as cathode. Currently the best Li-S batteries offer specific energies on the order of 500 Wh/kg, which is significantly better than most lithium-ion batteries which are in the 150 to 200 range. In this project, we will fabricate Li-S pouch cell batteries using Li foil anodes and carbon cathodes. The cathode will be made using a dry electrode fabrication method. The Li-S pouch cell batteries will be assembled in a dry room. The Li-S pouch cells will then be tested for performance including specific energy, cycle life, and temperature range.



Figure 1, Photos of pouch cells of test Li-S batteries with an electrode size 23cm^2 ($4.8\text{cm} \times 4.8\text{cm}$).

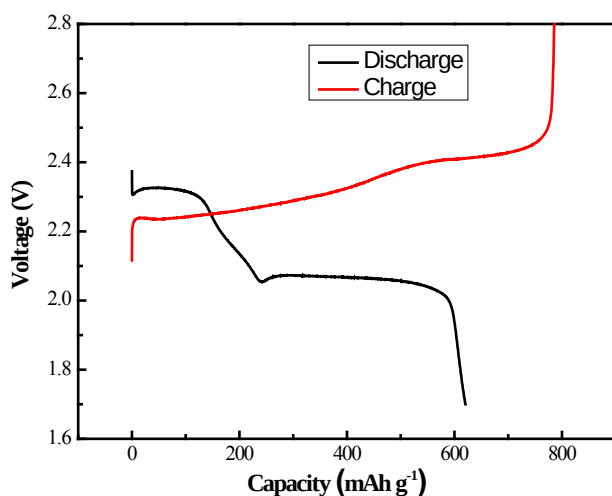


Figure 2, Cell voltage profile during charge and discharge from a Li-S pouch cell battery.

Project Title: Investigation of Pre-Lithiated Anodes for Li-ion Batteries and Li-ion Capacitors**Team Members**

Project Leader: Jim P. Zheng (Florida A & M University-Electrical and Computer Engineering)

Funding Agency: Department of Energy

Funding Period: 9/1/2015-8/31/2016

Project Abstract:

We propose to investigate pre-lithiated anodes to be used in Li-ion batteries and Li-ion capacitors for plug-in hybrid electric vehicle (PHEV) applications. We will develop methods to pre-dope Li into anodes and study the electrochemical and physical behaviors of the anode during charge and discharge cycles. The pre-lithiated anode is able to provide necessary active Li-ion sources facilitating the shuttling effect between two electrodes in Li-ion batteries and capacitors. The means and the amount of lithium (Li) required to be doped into anode electrodes can directly affect the batteries' or capacitors' assembly processes and performance including maximum energy/power density, cycle life, and round-trip energy efficiency. Our previous work has demonstrated that Li-ion capacitors can be made with activated carbon cathode and hard carbon/stabilized lithium metal powder (SLMP) anode, and can be rapidly charged and discharged with a specific energy over 25 Wh/kg. With such structure, the anode electrode was simply made with hard carbon and a layer of SLMP on the surface; when the electrolyte was filled in, the Li will be intercalated into hard carbon and serve as an ion source during late charge and discharge processes. The high energy density of Li-ion capacitors benefits from the high concentration of Li pre-doped into the anode vs. low concentration ion source available in liquid electrolytes. Therefore, much less electrolyte is needed in our Li-ion capacitors than conventional electrochemical (electric double-layer) capacitors. In this white paper we further propose to explore the effects of different lithium intercalation methods, electrolytes, and binders to the performance of Li-ion batteries and capacitors in terms of specific energy and power, cycle life, and safety as well as energy efficiency. This project will collectively target a major unsolved problem concerning the lower specific energy of supercapacitors relative to rechargeable batteries, in spite of the higher power densities typically associated with EC capacitors. The significant improvement in specific density is critical to the success of PHEV applications.

Project Title: Li-ion Battery and Li-ion Capacitor Hybrid Energy Storage Devices

Team Members

Project Leader: Jim P. Zheng (Florida A & M University-Electrical and Computer Engineering)

Funding Agency: Florida State University Research Foundation

Funding Period: 9/1/2015 – 8/31/2016

Project Abstract:

The Li-ion capacitor (LIC) is a new energy storage device which consists of a supercapacitor cathode and a Li-ion Battery (LIB) anode and was invented by the PI (Jim P. Zheng) at FSU. The LIC not only retained all the advantages of a supercapacitor such as specific power >5 kW/kg and cycle life $> 100,000$ cycles; but also had higher specific energy of 15-30 Wh/kg and higher maximum cell voltage of 4.1 V than that of a traditional supercapacitor^{1,2}. Because the potential of the anode and cathode as well as the maximum cell voltage of LIC is comparable to that of LIB, it allows the LIC and LIB to be assembled in one package as a monolithic LIB and LIC hybrid cell. The energy density and power density of the hybrid cell will be designed to meet the requirements by a reasonable distribution of the ratio between LIB and LIC electrodes in a hybrid cell.

We propose a new hybrid electrochemical device, which combines the LIB's and the LIC's advantages and can avoid their inherent defects. The voltage profiles for cells shows that at low current, the new device has a higher energy density than LIC. In a hybrid cell, the electrode is an inner combination of LIB material and LIC material. The advantage of this hybrid cell is that, at a low output, it will reflect the characteristic of LIB and provide a high energy density; while at a high output, the hybrid cell may exhibit the features of LIC and provide a high power density; consequently, a high power density and a high energy density can be achieved.



Figure 1, A photo of a Li-ion capacitor made by General Capacitor LLC, a spin-off company from FREEDM. The cells were used in Army Rifleman Radio.

GC 200 F LIC	
Operating Temperature (°C)	-40 to 65
Rated Voltage (V)	2.2 to 3.8
Capacitance (F)	200
ESR (mW)	30
Specific Energy (Wh/kg)	14
Energy Density (Wh/L)	28
Max. Specific Power (kW/kg)	6
Max. Power Density (kW/L)	12
Self Discharge (3 Months)	<5%
Dimension (L×W×T) (cm)	5×5×0.4
Weight (g)	20

Table 1. The specification of the 200 F Li-ion Capacitor

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- [1] W.J. Cao and J.P. Zheng, "Li-ion Capacitors with Carbon Cathode and Hard Carbon/SLMP Anode Electrodes", *J. Power Sources*, **213**, 180 (2012).
- [2] W.J. Cao, J. Shih, J.P. Zheng, and T. Doung, "Development and characterization of Li-ion capacitor pouch cells", *Journal of Power Sources*, **257**, 388 (2014).

Project Title: Monolithic Li-Ion Battery and Li-Ion Capacitor Hybrid Cells for Brigade, Soldier and Small Unit Power

Team Members

Project Leader: Jim Zheng (FAMU)

Funding Agency: Army Research Labs

Funding Period: 9/01/2015 –8/31/2016

Project Abstract

In this project, we are developing new hybrid electrochemical devices, which combine a battery and a capacitor's advantages and can avoid their inherent defects. The voltage profiles for cells shows that at low current, the new devices have a higher energy density than LIC. In a hybrid cell, the cathode electrode is an inner combination of LIB material (e.g. LiCoO_2) and LIC material (activated carbon), and the anode electrode is Li intercalating carbon such as graphite, hard carbon, soft carbon, and their mixture. The advantage of this hybrid cell is that, at a low output, it will reflect the characteristic of a LIB and provide a high energy density; while at a high output, the hybrid cell may exhibit the features of a LIC and provide a high power density; consequently, a high power density and a high energy density can be achieved as shown in Figure 1.

In high energy and low power applications, the LIB is the best choice; in high power and long cycle applications, the EDLC is used; however, in many civilian and military applications, the power requirement is not a constant but rather spans over a range of power levels. It has been demonstrated that when batteries and supercapacitors were externally connected to form a hybrid power source, the voltage drop during the pulsed current for the hybrid power source was less than that for the battery, and operating time of the hybrid power source was significantly extended. However, because the maximum cell voltage of single cell EDLC is less than that of LIB; therefore, hybrid power sources could only be made with two separate battery and EDLC cells and electrically connect them with or without electric circuits.

The Li-ion capacitor (LIC) is a new energy storage device which consists of an EDLC cathode and a LIB anode, between which the ions shuttle during charge and discharge processes. The LIC not only retained

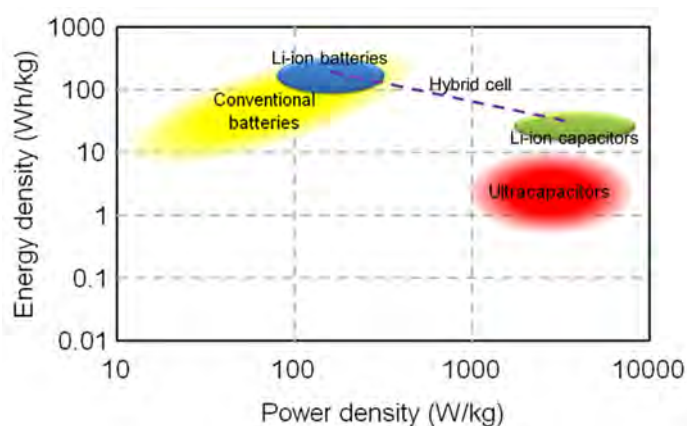


Figure 1, Ragone Plot showing energy density vs. power density for batteries, ultracapacitors, Li-ion capacitors, and proposed hybrid cells.

all the advantages of EDLC such as specific power $>5 \text{ kW/kg}$ and cycle life $> 100,000$ cycles; but also had higher specific energy of 15-30 Wh/kg and higher maximum cell voltage of 4.1 V than that of EDLC. Because the potentials of anode and cathode as well as the maximum cell voltage of LIC is comparable to that of LIB, it allows the LIC and LIB to be assembled in one package as a monolithic LIB and LIC hybrid cell. The energy density and power density of the hybrid cell will be designed to meet the requirements by a reasonable distribution of the ratio between LIB and LIC electrodes in a hybrid cell.

Project Title: Solar Electric Home Energy Management Program – Task 2.Cooperative Distributed Home Energy Management Systems

Team Members

Project Leader: Dr. Mo-Yuen Chow (North Carolina State University / Electrical and Computer Engineering Department)

Students: Bharat Balagopal (EEPhD), Alberto Castelo-Becerra (EEPhD), Cong Sheng Huang (EEPhD), Rakesh Mishra (EEMSc), Waleed Aslam (EEMSc), Jian Hu (EEPhD), Zheyuan Cheng (EEMSc), Dr. Wenten Zeng (Research Associate), Dr. Habiballah Rahimi Eichi (Research Associate), Yuan Zhang (EEPhD)

Funding Agency: TOTAL S.A. (FREEDM Full Member)

Funding Period: 09/01/2015 – 08/31/2018

Project Abstract

The goal of this task is to develop a cooperative distributed Home Energy Management System (HEMS) for 1) a single house, and 2) aggregated houses. In this cooperative distributed HEMS, energy sources and loads can coordinate and cooperate with each other to maximize the user comfort, meet the power constraints (e.g., avoid over-loading), optimize the power flows, decrease the system cost and the electricity bill in a single house and among aggregated houses. It also includes smart battery charging/discharging strategies to optimize the integration of the energy storage system. The project consists of design, development and demonstration phases.

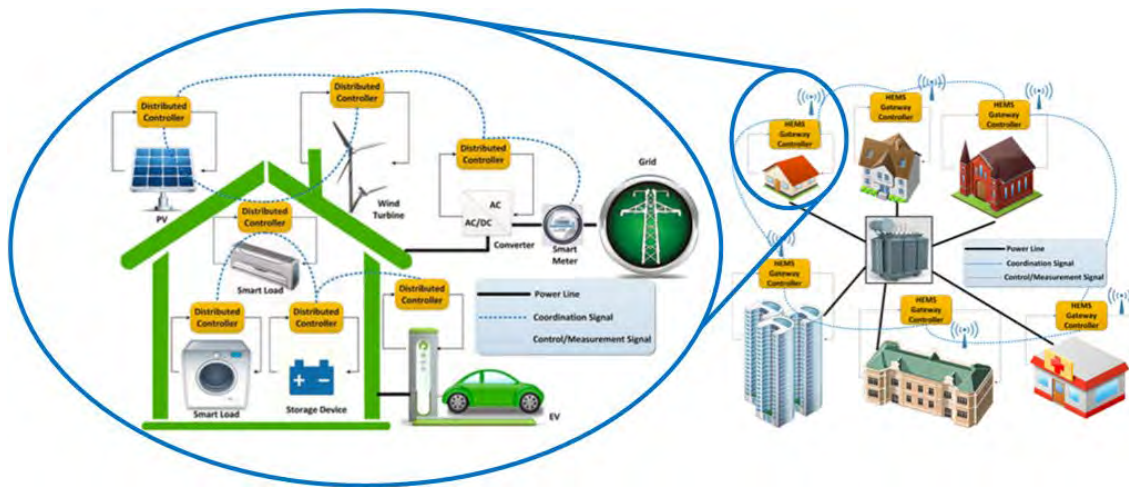


Figure 1: Cooperative Distributed Home/Aggregated Houses Energy Management Framework.

Project Title: Determining Security Threats through Information Flow Analysis

Team Members

Project Leader: Bruce McMillin

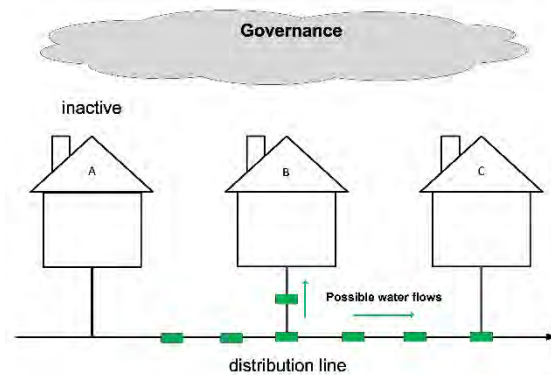
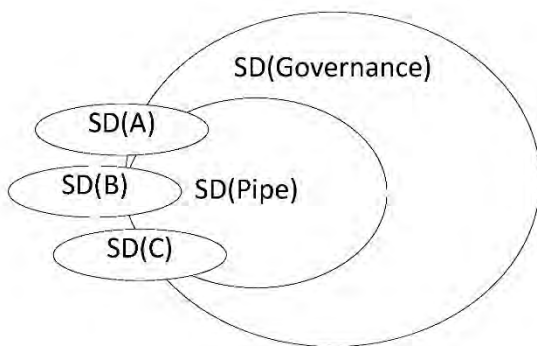
Students: Anusha Thudimilla, Missouri S&T, MS

Funding Agency: NIST

Funding Period: 01/01/2016-12/31/2016

Project Abstract:

Providing Cyber-Physical System (CPS) security goes beyond traditional IT/enterprise cyber-security and beyond purely physical security to combine both into Cyber-Physical Security (CPS). In CPS, threats can arise through both the cyber and physical aspects, in combination. Moreover, in a CPS system, ideas of high and low and inside and outside no longer represent modern systems; security domains can overlap as shown in the figure below for multiple houses within a water distribution grid. This proposal extends work in information analysis to detect the possibility of confidentiality leakages and integrity attacks, develop tools for assessment, and provide design parameters for reducing risk among security partitions of a CPS. The proposed work will be measured against developed use cases from NIST and the Smart Grid Interoperability Panel (SGIP).



Project Title: Missouri Advanced Security Training Education and Research**Team Members**

Project Leader: Dan Lin (non FREEDM), Bruce McMillin

Students: Dalton Cole, Joshua Herman, Missouri S&T, Ph.D.

Funding Agency: NSF

Funding Period: 08/15/2014-7/31/2019

Project Abstract:

This project seeks to establish a new CyberCorps®: Scholarship for Service (SFS) program at the Missouri University of Science and Technology (S&T) to prepare highly-qualified Cybersecurity professionals for entry into the government workforce. The proposed CyberCorps®: SFS program is called Missouri Advanced Security Training, Education and Research (MASTER). Missouri S&T has been the first institution in the state of Missouri to be designated as a National Center of Academic Excellence in Information Assurance Education as well as a National Center of Academic Excellence in Information Assurance Research. The project will produce 20 MS and PhD graduates in the field of cybersecurity to serve the nation. It will increase the number of minorities and women in cybersecurity professionals and workforce. It will provide outreach and disseminate research findings to broader communities including high schools, community colleges, HBCU partner universities, and academic communities in the field of cybersecurity. Such awareness will be generated through workshops and summer camps organized by the MASTER project team, as well as research publications and presentations in the academic and professional venues.

The proposed MASTER project will offer experiential learning by participating in the university's strategic plan themed Smart Computing and Smart Living, in which Cybersecurity plays a major integral role. Currently, the Computer Science Department building is being instrumented to act as a smart environment that can track and predict activities, occupancy, surveillance monitoring, energy usage, and so on. SFS students will design and operate security monitoring software and tools. Furthermore, a new course "Experiential Entrepreneurship for Computer Scientists" will be offered to provide the Missouri S&T CyberCorps® scholars a first-hand experience with real information-security tools applied to real-world scenarios. The Cybersecurity curriculum has been certified for National Standards 4011 (INFOSEC) and 4014E (ISSO). It includes a wide range of courses on security, privacy, trustworthiness and reliability issues. This project will also develop several new courses such as Big Data Security or Security and Privacy in Social Networks which are current research topics of the faculty team

Project Title: Resilient Information Architecture Platform for the Smart Grid

Team Members

Project Leader: Srdjan Lukic (ECE/NCSU).
Faculty: David Lubkeman
Students: Yuhua Du, Gholomreza Jalali

Funding Agency: Department of Energy

Funding Period: 5/1/2016-4/30/2019

Project Abstract:

The proposed Resilient Information Architecture Platform for the Smart Grid (RIAPS) will create an open source software platform to run Smart Grid applications and demonstrate it on selected applications. The software platform will define the programming model (for distributed real-time software), the services (for application management, fault tolerance, security, time synchronization, coordination, etc.), and the development toolkit (for building and deploying apps). The NC State team will demonstrate microgrid operation in both grid-connected and islanded mode as the application for development in the RIAPS project. The main application scenario (use case) will be the unplanned transition from grid-connected to islanded mode and re-synchronization from island mode to the grid. The reason we have selected this application is because (1) NC State can build on their ongoing work on a DOE Microgrid controller project (Olney Microgrid) and (2) the proposed use case provides a rich scenario for demonstrating capabilities of the RIAPS platform. Our focus is on microgrid stability during the grid-connected to islanded transitions. Optimal energy management is beyond the scope of this work. The focus is more on the power management and fault management capabilities required for near instantaneous microgrid transition.

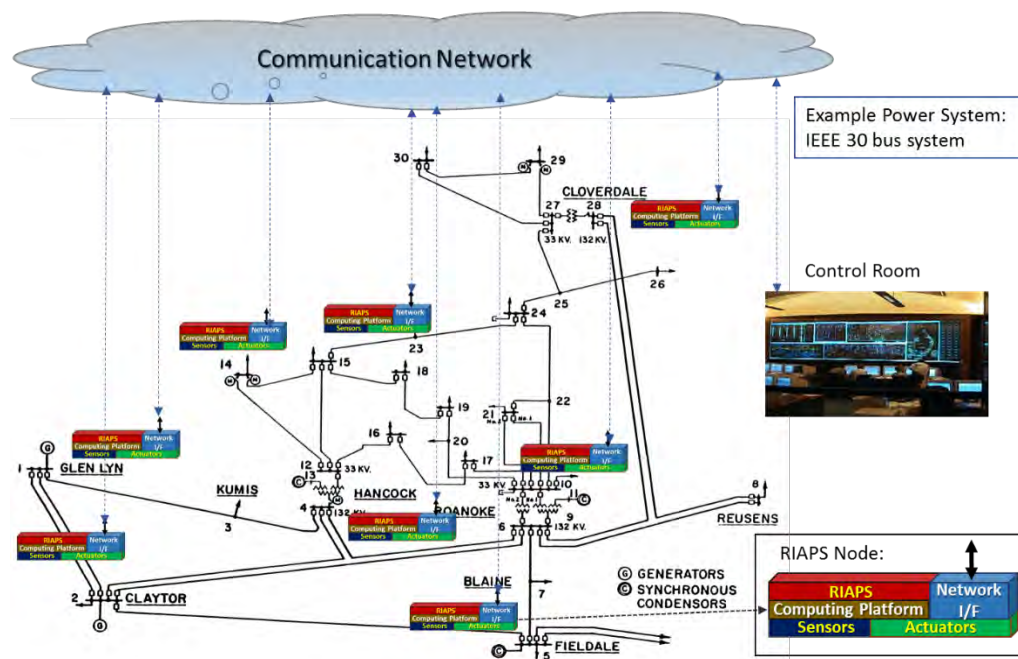


Figure 1. Conceptual representation of the Resilient Information Architecture Platform for the Smart Grid

Project Title: CPS: Synergy: Collaborative Research: Diagnostics and Prognostics Using Temporal Causal Models for Cyber Physical Systems - A Case of Smart Electric Grid

Team Members

Project Leader: Srdjan Lukic (ECE/NCSU)

Students: Rishabh Jain (PhD), Yuhua Du (PhD)

Funding Agency: NSF

Funding Period: 10/01/2013 - 09/30/2016

Project Abstract

Reliable operation of cyber-physical systems (CPS) such as Smart Electric Grids is critical of societal importance. Efficient models and tools for fault diagnosis and prognostics are necessary for curtailing systematic failures such as power blackouts by performing fault diagnosis and prognostics are necessary. Varying physical system state such as power consumption, changing requirements, physical component degradation, and interaction with possible software anomalies make the failure analysis, prediction, and mitigation difficult. The Smart Electric Grid is a CPS: it consists of networks of physical components (including generation, transmission, and distribution facilities) interacting with cyber components (e.g. intelligent sensors, communication networks, computational and control software). Today's grid protection systems use a logic-based approach that rely on hard thresholds and local information, often ignoring system-level effects introduced by the distributed control algorithms. This leads to scenarios where a local mitigation in a subsystem, especially in case of malfunction of protection devices results in a larger fault cascade, leading to a blackout. A 2012 report from NERC identified the importance of preventing wrong local control operations. Clearly, an integrated CPS-based approach is needed. The proposed research will develop new methods to build fault propagation models for complex CPS such as smart grid that represent the failure dependencies in the cyber as well as physical components. Additionally, an integrated system-wide solution for isolating faults and predicting future failure propagations that accounts for the existing protection mechanisms designed into the system will be developed. The proposed research will consider transmission and active distribution systems of the Smart Grid for now, but can be extended to other CPS in future. Use of timed discrete event models of the systems is proposed to capture the causal and temporal relationships between failure modes (causes), discrepancies (effects) in a system, and the controller actions in the system.

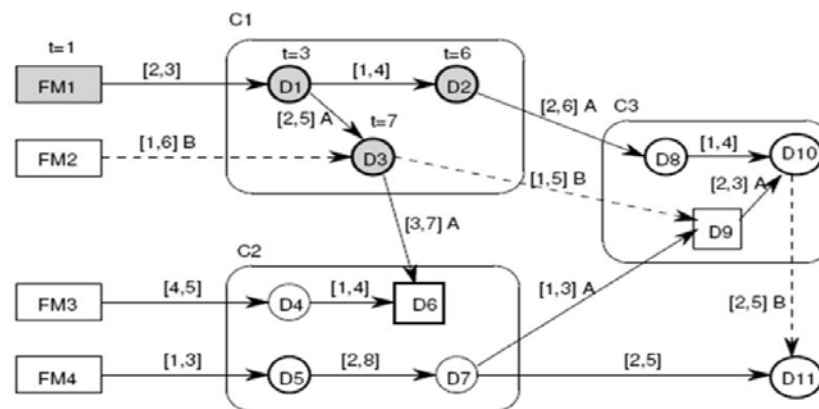


Figure 1: Sample Timed Failure Propagation Graphs Model with Failure Modes (FM), Discrepancies (D), and fault propagation links (edges). Labels on edges indicate delay (min,max) values and modal dependencies

Project Title: Fast Electromechanical Disconnect Switching Chamber with Integrated Drive Mechanism

Team Members

Project Leaders: Lukas Graber (PI), Mischa Steurer (Co-PI)
Staff: Dionne Soto
Students: Samantha Smith (MS), Ian Nowak (Undergraduate),
James Owens (Undergraduate)

Funding Agency: Florida State University Research Foundation

Funding Period: 11/25/14 – 8/31/15

Project Abstract

The rapid development of highly efficient and compact power electronic converters is expected to cause a paradigm shift in electric power distribution system designs. Those systems will be highly fault current limited and eventually migrate from AC to DC. The key for success of such new systems is the availability of a very fast disconnect switch which can carry load currents of several hundred amps with virtually no losses and withstand tens of kilovolts within less than a millisecond after opening without interrupting current (current interruption is done by the power electronic converters). Currently there is no disconnect switch available that would satisfy these requirements. The idea to use a vacuum chamber with internal piezoelectric-actuator-driven contacts for an electrical switch that can provide ultra fast voltage withstand capability is novel and non-obvious. It fills a need for use in hybrid breaker applications in current-limited electrical distribution systems and possibly other applications.

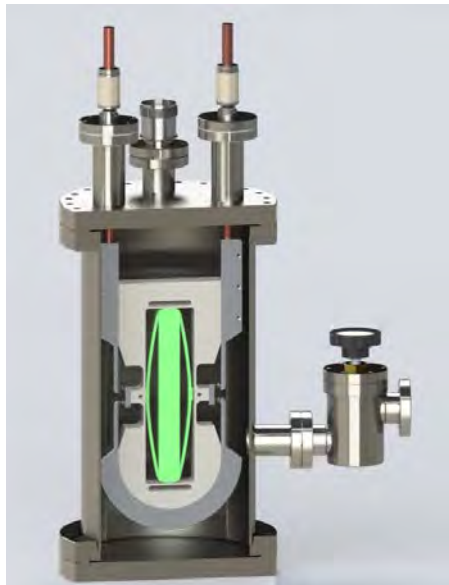


Fig. 1: CAD model of the disconnect switch

Project Title: Testing, Characterization and Design Optimization of High Voltage SiC Gate Turn-off (GTO) Thyristors

Team Members

Project Leader: Dr. Alex Huang (ECE / North Carolina State University)

Industrial Participants: Cree Inc.

Funding Agency: Army Research Lab/Cree Inc.

Funding Period: 02/01/2013 - 03/30/2016

Project Abstract

This project conducted testing, characterization, and design optimization of a ultra-high voltage SiC gate turn-off (GTO) thyristor as well as other high voltage devices such as a PIN diode, IGBT etc. The testing will assess the performance of the GTO device at room and elevated temperatures. The test and characterization will also include DC testing and dynamic testing.

In 2015-2016, the Safe Operation Area (SOA) of 15-22 kV GTO has been studied. Significant results are highlighted below.

Target: Towards 1000A/cm² turn-off capability (>20X time improvement over silicon)

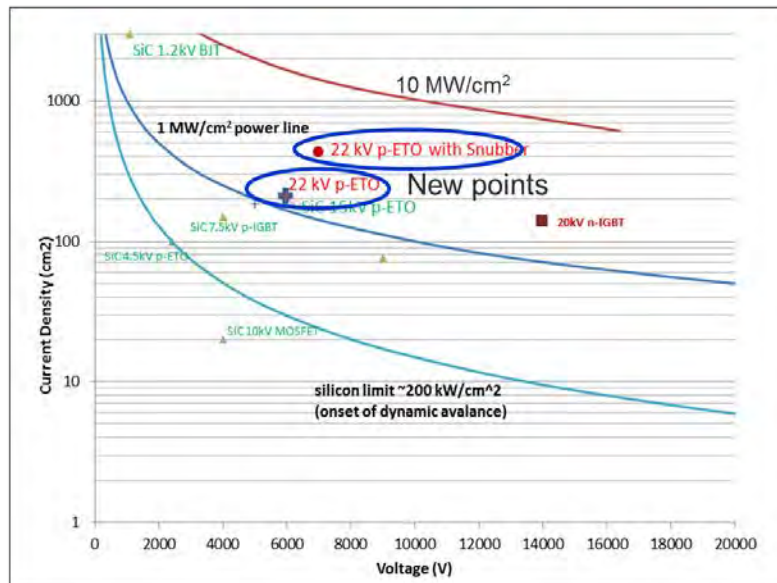


Figure 1. Target: Towards 1000A/cm² turn-off capability (>20X time improvement over silicon)

Project Title: Development and Testing of Silicon Carbide Gate Turn-Off Thyristor Based High Power Solid State Circuit Breaker (SSCB) for DC Power Distribution System

Team Members

Project Leader: Dr. Alex Huang (ECE / North Carolina State University)

Industrial Participants: Cree Inc.

Funding Agency: ABB

Funding Period: 07/01/2015 - 06/30/2016

Project Abstract

The objective of the project in the current funding cycle is to study the ability of a high current solid state circuit breaker using a SiC gate turn-off (GTO) thyristor. Parallel device operation is currently being studied with significant results shown below.

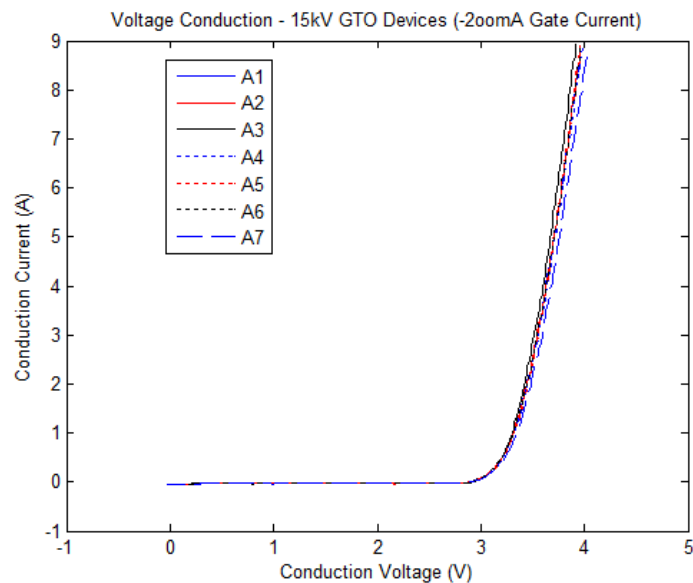


Fig.1 Current sharing of seven GTO samples

Project Title: Development of a Medium Voltage Fast Charger**Team Members**

Project Leader: Srdjan Lukic (ECE/NCSU)

Students: Chi Zhang (PhD), Xinyu Liang (PhD), Srdjan Srdic (Post Doc)

Funding Agency: US Department of Energy

Funding Period: 12/01/2014 – 06/01/2016

Project Abstract

The objective of this task is to design and build a medium voltage electric vehicle (EV) fast charger using WBG devices. The proposed converter will utilize off-the-shelf SiC and potentially GaN devices to step down and rectify the single phase medium-voltage input. The NC State team will bring this concept from TRL 3-4 to TRL 6-7 proving the viability of the concept in an “open-source” manner, so that the technology can be offered to the Institute partners and industry members for further commercialization and mass production. The fast charge prototype will be a building block for the commercialization of a whole new product line, serving a set of emerging applications, including DC data centers or other DC power distribution systems. The motivation for introducing a WBG solution for the MV rectification application is: (1) potential for higher efficiency (2) higher power density and (3) system-level cost savings. In the case of the EV charger, feeding power directly from a single phase medium voltage line will substantially reduce the installation cost (EPRI has estimated that the installation costs would be reduced by 50% or more, depending on the site), and reduce the system footprint (important criteria in densely populated areas). As a result, the WBG solution would have a distinct competitive advantage if it can be manufactured at parity or even at a premium over the conventional solution.

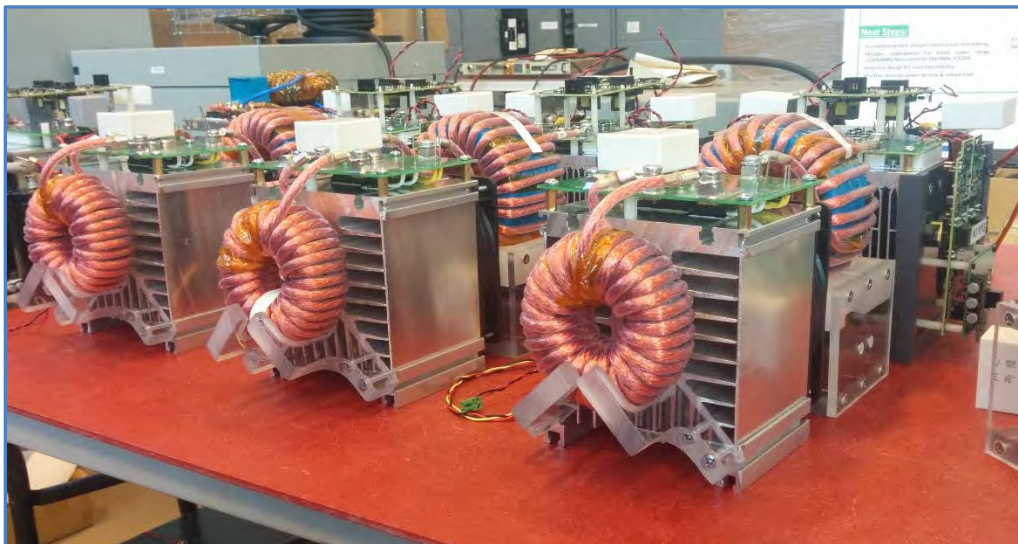


Figure 1: Fast Charger Prototype

Project Title: Development of SiC/GaN Based High Performance PV String Inverters and Micro Inverters

Team Members

Project Leader: Raja Ayyanar, ASU

Students: Yinglai Xia (PhD), Jinia Roy (PhD) and Robert Mongrain (PhD)

Funding Agency: DOE PowerAmerica Institute

Funding Period: 02/01/2015 – 03/31/2016

Project Abstract

This project focuses on developing high performance, single phase PV string and micro inverters through a combination of wide bandgap (WBG) devices and an innovative converter topology. The topology addresses the two major issues in transformer-less, single-phase PV inverters namely the common-mode ground currents and the need for large electrolytic capacitors to support 120 Hz power pulsations. The topology allows the AC neutral (ground) of the transformer-less inverter to be connected directly to the PV negative thus eliminating common-mode PV ground currents. The topology has an inherent active power decoupling feature which supports 120 Hz power pulsation through dynamically variable dc link and use of only reliable film capacitors. High voltage (1.2 kV) SiC devices are key to efficient implementation of this particular topology since the switch stress is above 1 kV and switching frequency in the range of 100 kHz is preferred for inductor size reduction. The developed concepts have been successfully demonstrated in WBG and film capacitor based string inverter prototype (Fig. 1) achieving $>30 \text{ W/in}^3$ power density, CEC efficiency of 96% at 75 kHz switching frequency, and one of the lowest reported capacitor required per kW. For the microinverters high performance dc-dc converter concepts with high voltage conversion ratios have been developed. The developed PV inverter is capable of supporting a wide range of power factors to provide interactive grid support.

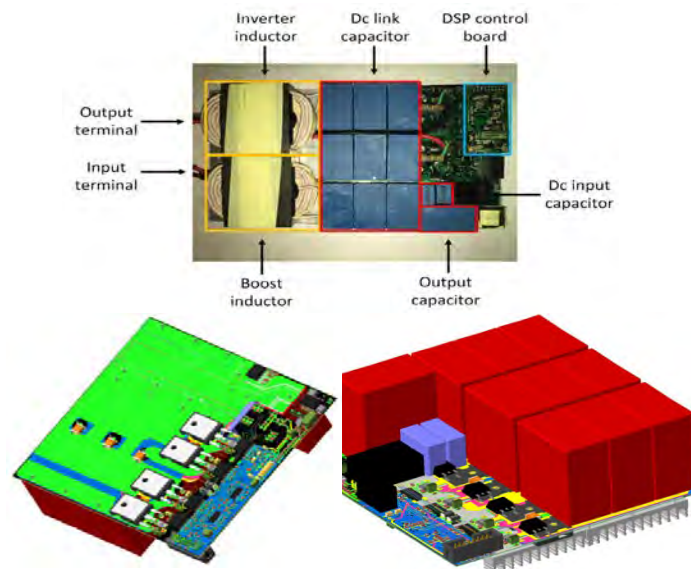


Figure 1: 3 kW PV string inverter prototype with $>30 \text{ W/in}^3$ power density

Project Title: Resilient Multi-terminal HVDC Using High Voltage High Frequency Electronics Capability

Team Members

Project Leader: Subhashish Bhattacharya, (ECE/NCSU)

Students: Sayan Acharya (PhD), Ali Azidehak (PhD), Mahsa Kashani (PhD), Kasunaidu Vechalapu (PhD), Govind Chavan (PhD), Nima Yousefpoor (PhD, graduated), Sungmin Kim (visiting PhD student), Ajit Narwal (MS, graduated), Akash Gujarati (MS, graduated)

Industrial Partners: GE

Funding Agency: ARPA-E

Funding Period: 4/1/2012-1/22/2017

Project Abstract:

A fault resilient multi-terminal Voltage Source Converter (VSC) based High Voltage Direct Current (HVDC) transmission technology has been established to enable dynamic routing of electric power with high efficiency and reliability. The direct integration of Solar Power to the HVDC grid is also accomplished to harvest more yields from renewable energy sources. The overall system control was developed and the fault resiliency of the system was demonstrated using real time simulation platforms (such as RTDS and OPAL RT). A scaled prototype of the converter system was built and tested to prove the proposed control algorithm.

The VSC based HVDC technology is modular in structure which allows system scalability to achieve any voltage and power rating. From the manufacturing point of view this is a huge advantage. Each module is based on a high-voltage high-frequency power conversion topology in which the galvanic isolation is achieved by a high-frequency (20-50 kHz) step-up transformer. Hence, the low-frequency grid side transformer is eliminated which results significant reduction in the system footprint. Furthermore, because of the high frequency operation of the converters, the contingency issues can be handled more efficiently than the low frequency converters. Therefore the system is resilient to the short circuit faults in either the AC or DC side. Another benefit of this system is that the renewable energy sources like solar energy can be integrated to the DC grid in a single stage power conversion (DC to DC) unlike the AC grid system where two stage power conversion (first DC to DC then, DC to AC) has to be implemented to push power into the AC grid. This increases the overall system efficiency and enables more clean energy with minimum waste. HVDC technology has several distinct advantages when compared to conventional High Voltage AC transmission:

- A long distance HVDC transmission scheme generally has lower capital costs than an equivalent AC transmission scheme. This is because HVDC requires less conductor per unit distance than an AC line.
- HVDC can transfer power between separate AC networks, which can be automatically controlled to support either network during transient conditions, without the risk of a cascading grid collapse.

The configuration of a four terminal hybrid Multi-Terminal HVDC system is illustrated in Figure 1(a). The whole system is interconnected via cables. Figure 1(b) Shows the real time simulation platforms (RTDS

and OPAL RT). These two systems are interconnected and synchronized to simulate the whole system in real time.

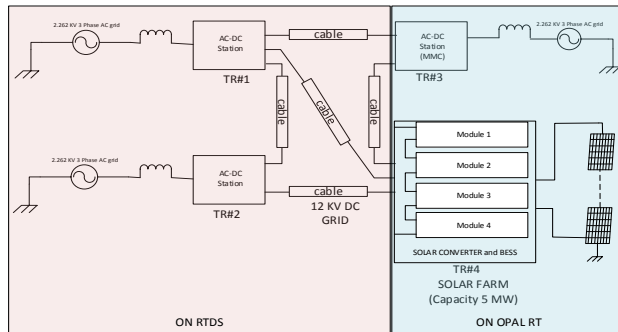


Figure 1: (a) MTDC SYSTEM LAYOUT

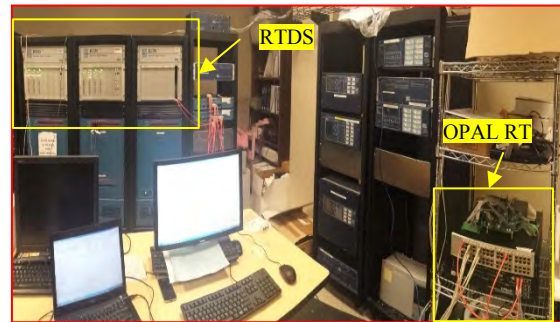


Figure 1: (b) REAL TIME SIMULATION PLATFORMS

Project Title: SiC power devices & DC power distribution system

Team Members

Project Leader: Dr. Alex Q. Huang

Students: Suxuan Guo, Liqi Zhang, Pengkun

Funding Agency: Cree

Funding Period: 08/01/2013 - present

Abstract: The goal of this project is to develop a fundamental understanding of the electrical and thermal limitations of SiC power MOSFETs at high switching frequencies. Gate driving and sensing techniques are being studied and explored in detail to achieve the full potential of the SiC power MOSFET module. In this reporting year, a highly integrated 1200V SiC MOSFET module is developed which has demonstrated **zero turn-off loss** (ZTL) and noise free operation. ZTL is a new concept and major contribution to the WBG power electronics community. Results from this project were widely reported at IEEE WIPDA 2015 and IEEE 2016 APEC. Operation of the module at 3.36 MHz has been demonstrated under the soft switching condition. This is the highest reported switching frequency for a 1200V SiC power MOSFET module.

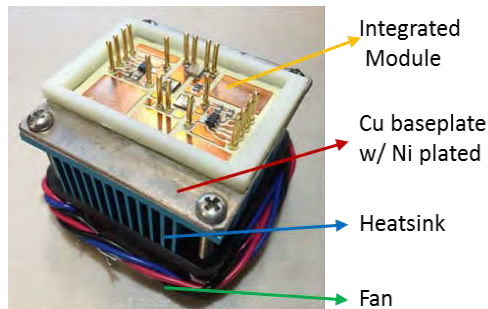


Fig.1 Integrated 1200V High Frequency SiC module

$$V_{ds} = 800V \quad I_d = 10A \quad R_{g\_ext} = 0\Omega$$

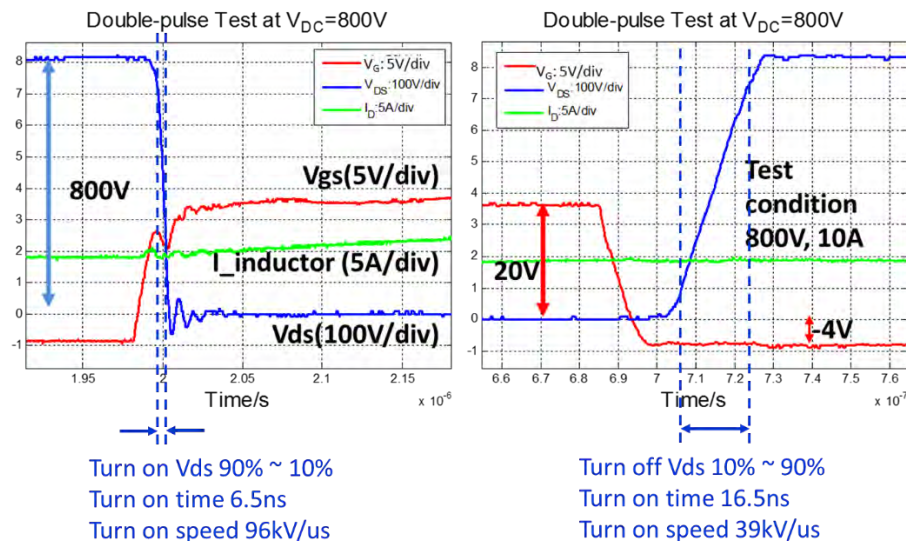


Fig.2 Noise free ultra-fast turn-on and turn-off operation of the developed module

Associated Projects

Fundamental Science

Project Title: Medium Voltage Gate Drive with 10 kHz 10 kV SiC MOSFET for 2.3 kV, Motor Drives

Team Members

Project Leader: Dr. Subhashish Bhattacharya (NCSU/ECE)

Students: Awneesh Tripathi, Sachin Madhusoodhanan (ECE PhD), Dr. Krishna Mainali (Post Doc ECE)

Funding Agency: DOE PowerAmerica Institute

Funding Period: 01/01/2015 – 12/31/2015

Project Abstract

The primary objective of the project is to design, develop and validate a 15 kV isolated gate driver (GD) for a SiC MOSFET suitable for operating at 10 kHz to 20 kHz with integrated diagnostics and active gate driving capability as shown in Figs 1-2. Tasks such as Intelligent Gate Driver (IGD) development, isolation transformer design with low coupling capacitance and high fundamental frequency converter design for MV motor drives are implemented as shown in Figs 3-4. An intelligent gate driver board is designed and developed with features such as device temperature measurement, device collector-emitter voltage measurement during on-state, device current measurement, active gate drive features and de-sat protection. The developed IGD board is tested on double-pulse test circuit for validating active gate drive section, boost converter for low side measurement and boost-buck converter for high side measurement.

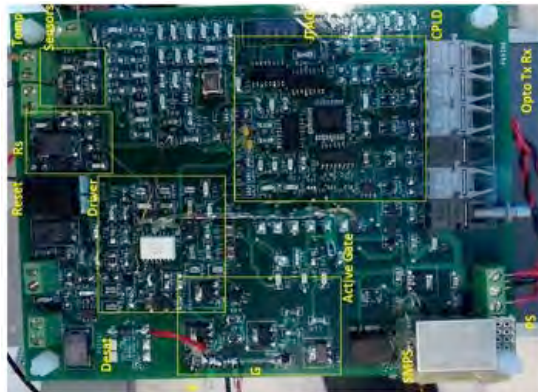


Figure 1: Intelligent gate driver (IGD)

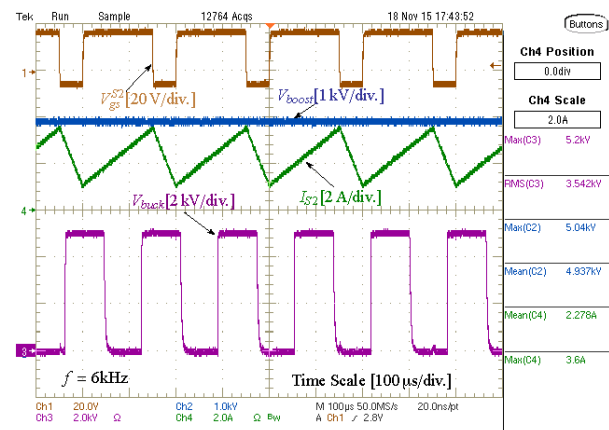


Figure 2: Boost-buck test waveforms for the IGD

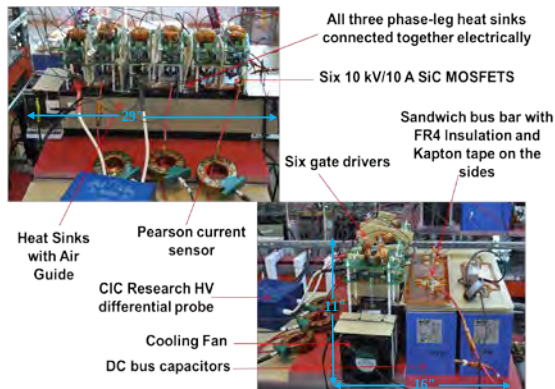


Figure 3: Three-phase high frequency converter

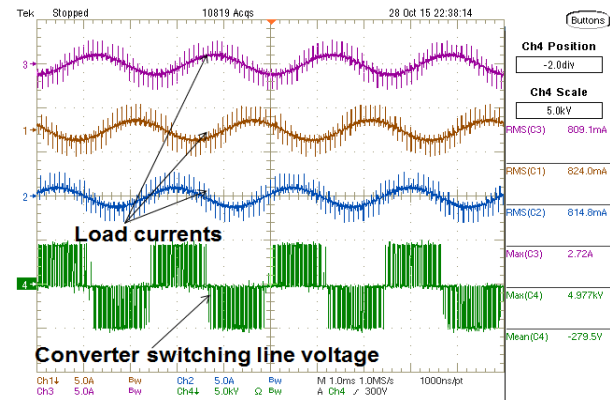


Figure 4: Converter waveforms, 400 Hz fundamental frequency

Project Title: Collaborative Research: Computational Methods for Stability Assessment of Power Systems with High Penetration of Clean Renewal Energy

Team Members

Project Leader: Aranya Chakraborty (NC State, Electrical and Computer Engineering)

Students: Sayak Mukherjee (EE PhD)

Funding Agency: National Science Foundation

Funding Period: 09/01/2015 – 08/31/2017

Project Abstract

The electrical power grid is currently undergoing the architectural revolution with the increasing penetration of renewable and distributed energy sources and the presence of millions of active endpoints. Introduction of these novel components affects the stability of the system, i.e. its ability to return to normal operating conditions after disturbances. This lack of stability may compromise the reliable power supply and result in cascading blackouts in the most dramatic scenarios. The key intellectual merit of the project will be demonstrated through the development of a theoretical foundation for the problem of stability assessment of future power grids with high levels of renewable energy penetration. An interdisciplinary team of researchers from 3 US institutions will bring in cutting edge innovations from a number of fields like power systems dynamics and control, numerical algebraic geometry, and nonlinear systems in order to develop the computational tools to analyze the highly nonlinear dynamic behaviors and to certify stability/feasibility of operating points in the next generation power grids. From a broader impact perspective the project addresses some of the most difficult and important challenges of modern society.

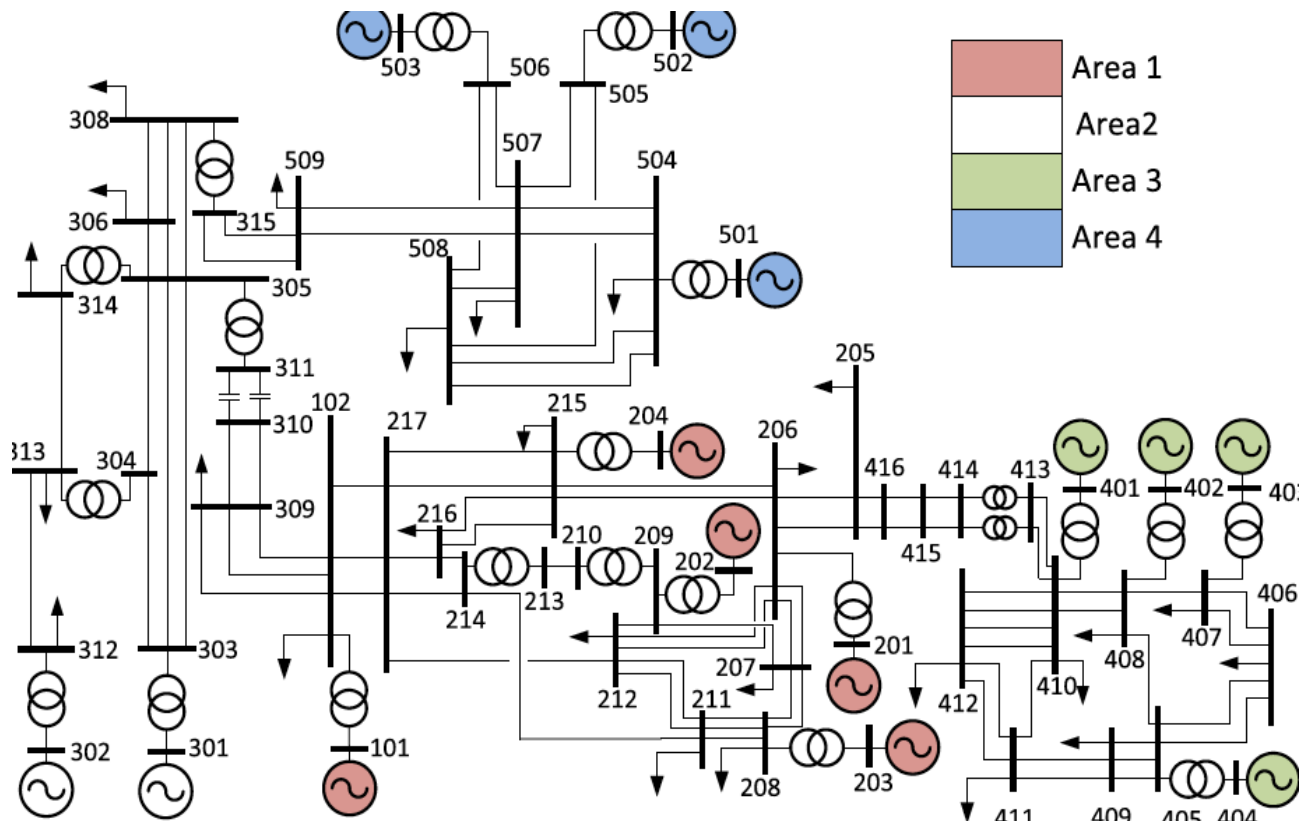


Figure 1: Power Flow Methods for Large Power Systems with Renewable Penetrations

Project Title: CPS: Breakthrough: Collaborative Research: Securing Smart Grid by Understanding Communications Infrastructure Dependencies

Team Members

Project Leader: Mariesa Crow (Missouri University of Science and Technology-Electrical and Computer Engineering)

Funding Period: 9/1/2015 – 8/31/2016

Project Abstract:

The breakthrough research of this project is to undertake a holistic approach to understand and characterize the interdependencies between the smart grid and its overlaid communications infrastructure, and securing them against attacks and/or failures. We will examine the standard protocols used in smart grid communications via their open-source implementation, investigate their vulnerabilities, and explore ways of hardening the protocols. For hardening, we will explore both the addition of lightweight security features and changes to the protocol so that the protocols become less vulnerable to attacks without significantly impacting its latency properties. This is critical since communications latency directly impacts the stability and reliability of the smart grid. Additionally, since a reliable state estimation is central to the proper control of the power grid, we will study robust state estimation techniques that can tolerate and detect meters supplying bad data. To this end, we will explore trust based schemes to identify and isolate faulty/suspicious communications nodes and use this information, coupled with known vulnerabilities, for reconfiguration that minimizes the impact of attacks and the spread of instabilities/failures. In order to thwart persistent attacks by intelligent adversaries, we will examine dynamic defense mechanisms modeled in game theoretic settings, with attackers and defenders, with each optimizing his/her own objectives. Finally, we will validate our mechanisms via detailed smart-grid simulations as well as through limited experiments on our micro grid facilities.

Project Title: CPS: TTP Option: Synergy: Collaborative Research: Hardening Network Infrastructures for Fast, Resilient and Cost-Optimal Wide-Area Control of Power Systems

Team Members

Project Leader: Aranya Chakraborty (NC State, Electrical and Computer Engineering)

Students: Mang Liao (EE PhD)

Funding Agency: National Science Foundation

Funding Period: 09/01/2015 – 08/31/2018

Project Abstract

The goal of this NSF CPS project is to construct a massively deployable cyber-physical architecture for wide-area control that is fast, resilient and cost-optimal (FRESCO). The FRESCO grid will consist of a suite of optimal control algorithms for damping oscillations in power flows and voltages, implemented on top of a cost-effective and cyber-secure distributed computing infrastructure connected by high-speed wide-area networks that are dynamically programmable and reconfigurable. The value of constructing FRESCO is twofold (1) If a US-wide communication network capable of transporting gigabit volumes of PMU data for wide-area control indeed needs to be implemented over the next five years then power system operators must have a clear sense of how various forms of delays, packet losses, and security threats affect the stability of these control loops. (2) Moreover, such wide-area communication must be made economically feasible and sustainable via joint decision-making processes between participating utility companies, and testing how controls can play a potential role in facilitating such economics. Currently, there is very limited insight into how the PMU data transport protocols may lead to a variety of such delay patterns, or dictate the economic investments.

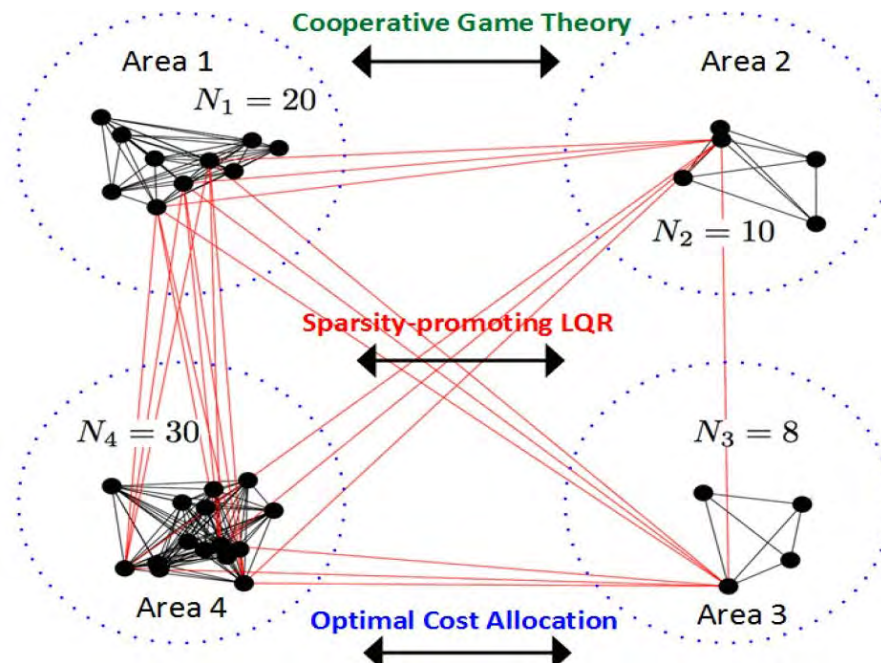


Figure 1: Fast, Reliable, Cost Optimal (FRESCO) Wide-area Control of Power Systems.

Project Title: Design of High Performance, Low-cost, Non-rare Earth Electric Machines Meeting IE4/IE5 Efficiency Requirements

Team Members

Project Leader: Dr. Iqbal Husain (ECE, North Carolina State University)

Students: Md. Ashfanor Kabir (PhD)

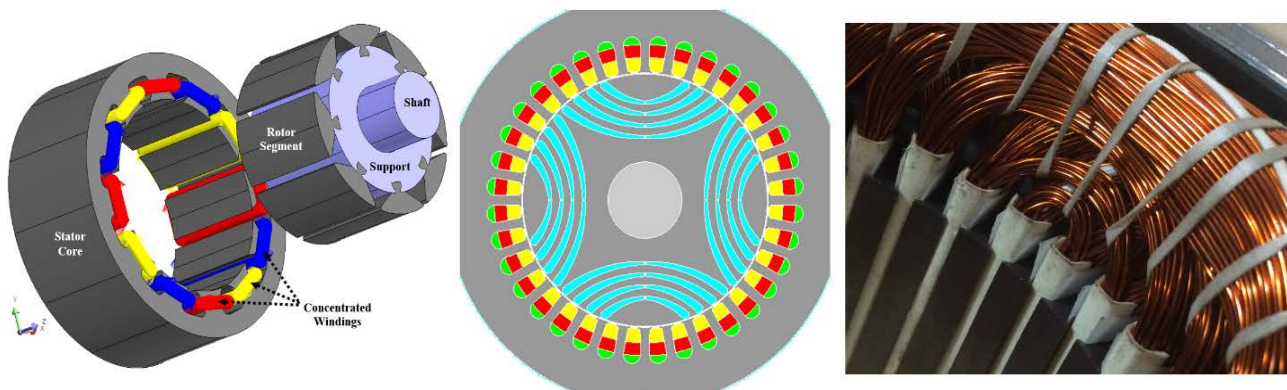
Industry Participants: ABB US Corporate Research (USCRC), Raleigh, NC.

Funding Agency: ABB US Corporate Research (USCRC)

Funding Period: 1/1/2016-12/31/2016

Project Abstract:

The objective of the project is to design, fabricate and test a non-rare earth, air-cooled electric machine that meets the efficiency requirements of super-premium (IE4) or ultra-premium (IE5) design classes imposed by the IEC 60034-30 nominal efficiency standard. First, a squirrel cage induction machine (SCIM) has been selected as the first topology to investigate. Initially, an accurate FEA based model of SCIM is being developed to investigate the design-tradeoffs in terms of starting and rated performance to select a set of design guidelines for its cage geometry. Second, the application of lightly ferromagnetic cage materials have been investigated. It was found through detailed time-harmonic and transient FEA analysis that with ferromagnetic rotor bar/ring, both the secondary resistance and inductance gets affected, which does not improve machine's performance. The current research focus is on a 3-phase variable speed drive (VSD) system for higher system level efficiency than its line-fed counterparts. Moving towards synchronous machine technologies from induction machines helps in eliminating rotor I^2R losses, which is around 20% of the total loss for the selected power range (≤ 7.5 kW). Both Switched (SRM) and Synchronous (SynRM) reluctance machines have been considered as the low-cost, non-PM alternatives. For the SRM, a new concentrated winding configuration using segmented rotor is proposed that can use a 3-phase standard VSI topology as in Figure 1a. Moreover, a new multilayer winding design for SynRM is proposed as in Figure 1b and 1c that improves overall machine performances. Currently, both of these machines are in the prototype building stage. A 5 hp test-bed is under development for the experimental verification of the proposed Segmented SRM and Multilayer SynRM topologies.



(a) 3D FEA model of Segmented Rotor SRM (b) Designed multilayer SynRM in 2D FEA (c) Stator details of the multilayer SynRM prototype.

Figure 1: Selected non-rare machine topologies for analysis

Project Title: Load Regulation with PV-Storage and Electric Vehicle with Dynamic Programming

Team Members

Project Leader: Dr. Iqbal Husain (ECE, North Carolina State University)

Students: Faeza Hafiz (PhD)

Funding Agency: State of North Carolina

Funding Period: 9/1/2015 -8/31/2016

Project Abstract:

The objective of this project is to regulate household load by means of coordinated control between solar PV storage and electric vehicle battery storage. The solar energy available can be optimally utilized with the help of storage in a smart household system. When the demand is low, especially during daytime working hours, solar power can be stored and then used later, when demand increases especially in the early evening, when the household members come back from work or other activities. Similarly, when the homeowner plugs in his/her plug-in electric vehicle (PEV or PHEV) to the grid at night, it will also increase the power demand of the household. If a PEV or PHEV is capable of delivering power to the household, then it may discharge at times of higher demand and charge up whenever the demand is low. Therefore, the charging and discharging of the two storage components require a coordinated control strategy capable of balancing the household systems' power demand.

A Dynamic Programming (DP) technique is an effective method for solving the optimization problem for charging and discharging of storage devices. However, it is quite complicated to handle a multi-dimensional problem through DP because it requires a lot of time and memory. To manage the computational complexity, a Dynamic Programming Successive Algorithm (DPSA) has been used to obtain the optimal charging strategies by minimizing the daily grid power demand of a household.

The household system, including the solar storage and PHEV storage shown in Fig. 1 (a) and (b) shows the reduction of grid power demand in the 'regulated profile' and improvement of overall load variance with the control strategy. This method is being expanded to minimize the load variance in a distribution level and study the effect of coordinated control among distributed energy sources using DPSA.

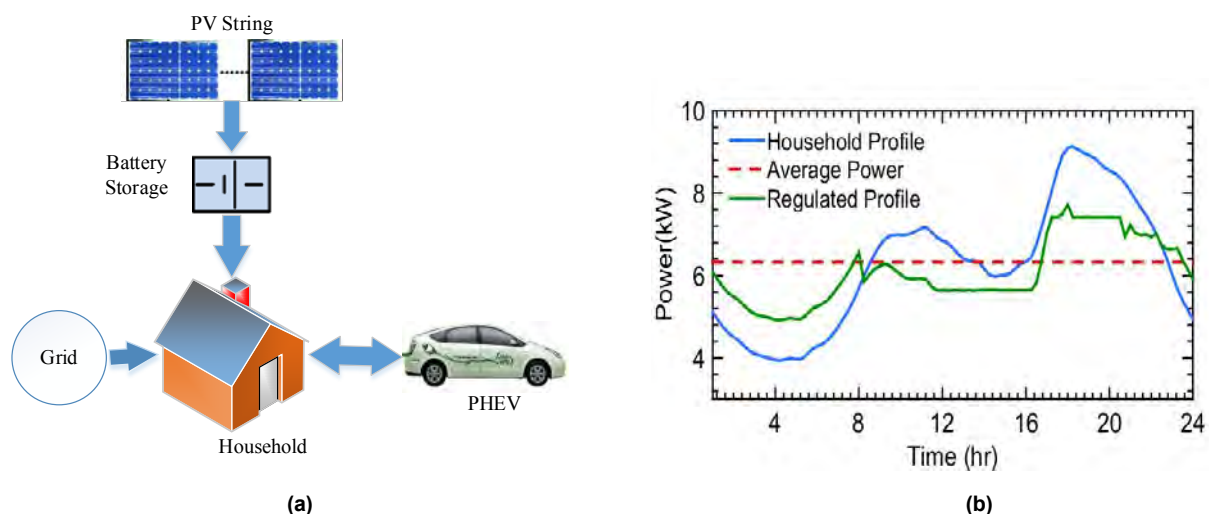


Fig.1: (a) Smart Household System. (b) Household profile, Average power and Regulated profile after control.

Project Title: The MidAmerica Regional Microgrid Education and Training (MARMET) Consortium

Team Members

Project Leader: Mariesa Crow, Missouri University of Science & Technology (PI)
Jonathan Kimball, Missouri S&T
University of Illinois Urbana-Champaign
Iowa State University
University of Wisconsin
National Rural Electric Cooperative Association

Funding Agency: Department of Energy

Funding Period: 10/1/2013-9/30/2019

Project Abstract

The primary goal of this project is to integrate cutting-edge research and advanced instructional methods to create a flexible, evolving approach to microgrid and distributed energy resources training for all levels of student. This goal entails the rapid development of modular material to capture and reflect the newest trends in electric power microgrid engineering and to make it available in traditional and non-traditional settings. It is our goal to develop course material that can be integrated into either existing courses or organized into new courses. The target audience ranges include technicians, contractors and consultants, inspectors, policy makers, supervisors, and engineers and undergraduate and graduate students.



Figure 1: MARMET fosters the development of curriculum for the next generation power engineer

Project Title: Solar Electric Home Energy Management Program

Team Members

Project Leader: Ning Lu (NC State University/ECE)

Students: Xiangqi Zhu and Jian Lu (EEPhD)

Funding Agency: Total Inc.

Funding Period: 11/01/2015 – 31/10/2017

Project Abstract

There are several major tasks performed under this contract by teams at North Carolina State University under this contract. The detailed scope of work and program deliverables for this program are considered proprietary and are not able to be shared beyond project participants and the funding agency.

Total is a full member of the Center and continues to be highly engaged in both pre-commercial research as well as fully commercial research.

Project Title: US Ignite: Track 1: Collaborative Research: DISTINCT: A Distributed Multi-Loop Networked System for Wide-Area Control of Large Power Grids

Team Members

Project Leader: Aranya Chakraborty (NC State, Electrical and Computer Engineering)

Students: Jianhua Zhang (EE PhD), Matthew Weiss (EE PhD)

Funding Agency: National Science Foundation

Funding Period: 09/01/2015 – 08/31/2018

Project Abstract

Developing a reliable wide-area communication network that guarantees just-in-time data delivery is the greatest challenge. Unfortunately, neither the architecture of such networks nor the impacts of delays and data losses on control actions are well understood. This project seeks to address this gap, and develop a highly resilient, fault-tolerant, and reliable distributed network control system for tomorrow's power grids using cutting-edge emerging technologies, such as cloud computing and software defined networks. Power systems are a critical infrastructural component in modern society. Therefore, results of this research can have a tremendous scientific impact on the smart grid and smart city research communities. The proposed multidisciplinary approach, test bed prototyping, and industry collaborations will help in educating next-generation workforce in the fields of smart grids and cyber-physical systems.

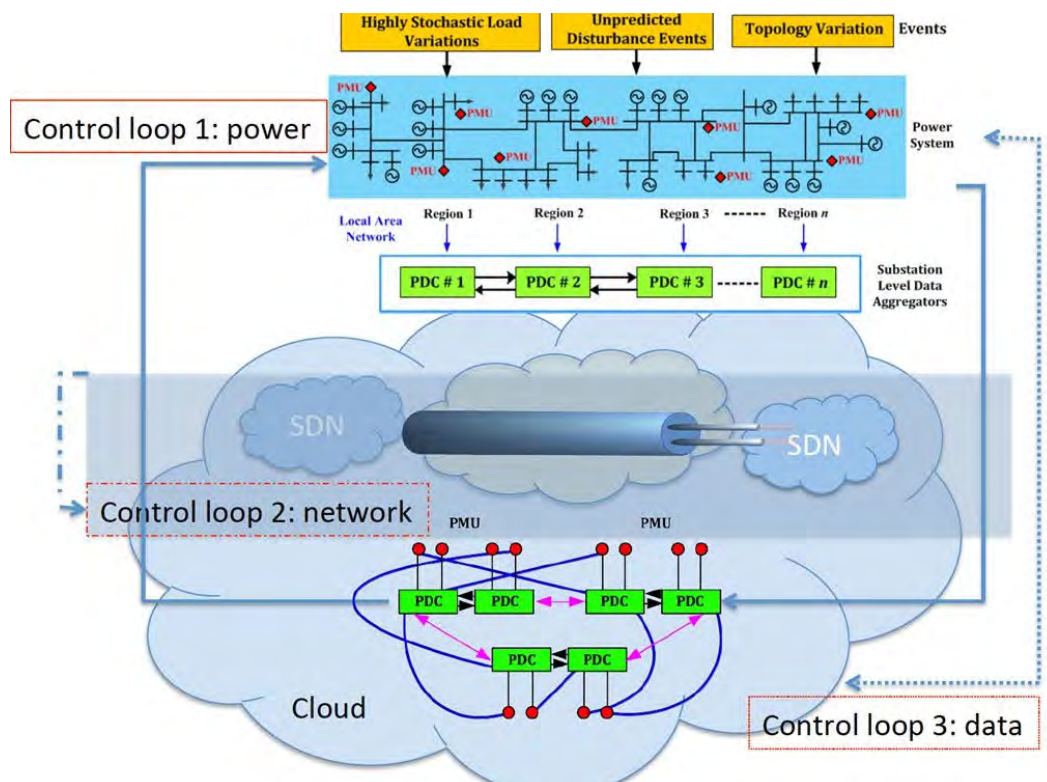


Figure 1: Distributed Network Control for Wide-area Control of Power Systems using Cloud Computing

Education Projects

Project Title: Engineering Guides of NC

Team Members

Project Leader: Pam Carpenter (FREEDM/NCSU)
Team Members: Gail Jones (ERC ASSIST/NCSU), Amy Chilcothe (NCCES/NCSU)
Students: Rebecca Hite (College of Education, NCSU)

Funding Agency: North Carolina State University, Office of Outreach and Engagement

Funding Period: 07/01/2014 – 07/01/2015

Project Abstract

Education in Science, Technology, Engineering, and Math (STEM) has had national importance for several years. And within the past few years, North Carolina (NC) has stressed integration of engineering within the K-12 STEM curriculum. This new emphasis has many middle and high school educators as well as informal education groups such as home schools, civic clubs, and NCCES 4-H struggling with content knowledge and resources. North Carolina has a small number of K-12 programs focused on engineering that include Project Lead the Way (PLTW), Wake-NC State Early College High School, and various outreach efforts but many programs are limited to reaching specific NC counties.

An Outreach and Engagement Seed grant was awarded in 2014 to help to develop a state-wide, adult volunteer-based engineering outreach program called Engineering Guides of NC. This grant will provide support for program model development, forming partnerships between industry and university groups, and conceptualization for grant writing. The program will support NC K-12 educators in formal and informal settings by offering basic engineering hands-on activities targeting two national engineering grand challenges (health, energy and environment). This volunteer-based program models the existing NC Cooperative Extension Service (NCCES) programs, Master Gardener and Regional Equine Information Network System (REINS). The lesson plans and activities are in the final stages of development and pilot tests are underway prior to a wider distribution of the kits.

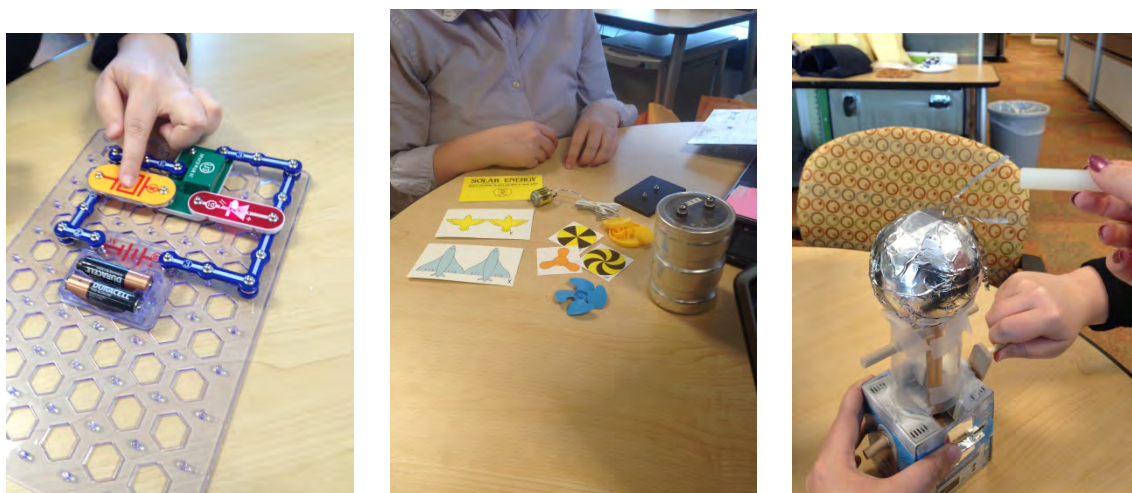


Figure 1: Hands-on activities

Project Title: Kenan Fellow for the FREEDM Systems Center

Team Members

Project Leader: Pam Carpenter (FREEDM/NC State)

Funding Agency: FREEDM Systems Center

Funding Amount: \$50,000

Funding Period: 7/1/2015 – 6/30/2016

Project Abstract

The Kenan Fellows Program for Curriculum and Leadership Development is a competitive fellowship offered to K-12 public school teachers. The mission of the Kenan Fellows Program is to enhance curriculum relevance for the benefit of all students; engage teachers, business, and universities through unique professional collaboration; and promote growth opportunities for teachers and the teaching profession. The Kenan Institute for Engineering, Technology & Science provided funding to the FREEDM Systems Center that allowed one fellow to experience the Center from the extended RET vantage afforded by the expanded support and resources offered to Kenan Fellows.

In Year 8, the Center hosted a middle school teacher, Ms. Joanne Jeffries, who developed lesson plans and a project on the business of solar energy.

Ms. Jeffries' Project Summary:

Participants will conduct independent research on solar energy and use this research to create a Marketing Powerpoint. Participants will apply the Marketing Mix principles of product, price, place and promotion to a new solar business they will manage. Participants will be expected to create a 3-5 minute presentation about this solar business. Participants will use internet resources to research, and industry guest speakers to obtain project information and to create the Powerpoint presentation. A rubric will be used to assess the final presentation.



Dr. Carpenter's visit to Ms. Jeffries' classroom Fall 2015

Data Management Plan

FREEDM Data Management Plan – Revised 04/09/2016

This document presents a high level plan for how the ERC manages the data generated by the Center and the specific tools that will be used to ensure the confidentiality, security, and use of data generated by the Center and its partners in the conduct of the program. Personal data such as social security numbers and other personal identifying information is covered by other existing standards and regulations and is not covered here.

Intellectual property is a related issue that is described in the by-laws of the ERC and processes for its management and dissemination are not discussed here. Further, each university has its own policies for data security, retention, and confidentiality and these local policies take precedence over this document.

Expected Types of data

Numerous forms of data will be generated by the Center in the course of conducting the research and education activities. These include material composition and properties, processing variables, modeling and simulation results, circuit architecture, software/firmware/middleware, control parameters, mathematical and computer models, experimental results, and many other types of material, device, and system data. In addition, program results from education activities (but not personal information) will be collected and stored. These data will be generated throughout the ERC enterprise and will have different needs for storage, sharing, and archiving.

Format and Content Standards

There is not currently a uniform standard for the many types of data being generated by the ERC. The core partner universities and the industry members that participate in the research program are unlikely to establish a uniform standard as this might cause an unnecessary additional administrative burden that would add additional cost to each project without significant benefit.

Access and Sharing

All data generated in the course of conducting the programs of the ERC will be stored locally by the organization that generates the data. Each organization will be responsible for protecting the data in accordance with the governing university standards and the center's bylaws. As all universities retain rights in data and other intellectual property generated in the course of its research (In accordance with the Bayh-Dole Act) each participant has the obligation to protect such data and share it with other participants in accordance with the center by-laws.

Period of Retention

All data generated by the Center will be retained by the originator for a period of no less than three years beyond the date of generation, in accordance with existing NSF guidelines.

Data Storage and Preservation

Each participating organization will be responsible for determining the most efficient system for data storage and preservation. The FREEDM intranet will serve as the central repository for high level project data that needs to be shared among participants for ongoing project activities. This is a secure website accessible by students, faculty and industry members only. Data will be saved on site in multiple common electronic formats; Secure central storage, hard drives, and each participants "cloud" storage system. Regular checks are conducted to determine those students, faculty and industry representatives who are no longer part of the center. Once determined, their access is removed. For students at N.C. State University, this process is automatic when students leave the university as a part of the Shibboleth authentication system.

Biographical Sketches

Petru Andrei

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<http://www.eng.fsu.edu/~pandrei>

A. Professional Preparation

Al. I. Cuza University, Romania	Physics	B.S., 1997
Al. I. Cuza University, Romania	Physics	M.S., 1999
University of Maryland, College Park	Electrical Engineering	Ph.D., 2004

A. Appointments

Associate Professor of Electrical and Computer Engineering 2010-present
Florida A&M University and Florida State University, Tallahassee, Florida

Assistant Professor of Electrical and Computer Engineering 2004-2010
Florida A&M University and Florida State University, Tallahassee, Florida

Summer Research Faculty, Naval Research Laboratory (NRL), Summers 2007&2008
University of Maryland, College Park, MD

Faculty Research Assistant, Electrical and Computer Engineering, Summer 2004
University of Maryland, College Park, MD

Graduate Research Assistant, Electrical and Computer Engineering, 2000-2004
University of Maryland, College Park, MD

Graduate Teaching Assistant, Electrical and Computer Engineering, 1999-2000
University of Maryland, College Park, MD

C1. Five relevant products:

- [1] M Mehta, V Bevara, and P Andrei, "Maximum theoretical power density of lithium-air batteries with mixed electrolyte", *Journal of Power Sources*, vol. 286, 299-308, 2015.
- [2] M. Mehta, V. Bevara, and P. Andrei, "Maximum theoretical power density of lithium-air batteries with mixed electrolyte", *Journal of Power Sources*, vol. 286, 299-308, 2015.
- [3] V. Bevara, and P. Andrei, "Changing the cathode microstructure to improve the capacity of Li-air batteries: theoretical predictions", *Journal of The Electrochemical Society*, vol. 161, pp. A2068-A2079, 2014.
- [4] X. J. Chen, V. Bevara, and P. Andrei, "Combined effects of oxygen diffusion and electronic resistance in Li-air batteries with carbon nanofiber cathodes", *Journal of The Electrochemical Society*, vol. 161, pp. A1877-A1883, 2014.
- [5] M. Mehta, G. Mixon, J.P. Zheng, and P. Andrei, "Analytical electrochemical impedance modeling of Li-air batteries under dc discharge", *Journal of The Electrochemical Society*, vol. 160, pp. A2033-A2045, 2013.

C.2 Five other significant products (selected out of more than 60 refereed journal papers and one book)

- [1] M. Dimian, P. Andrei, M. Mehta, and A. Idubor, "Thermal relaxation in magnetic multi-layer materials with mixed hysteretic behavior", *Journal of Applied Physics*, vol. 117, art. no. 17A745, 2015.

- [2] M. Hagmann, P. Andrei, S. Pandey, and A. Nahata, "Possible applications of scanning frequency comb microscopy for carrier profiling in semiconductors", *Journal of Vacuum Science & Technology B*, vol. 33, art. no. 02B109, 2015.
- [3] M. Dimian and P. Andrei, *Noise-driven phenomena in hysteretic systems*, Springer, ISBN: 1461413737, 2014.
- [4] M. Dimian, P. Andrei, and M. Grayson, "Hybrid models of hysteresis for mixed hysteretic loops in heterogeneous magnetic materials", *Journal of Applied Physics*, vol. 115, art. no. 17D103, 2014.
- [5] P. Andrei, J.P. Zheng, M. Hendrickson, E.H. Plichta, "Modeling of Li-air batteries with dual electrolyte", *J. Electrochem. Soc.*, vol. 159, pp. A770-A780, 2012.

D. Synergistic activities

1. Developed models and algorithms for the simulation and optimization of materials in fuel cells, Li-ion, and Li-air batteries, and for the optimization of the doping profiles in semiconductor devices. The developed simulators (RandFlux[®] and HysterSoft[®]) are being used by thousands of people worldwide in the academia and in the industry. Developed sensitivity analysis techniques for the random doping fluctuations, variability and uncertainty in semiconductor devices. Some of these techniques were recently implemented by commercial companies in their products, e.g. Sentaurus-Device, former DESSIS-ISE, Synopsis.
2. *Education Director* for the NSF-FREEDM Engineering Research Center at FSU (<http://www.freedom.ncsu.edu/>) I am responsible with the hiring, placement, and advising of the REU, RET, and high-school students for the Center at FSU since 2008. I am also the leader of the Modeling and Simulation Group at FAMU-FSU (<http://www.eng.fsu.edu/ms/>).
3. *Treasurer* for the Magnetism and Magnetic Materials Conference (this is the largest international conference in magnetics): Washington DC, 2010; IEEE International Magnetism Conference: Taipei, Taiwan, April 25-29, 2011; Vancouver, Canada, May 7-11, 2012; Dresden, Germany, May 4-8, 2014; Beijing, China, May 4-8, 2015. *Printing and Publicity Chair* for the IEEE International Magnetism Conference (this is the largest international conference in magnetics for engineers): San Diego, May 4-8 2006; Madrid, Spain, May 8-12, 2008; Sacramento, May 4-8, 2009. *Program Committee Member* for 12 international conferences on semiconductor devices and magnetism.
4. Serves as a regular reviewer for the J. of Applied Physics, Applied Physics Letters, Solid-State Electronics, IEEE Trans. on Magnetism, IEEE Trans. on Electron Devices, IEEE Trans. on Education, Microwave Engineering, Physica B, J. of Magnetism and Magnetic Materials, J. of Optoelectronics Devices, J. of Visualization, J. of Vacuum Science and Technology, J. for Computation and Mathematics in Electrical and Electronic Engineering. Serves as reviewer for the Oxford University Press and Cambridge University Press (publishing houses).
5. Senior Member of IEEE; Life Fellow of the APS; Received the FAMU-FSU College of Engineering Research Award (2008).

E. Collaborators and Other Affiliations

a) collaborators and co-editors (5): M. Ancona (Naval Research Laboratory, Washington D.C., USA); M. Dimian (Howard University, Washington D.C., USA); C. Kraft (Laboratory of Physical Sciences, College Park, USA); L. Spinu (U. of New Orleans, USA); J. Zheng (Florida State University, USA);

b) graduate and postdoctoral advisors (1): I. Mayergoyz (graduate and PhD advisor), University of Maryland, College Park, USA;

c) thesis advisor and postgraduate-scholar sponsor (6). Graduated 4 PhD students and 2 MS students; currently supervising other 3 PhD students and 2 MS students.

Biographical Sketch

Aranya Chakrabortty

Professional Preparation

2000 - 2004, B.E, Electrical Engineering
Jadavpur University, Calcutta, India.

2004 - 2005, M.S, Electrical Engineering
Rensselaer Polytechnic Institute, Troy, New York.

2005 - 2008, Ph.D, Electrical Engineering
Rensselaer Polytechnic Institute, Troy, New York.

2008 - 2009, Post-doctoral Research Associate
Aeronautics and Astronautics Department, University of Washington, Seattle, WA.

Appointments

2010-present, Associate Professor
Electrical & Computer Engineering, North Carolina State University, Raleigh, NC.

2009-2010, Assistant Professor
Electrical & Computer Engineering, Texas Tech University, Lubbock, TX.

Five Publications Related to this Project

1. A. Chakrabortty and M. D. Ilić (Editors), *Control & Optimization Methods for Electric Smart Grids*, Springer, MA, Jan. 2012.
2. T. R. Nudell and A. Chakrabortty. Graph-Theoretic Methods for Measurement-Based Input Localization in Large Networked Dynamic Systems, *IEEE Transactions on Automatic Control*, vol. 60(8), pp. 2114-2128, 2015.
3. A. Chakrabortty and C. F. Martin. Optimal Measurement Allocation Algorithms for Parametric Model Identification of Power Systems. *IEEE Transactions on Control Systems Technology*, vol. 22(5), pp. 1801-1812, 2014.
4. S. Chandra, D. F. Gayme, and A. Chakrabortty. Coordinating Wind Farms and Battery Management Systems for Inter-Area Oscillation Damping: A Frequency-Domain Approach. *IEEE Transactions on Power Systems*, vol. 29(3), pp. 1454-1462, 2014.
5. A. Chakrabortty. Wide-Area Control of Large Power Systems Using Dynamic Clustering and TCSC-Based Redesigns, *IEEE Transactions on Smart Grid*, vol. 3(4), 2012.

Five Other Publications

1. D. Soudbaksh, A. Chakrabortty, and A. Annaswamy. Computational Co-Designs for Wide-Area Control of Power Grids. *in proceedings of the 55th IEEE Conference on Decision and Control*, Los Angeles, CA, Dec. 2014.
2. A. Chakrabortty and P. Khargonekar. Introduction to Wide-Area Control of Power Systems, *in proceedings of American Control Conference*, Washington DC, pp. 6758 - 6770, Jun. 2013.

3. J. Zhang, P. Jaipuria, A. Hussain, and A. Chakraborty. Attack-Resilient Estimation of Power System Oscillation Modes using Distributed and Parallel Optimization: Theoretical and Experimental Methods. *in proceedings of GameSec* (Springer), Los Angeles, 2014.
4. A. Chakraborty, J. H. Chow and A. Salazar. A Measurement-based Framework for Dynamic Equivalencing of Large Power Systems using Wide-Area Phasor Measurements. *IEEE Transactions on Smart Grid*, vol. 1(2), pp. 68-81, 2011.
5. A. Chakraborty and M. Arcak. Robust Stabilization and Performance Recovery of Nonlinear Systems with Unmodeled Dynamics. *IEEE Transactions on Automatic Control*, vol. 54(6), pp. 1351-1356, June 2009.

Awards, Honors and Synergistic Activities

1. NSF CAREER Award, 2011.
2. Alan B. Dumont Prize for best PhD dissertation in ECE department, Rensselaer Polytechnic Institute, NY, 2008.
3. 2004- present, Reviewer for IEEE Transactions on Automatic Control, IEEE Transactions on Power Systems, IEEE Transactions on Smart Grid, Automatica, IEEE Transactions on Control Systems Technology, IEEE Transactions on Circuits and Systems, European Transactions on Power Systems, IEEE PES General Meeting, IEEE Conference on Decision and Control, National Science Foundation, Skolkovo Foundation, etc.
4. Senior Member of IEEE. Vice-Chair for Industry Applications in American Control Conference 2016; Technical Program Committee Member for IEEE SmartGridComm 2011-2013, American Control Conference 2012, ICCPS 2013, IEEE Infocom 2013; Symposia Chair (for Wide-Area Protection) in SmartGridComm 2012; Vice-Chair for Virtual Control Conference 2013; Invited member of IEEE CSS Smart Grid Vision Committee, 2011. Editor for IEEE CSS Conference Editorial Board, 2012-present
5. Invited talks (2011-present): Stanford Univ, UC Santa Barbara, UIUC, Tokyo Tech Univ, Los Alamos National Lab, Carnegie Mellon University, Iowa State University, Skolkovo Foundation (Moscow), Lund University, KTH Stockholm, University of Tennessee (Knoxville).

Collaborators & Other Affiliations

- Collaborators in past 5 years (total number of collaborators/co-editors = 15): Anu Anaswamy (MIT), Terry Benzel (USC), Rakesh Bobba (Univ of Illinois), Tim Bradberry (Duke Energy), Francesco Bullo (UC Santa Barbara), Juan Castaneda (Southern Calif. Edison), Jeff Chase (Duke University), Dennice Gayme (Johns Hopkins), Vijay Gupta (Notre Dame), Manimaran Govindarasu (Iowa State), Alefiya Hussain (Univ. of Southern California), Marija Ilic (CMU), Pramod Khargonekar (U Florida), Nitin Validya (Univ of Illinois), Yufeng Xin (UNC Chapel Hill).
- Graduate Advisors:
 1. Dr. Joe H. Chow, Rensselaer Polytechnic Institute, Troy, NY
 2. Dr. Murat Arcak, University of California Berkeley, CA
- Postdoctoral Sponsor: Dr. Mehran Mesbahi, University of Washington, Seattle, WA.
- Thesis advisor & Postgraduate-scholar Sponsor: Tom Nudell (2014, MIT), Behzad Nabavi (2015, Quanta Technologies), Kathleen Sico (2014, Duke Energy), Shangmin Lin (2014, Booz Allen Corp.), Sina Parhizi (2013, Univ of Colorado).

Biographical Sketch of Rajapandian Ayyanar

Education

PSG College of Technology, India	Electrical/Electronics Engg.	B.E. 1989
Indian Institute of Science, Bangalore	Electrical Engineering	M.S. 1995
University of Minnesota, Minneapolis	Power Electronics	Ph.D. 2000

Appointments

2006 – Present	Associate professor, EE, Arizona State University, Tempe
2000 – 2006	Assistant professor, EE, Arizona State University, Tempe
1997 – 2000	Graduate research assistant, University of Minnesota, Minneapolis
1995 – 1997	Project associate, Indian Institute of Science, Bangalore, India
1989 – 1992	Senior design engineer, R&D, Premier Instruments & Controls Ltd, India

Major Awards and Recognitions

Office of Naval Research Young Investigator Award, 2005
IEEE PES Phoenix Chapter Outstanding Engineer of the Year Award, 2012
Associate Editor for IEEE Transactions on Power Electronics

List of peer reviewed publications most closely related to the project

1. A. Nagarajan, R. Ayyanar, "Design and Strategy for the Deployment of Energy Storage Systems in a Distribution Feeder with Penetration of Renewable Resources," *IEEE Transactions on Sustainable Energy*, vol. 6, 2015, pp. 1085-1092.
2. T. Joshi, G. T. Heydt, R. Ayyanar, "An Analysis Approach for the Assessment of Pulse-width Modulated Carrier Frequency Spectral Components in Power Distribution Systems with Photovoltaic Resources," *ELECTRIC POWER COMPONENTS AND SYSTEMS*, vol. 43, pp. 2094-2104, 2015.
3. L. Breazeale, R. Ayyanar, "A Photovoltaic Array Transformer-Less Inverter with Film Capacitors and Silicon Carbide Transistors," *IEEE Transactions on Power Electronics*, vol. 30, 2015, pp. 1297-1305.
4. J. Steenis, K. Tsakalis, R. Ayyanar, "An Approach to Bumpless Control for LPV Modeled Inverters in a Microgrid," *IEEE Transactions on Power Electronics*, vol. 29, 2014, pp. 6214-6223
5. S. Kulasekaran, R. Ayyanar, "Analysis, Design, and Experimental Results of the Semi Dual-Active-Bridge Converter," *IEEE Transactions on Power Electronics*, vol. 29, 2014, pp. 5136-5147
6. S. Falcones, R. Ayyanar, X. Mao, "A DC-DC Multiport-Converter-Based Solid-State Transformer Integrating Distributed Generation and Storage," *IEEE Transactions on Power Electronics*, vol. 28, May 2013, pp. 2192 – 2203.
7. M. Fan, V. Vittal, G.T. Heydt, R. Ayyanar, "Probabilistic Power Flow Analysis with Generation Dispatch Including Photovoltaic Resources," *IEEE Transactions on Power Systems*, vol. 28, May 2013, pp. 1797-1805.
8. X. Mao, R. Ayyanar, H.K. Krishnamurthy, "Optimal Variable Switching Frequency Scheme for Reducing Switching Loss in Single-Phase Inverters Based on Time-Domain Ripple Analysis," *IEEE Transactions on Power Electronics*, vol. 24, April 2009, pp. 991-1001.
9. X. Mao, R. Ayyanar, "An Adaptive Controller for Inverter-Interfaced DGs Connected to Grids with a Wide Range of Unknown Impedances," *Proc. IEEE Energy Conversion Congress and Expo (ECCE 2010), Atlanta, GA, Sept. 2010*.
10. Z. Yu, R. Ayyanar, I. Husain, "A detailed analytical model of a solid state transformer," *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2015, pp. 723 – 729

List of other significant peer reviewed publications

1. G.T. Heydt, R. Ayyanar, K.W. Hedman, V. Vittal, "Electric Power and Energy Engineering: The First Century," *Proceedings of the IEEE*, vol. 100, Special Centennial Issue, 2012, pp. 1315 – 1328.
2. M. Fan, V. Vittal, G.T. Heydt, R. Ayyanar, "Preprocessing Uncertain Photovoltaic Data," *IEEE Transactions on Sustainable Energy*, vol. 5, 2014, pp. 351-352.
3. X. Mao, A.K. Jain, R. Ayyanar, "Hybrid Interleaved Space Vector PWM for Ripple Reduction in Modular Converters," *IEEE Transactions on Power Electronics*, vol. 26, July 2011, pp. 1954-1967.
4. D. Gautam, L. Goel, R. Ayyanar, V. Vittal, T. Harbour, "Control Strategy to Mitigate the Impact of Reduced Inertia due to Doubly Fed Induction Generators on Large Power Systems," *IEEE Transactions on Power Systems*, vol. 26, Feb. 2011, pp. 214-224
5. A.K. Jain, R. Ayyanar, "PWM Control of Dual Active Bridge: Comprehensive Analysis and Experimental Verification," in *IEEE Transactions on Power Electronics*, vol. 26, April 2011, pp. 1215-1227.
6. R. Giri, V. Choudhary, R. Ayyanar, N. Mohan, "Common-Duty-Ratio Control of Input-Series Connected Modular DC-DC Converters With Active Input Voltage and Load-Current Sharing," *IEEE Transactions on Industry Applications*, vol. 42, July-Aug. 2006, pp. 1101-1111.
7. G. Narayanan, H. Krishnamurthy, D. Zhao, R. Ayyanar, "Advanced Bus-Clamping PWM Techniques Based on Space Vector Approach," *IEEE Transactions on Power Electronics*, vol. 21, July 2006, pp. 974-984.
8. R. Ayyanar, R. Giri, N. Mohan, "Active input-voltage and load-current sharing in input-series and output-parallel connected modular dc-dc converters using dynamic input-voltage reference scheme," *IEEE Transactions on Power Electronics*, vol. 19, Nov 2004, pp. 1462-1473.
9. X. Gao, R. Ayyanar, "A High Performance, Integrated Magnetics Scheme for Buck-Cascaded Push-Pull Converter," *IEEE Power Electronics Letters*, vol. 2, March 2004, pp. 29-33.
10. W. J. Lambert, R. Ayyanar, S. Chickamenahalli, "Fast load transient regulation of low voltage converters with the low-voltage transient processor," *IEEE Transactions on Power Electronics*, vol. 24, July 2009, pp. 1839-1854.

List of related patents and books

1. X. Mao, R. Ayyanar, A.K. Jain, "Hybrid Space Vector PWM Schemes for Interleaved Three-phase Converters," US Patent 8,649,195, February 2014.
2. A.K. Jain, R. Ayyanar, "PWM Control of Dual Active Bridge Converters," US Patent 8,587,975, November 2013.
3. R. Ayyanar, W.J. Lambert, S. Chickamenahalli, "Transient Voltage Compensation System and Method," US Patent 8,243,410, August 14, 2012.
4. R. Ayyanar, N. Mohan, "Zero voltage switching dc-dc converter," US patent 6,611,444, August 2003.
5. R. Ayyanar, N. Mohan, "Zero voltage switching dc-dc converter," US patent 6,310,785, October 2001.
6. V. Vittal, R. Ayyanar, "Grid Integration and Dynamic Impact of Wind Energy" Springer, 2012, ISBN 1441993223, 9781441993229, Publication date: June 30, 2012

B. JAYANT BALIGA, Ph.D., FIEEE, NAE Member

Distinguished University Professor of Electrical Engineering
Founder & Director, Power Semiconductor Research Center
North Carolina State University, Raleigh, NC 27695-7924
Tel: 919-515-6169; Email: bjbaliga@ncsu.edu

Education:

Ph. D. Rensselaer Polytechnic Institute, Troy, NY, 1974 (4.0 GPA, Dumont Prize)
M. S. Rensselaer Polytechnic Institute, Troy, NY, 1971 (4.0 GPA)
B. Tech Indian Institute of Technology, Madras, India, 1969 (Valedictorian, Philips India Prize)

Experience:

2003-2010 Founder and CTO, Silicon Semiconductor Corporation, RTP, NC.
2000-2003 Founder and CTO, Silicon Wireless Corporation, Raleigh, NC.
1998-2010 Founder and CTO, MicroOhm & Giant Semiconductor Corporation, Raleigh, NC.
1997-Now Distinguished University Professor, NCSU
1991-2001 Founder & Director, Power Semiconductor Research Center, NCSU
1988-1997 Full Professor, NCSU
1974-1988 Coolidge Fellow and Manager, Power Device Group, GE Research Laboratory, NY

Selected Awards and Honors:

2016 *National Inventors Hall of Fame*, (Highest recognition for a U.S. Inventor)
2015 IEEE EDS Celebrated Member (1 of only 6 Legendary Individuals)
2015 *Global Energy Prize* (President of Russian Federation)
2014 *IEEE Medal of Honor* (Highest recognition by IEEE)
2012 *North Carolina Award for Science* (Governor of North Carolina)
2011 *National Medal of Technology and Innovation* (President of the United States)
2011 *Alexander Quarles Holladay Medal of Excellence* (Highest recognition by NCSU)
2010 Inducted into *Engineering Hall of Fame* (Electronic Design Magazine)
2004 *IEEE-ISPSPD Contributory Award* for Establishing and Chairing New Int. Conference
1999 *IEEE Lamme Medal* for Invention and Development of the IGBT (IEEE BoG)
1998 *IEEE Ebers Award* for technical contributions to Electron Devices (ED Society)
1998 *O. Max Gardner Award* by UNC Board of Governors for 'greatest contribution to human race'
1997 Scientific American Magazine '*One of the Eight Heroes of the Semiconductor Revolution*'
1993 Elected into U. S. *National Academy of Engineering*
1993 *IEEE Liebmann Award* for contributions to 'Smart Power Technology' (IEEE BoG)
1991 *IEEE Newell Award* for technical contributions to power electronics (PE Society)
1984 Science Digest Magazine's '*100 Brightest Young Scientists in America*'
1983 *IEEE Fellow* for contributions to Power Semiconductor Devices
1983 *GE Dushman Award* for 'The Insulated Gate Bipolar Transistor'
1983 *GE Coolidge Award* (Highest Scientist Designation)

Contracts and Grants received at NCSU:

2015-Now *PowerAmerica*, U.S. DoE & Industry: **Sponsorship of \$ 140 Million over 5 years.**
2008-Now *Future Renewable Electric Energy Delivery and Management Systems*, NSF-ERC:
Sponsorship of **\$ 35 Million** plus Industry Support of **\$ 15 Million** over 11 years.
1991-2001 *Power Semiconductor Research Center Sponsorship of \$ 6 Million:*
Corporate Membership: ABB, CP Clare Corp., Daimler-Benz Corp., Digital Equipment Corp.,
Fairchild Semiconductor Corp., Ford Motor Co., Fuji Electric Co., General Semiconductor
Co., Hitachi Ltd., IBM Corp., Mitsubishi Electric Corp., Motorola Corp., Philips Laboratories,
Rockwell International Corp., Sanken Electric Comp., Shindengen Electric Manufacturing
Co., Sundstrand Aerospace Corp., Toshiba Corp., Toyoda Automatic Loom Works
1988-2001 *Contract Sponsorship of \$ 4 Million:*
Sponsoring Agencies: Office of Naval Research, Electric Power Research Institute, Army
Research Office, Semiconductor Research Corporation, DARPA, National Science
Foundation, Corporations (GE, TI, Allied Signal, etc).

Teaching and Research at NCSU:

1988-2015 Undergraduate Course on EE (Average Class Size = 100 students)
1988-2015 Graduate Courses on Power Devices (Average Class Size = 15 students)
1988-2015 Supervised and Sponsored to completion 25 M.S. Theses and 27 Ph.D. Theses

Books:

2015 Author: "The IGBT Device: Device Physics, Design, and Applications", Elsevier Press.
2011 Author: "Advanced High Voltage Power Device Concepts", Springer-Science.
2010 Author: "Advanced Power Transistor Concepts", Springer-Science.
2009 Author: "Advanced Power Rectifier Concepts", Springer-Science.
2008 Author: "Fundamentals of Power Semiconductor Devices", Springer-Science.
2006 Author: "Silicon Carbide Power Devices", World Scientific Publishing Company
2005 Author: "Silicon RF Power MOSFETs", World Scientific Publishing Company
1998 Co-Author: "Cryogenic Operation of Silicon Power Devices", Kluwer Press
1998 Co-Editor: "Power Electronics Technology and Applications", IEEE Press
1996 Author: "Power Semiconductor Devices", PWS Publishing Company
1993 Co-Editor: "Power Electronics Technology and Applications", IEEE Press
1988 Editor: "High Voltage Integrated Circuits", IEEE Press
1987 Author: "Modern Power Devices", John Wiley and Sons
1986 Editor: "Epitaxial Silicon Technology", Academic Press
1984 Co-Editor: "Power Transistors", IEEE Press

Selected Book Chapters (out of 20):

1999 "Electric Refractory Materials", Editor: Y. Kumashiro, Marcel Dekker Inc.
1998 "Modern Semiconductor Device Physics", Editor: S. M. Sze, John Wiley and Sons
1997 "Encyclopedia of Applied Physics", American Institute of Physics
1996 "Power Electronics Technology and Applications", Editor: B. Bose, IEEE Press
1992 "Encyclopedia of Science and Technology", McGraw Hill Company
1990 "Encyclopedia of Physical Sciences and Technology", Academic Press

Selected Refereed Journal and Conference Digest Publications (out of 550+):

- (1) "Power Devices for reducing Energy Usage and Carbon Dioxide Emissions", GaN Consortium Conference, **Invited Keynote Address**, October 14, 2015, Nagoya, Japan.
- (2) "Social Impact of Power Semiconductor Devices", IEEE International Electron Devices Meeting (IEDM), **Invited Focus Session Paper**, Abstract 2.1.1, pp. 20-23, December 15, 2014, San Francisco, California.
- (3) "Enabling an Industrialized Society with Power Semiconductor Devices", IEEE Industrial Electronics Society Annual Conference (IECON), **Invited Plenary Paper**, October 30, 2014 – attendance of 1500
- (4) "Role of Power Semiconductor Devices in Creating a Sustainable Society", **Invited Plenary Paper**, IEEE Applied Power Electronics Conference (APEC), Long Beach, CA, March 18, 2013 – attendance of 3800
- (5) "Analytical Modeling of IGBTs: Challenges and Solutions", **Invited Paper**, IEEE-TED, pp. 535-543, 2013.
- (6) "GaN Devices for Power Electronic Applications", **Invited Paper**, Semicond. Sci. Technol. 28 (2013).
- (7) "FREEDM System: Role of Power Electronics and Power Semiconductors in Developing an Energy Internet", **Invited Plenary Paper**, IEEE ISPSD, Barcelona, Spain, pp. 9-12, June 2009.
- (8) "Future of Power Semiconductor Technology", **Invited Paper**, Proc. IEEE, pp. 822-832, 2001.
- (9) "Trends in Power Discrete Devices", **Invited Plenary Paper**, IEEE ISPSD, pp. 5-10, 1998.
- (10) "Trends in Power Semiconductor Devices", **Invited Paper**, IEEE T-ED, pp. 1717-1731, 1996.
- (11) "Power ICs in the Saddle", IEEE Spectrum, **Invited Paper**, pp. 34-39, July 1995.
- (12) "Power Devices for Variable Frequency Drives", **Invited Paper**, Proc. IEEE, pp. 1112-1122, 1994.
- (13) "Smart Power Technology", IEEE IEDM, **Plenary Invited Paper**, pp. 3-6, 1990.
- (14) "Power Devices for the 1990s", IEEE APEC, **Invited Paper**, 1989.
- (15) "Evolution of MOS-Bipolar Power Technology", Proc. IEEE, **Invited Paper**, pp. 408-418, 1988.
- (16) "Innovations in Power Discrete Devices", IEEE IEDM, **Invited Paper**, pp. 102-105, 1986.
- (17) "Temperature Behavior of IGBTs", Solid State Electronics, pp. 289-297, 1985.
- (18) "Fast Switching Insulated Gate Transistors", IEEE EDL, pp. 452-454, 1983.
- (19) "The Insulated Gate Rectifier", IEEE-IEDM, pp. 264-267, 1982.

Issued U. S. Patents: 120 Total

Mesut E. Baran

Professor

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E-mail: baran@ncsu.edu

Education

Ph.D. in EE, 1988 University of California, Berkeley, California

M.S. in EE, 1981 Middle East Technical University, Turkey

B.S. in EE, 1979 Middle East Technical University, Turkey

Employment

2007 – Present Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC

1999 – 2007 Associate Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC

1991 – 1999 Assistant Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC

1989 – 1990 Senior Engineer, EMPROS, Plymouth, MN

1988 – 1989 Design Engineer, Scientific Systems, Inc., Woburn, MA

1986 – 1986 Assistant Engineer, BPA, Portland, OR

Five Relevant Publications

- [1] M. Baran, P. Carpenter, L. Borbye, D. Lubkeman, M. Ligett, D. Cavington, "A New Professional Science Master Program for Electric Power System Engineering," IEEE Trans. on Power Systems, July 2014, pp 1903 – 1910.
- [2] H. Hooshyar, M. Baran, "Fault Analysis on Distribution Feeders with High Penetration of PV Systems," IEEE Trans. on Power Systems, Aug. 2013, Vol 28 , Issue 3, pp. 2890-2896.
- [3] M. Baran, H. Hooshyar, Z. Shen, A. Huang, "Accommodating High PV Penetration on Distribution Feeders" IEEE Trans. on Smart Grid, June 2012, Volume: 3 , issue II, pp 1039-1045
- [4] S. Teleke, M.E. Baran, A. Huang, S. Bhattacharya, "Rule Based Control of Battery Energy Storage for Dispatching Intermittent Renewable Sources," IEEE Trans. on Sustainable Energy, vol. 1, no. 3, Oct 2010, pp: 117 – 124
- [5] M.E. Baran, I. El-Markabi, "A Multi-Agent-Based Dispatching Scheme for Distributed Generators for Voltage Support on Distribution Systems," IEEE Trans. on Power Systems, Feb. 2007, pp 52 - 59.

Five Additional Publications

- [1] C. Han, M. Baran, A. Q. Huang, W. Litzenberger, L. Anderson, A. Edris, "STATCOM Impact Study on the Integration of a Large Wind Farm into a Weak Loop Power System," IEEE Trans. on Energy Conversion, Sept. 2006.
- [2] M. Baran, N. Mahajan, "Overcurrent Protection on Voltage Source Converter Based Multiterminal DC Distribution Systems," IEEE Trans. on Power Delivery, March 2006.
- [3] M. Baran, J. Kim, "A Classifier for Distribution Feeder Over-Current Analysis," IEEE Trans. on Power Delivery, Jan. 2006, pp 456-462.

- [4] M.E. Baran, I. El-Markabi, “Fault Analysis on Distribution Feeders with Distributed Generators,” IEEE Trans. on Power Systems, Nov 2005, pp. 1757-1764.
- [5] M.E. Baran L. Freeman, F. Hanson, V. Ayers, “Load Estimation for Load Monitoring at Distribution Substations”, IEEE Trans. on Power Systems, Feb. 2005, pp. 164 - 170.

Synergistic Activities

- Editor, IEEE Power Engineering Letters, 8/06 – 8/07.
- Chair, IEEE Power Engineering Society subcommittee on Distribution System Analysis Methods, 10/95 – 1/02
- Assistant Editor, IEEE Transactions on Power Systems, 1/98 - 3/02
- Officer, IEEE PES Eastern North Carolina Chapter, 2/99 - 2/00
- Senior Member, IEEE Power Engineering Society (PES)

Collaborators During the Last 48 Months

A.Q. Huang (NC State University); S. Bhattacharya (NC State University); G. Heydt (Arizona State U.); M. Crow (Missouri Science & Tech.), B. McMillan (Missouri Science & Tech.

Graduate and Postdoctoral Advisement

- *Ph.D. Advisor:* Felix Wu

- *Ph.D. Graduates Supervised:* 10

Moyeen Kazi, 2015; Urvir Singh, 2015; Vahraz Zamani, 2014; Zhan Shen, 2013; Hossein Hooshyar 2011, Sercan Teleke, 2009 ; Jinsang Kim 2007; Nikhil Mahajan, 2004; Ismail El-Markabi 2004; Venkat Banunarayan, 1998.

- *Post-Doctoral Researchers Mentored:* 3

Otsebele Nare (Hampton University), Ricardo Rotoras (Asian Institute of Technology, Thailand), Gulcihan Ozdemir (Istanbul Tech. University, Turkey)

Pam Page Carpenter

9700 Ten Ten Road
Raleigh, North Carolina 27207
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pamelapagecarpenter@gmail.com

EDUCATION

North Carolina State University, Raleigh North Carolina
Doctorate of Education in Technology, Engineering, and Design Education with a minor
in Curriculum and Instruction. 2006.

Dissertation: *Cyber Connections across gender and age: How communication
technologies enhance social communication in online learning communities in
college level courses.*

North Carolina State University, Raleigh North Carolina
Master of Education in Higher Education and Organizational Training and 18 graduate
hours in Organizational Communication. 2003

Capstone project: University of North Carolina School of Medicine Instructional Design
project for the Adult and Community College Education degree.

Communication research: *How does cyberspace affect the sense of community and
cultural identity of Hmong refugees? Recreating home through an imagined past
and memory in a virtual community.*

North Carolina State University, Raleigh North Carolina
Bachelor of Arts in Philosophy with honors. 1997

PROFESSIONAL EXPERIENCE

Education Director-National Science Foundation Future Renewable Electric Energy and
Distribution (FREEDM) Systems Center. Pre-College through graduate programs
development and management, assessment, and advisory committees. 2015 – present.

Education Program Manager – Master of Science in Electric Power Systems Engineering
and Renewable Electric Energy Systems Graduate Certificate NSF FREEDM Center and
Electrical and Computer Engineering-North Carolina State University. 2011- present.
Program development and assessment and project management working with prospective
and current students, industry sponsors, and faculty.

Adjunct Associate Professor -Technology, Engineering, and Design Education in College
of Education-North Carolina State University. Development of an online graduate course
to teach renewable energy technologies and energy education. 2009 – present.

Online Instructor-Sustainable Technologies at the College of the Albemarle. Developed
and taught two courses in sustainable technologies. 2013.

Program Manager-Clean Energy Education and Workforce-K-16 STEM Education
North Carolina Solar Center-College of Engineering-North Carolina State University.
2007 – 2011. Principle Investigator for the regional Solar-Train-the Trainer program
under the Department of Energy. Grant writing and program development and
assessment, responsible for Graduate Assistants working on projects, developed and
provided daily operations for five programs focused on middle school through college
programs.

*Trainer, alternative transportation technologies, teacher workshop, North Carolina Solar
Center, 2007 – 2010.*

*Instructor, Communications, Central Carolina Community College, Sanford, NC, 2004 -
2008.*

Instructor, Instructional Technology, Appalachian State University, Boone, NC, 2006.

*Instructor, Communications, Guilford Technical Community College, Jamestown, NC,
2006.*

Instructor, Communications, Randolph Community College, Asheboro, NC, 2004 - 2007.

*Instructor, Broadcasting Production, Central Carolina Community College, Sanford, NC,
2003.*

*Graduate Research Assistant, National Initiative for Leadership and Institutional
Effectiveness (NILIE) at North Carolina State University. 2002. Personal Assessment of
the College Environment (PACE) and Student Assessment of College Environment
(SACE).*

*Instructor, Computer Technologies, Central Carolina Community College, Lillington,
NC, 2002.*

*Instructor, English as a Second Language, Central Carolina Community College, Siler
City, NC, 2001.*

*Instructor, Adult High School, English, Mathematics. Central Carolina Community
College, Siler City and Pittsboro, NC 1996 – 1999.*

*Instructor, Botanical Medicine, Central Carolina Community College, Siler City and
Pittsboro, North Carolina 1999 – 2003.*

COURSES TAUGHT

TED 621, Renewable Energy Technologies
Curriculum Development for community college instructors
Communications 110, Introduction to Communications, University Transfer Program.
Communications 120, Introduction to Personal Communication, University Transfer

Roy Anthony Charles
College of Engineering
North Carolina State University
Raleigh, NC

Professional Preparation

Roger Williams College	Business Administration	B.S., 1991
Cambridge College	Integrated Studies in K-12 Education & Non-Profit Management	M.Ed., 1997
American Evaluation Association /Dukes University	Graduate Education Diversity Internship Program	2007/2008
University of North Carolina At Chapel Hill	Educational Psychology, Measurement, and Evaluation	Ph.D., 2015

Appointments

December 2014 – Present	Diversity Director for Nanosystems Engineering Research Center (NERC) for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), North Carolina State University, Raleigh, NC
December 2014 – Present	Diversity Director for Future Renewable Electric Energy Delivery Management (FREEDM) Systems Center, North Carolina State University, Raleigh, NC
January 2010 – August 2014	Director of Diversity, Recruitment and Retention in The Graduate School, University of North Carolina at Chapel Hill, Chapel Hill, NC
October 2009 – December 2010	Program Evaluation Consultant, Institute for Families in Society, University of South Carolina, Columbia, SC
May 2007 – May 2009	Research Assistant, Research Education Support (RES) and NC Alliance for Graduate Education and the Professoriate (AGEP), University of North Carolina at Chapel Hill, Chapel Hill, NC
April 2007 – September 2007	Research Assistant, Center for Developmental Science (CDS) and National Research Center on Rural Education Support (NRCRES), University of North Carolina at Chapel Hill, Chapel Hill, NC
August 2004 – August 2006	Research Assistant, Research Education Support (RES) and NC Alliance for Graduate Education and the Professoriate (AGEP), University of North Carolina at Chapel Hill, Chapel Hill, NC
August 1994 – August 2004	Assistant Dean for Graduate Students, Massachusetts Institute of Technology, Cambridge, MA
November 1995 – August 1997	Director of K-8 Programs, Massachusetts Pre-Engineering Program, Inc (MassPEP), Boston, MA
November 1994 – November 1995	Special Projects Administrator for The Graduate Education Office, Massachusetts Institute of Technology, Cambridge, MA

August 1991 – November 1994

Staff Assistant IV for the Special Assistant to the President & Assistant Equal Opportunity Officer, Massachusetts Institute of Technology, Cambridge, MA

Synergistic Activities

1. Advisor to the FREEDM Systems Center Student Leadership Council, NC State University, Raleigh, NC
2. Representative for College of Engineering to the University Diversity Advisory Council, NC State University, Raleigh, NC

Graduate Advisor

Dr. George Noblit, School of Education, University of North Carolina at Chapel Hill

Mo-Yuen Chow

Department of Electrical and Computer Engineering
North Carolina State University

Professional Preparation:

University of Wisconsin-Madison	Electrical and Computer Engineering	B.S. 1982
Cornell University	Electrical Engineering	M.Eng. 1983
Cornell University	Electrical Engineering	Ph.D. 1987

Appointments:

1999 – Present	Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC
2009 – 2013	Changjiang Scholar Chair Professor (part-time), Zhejiang University, Hangzhou
2003	Senior Research Scientist, U.S. Army Tank Automotive Research, Development and Engineering Center
1995	Visiting Scientist, Automation Distribution Division, ABB, Cary, NC
1993 – 1999	Associate Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC
1987 – 1993	Assistant Professor, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC

Selected Five Relevant Publications:

- [1] Yuan Zhang, Navid Rahbari Asr, and Mo-Yuen. Chow, "A Robust Distributed System Incremental Cost Estimation Algorithm for Smart Grid Economic Dispatch with Communications Information Losses", Journal of Network and Control Applications, June 6, 2015.
- [2] N. Rahbari-Asr, U. Ojha, Z. Zhang, and M.-Y. Chow, "Incremental Welfare Consensus Algorithm for Cooperative Distributed Generation/Demand Response in Smart Grid," IEEE Transactions on Smart Grid, vol.5, no.6, pp.2836-2845, Nov. 2014.
- [3] W. Zeng and M.-Y. Chow, "Resilient Distributed Control in the Presence of Misbehaving Agents in Networked Control Systems," IEEE Transactions on Cybernetics, vol. 44, pp. 2038-2049, Nov. 2014.
- [4] H. Rahimi-Eichi, F. Baronti, and M.-Y. Chow, "Online Adaptive Parameters Identification and SOC Co-Estimation for Li-Polymer Battery Cells," IEEE Transaction on Industrial Electronics, vol. 61, pp. 2053-2061, 2014.
- [5] R. Deng, Z. Yang, J. Chen, N. R. Asr, and M.-Y. Chow, "Residential Energy Consumption Scheduling: A Coupled-Constraint Game Approach," IEEE Transactions on Smart Grid, vol. 5, pp. 1340-1350, May 2014.

Selected Five Other Significant Publications:

- [1] Yuan Zhang, Navid Rahbari Asr, and Mo-Yuen. Chow, "A Robust Distributed System Incremental Cost Estimation Algorithm for Smart Grid Economic Dispatch with Communications Information Losses", Journal of Network and Control Applications, June 6, 2015.
- [2] H. Yin, C. Zhao, M. Li, C. Ma, and M.-Y. Chow, "A Game Theory Approach to Energy Management of An Engine-Generator/Battery/Ultracapacitor Hybrid Energy System," IEEE Transaction on Industrial Electronics, Accepted on 2016-01-26.
- [3] J. Qiu, H. Gao, and M.-Y. Chow, "Networked Control and Industrial Applications," IEEE Transactions on Industrial Electronics, vol. 63, pp. 1203-1206, February 2016.
- [4] N. Rahbari-Asr, M.-Y. Chow, "Cooperative Distributed Demand Management for Community Charging of PHEV/PEVs Based on KKT Conditions and Consensus Networks," IEEE Transactions on Industrial Informatics, vol.10, no.3, pp.1907-1916, Aug. 2014.
- [5] H. Rahimi Eichi, U. Ojha, F. Baronti, and M.-Y. Chow. "Battery Management System in Smart Grid and Electric Vehicles: An Overview." IEEE Industrial Electronics Magazine, vol. 7, No. 2, June 2013.

Synergistic Activities:

- [1] A keynote speaker of "2015 IEEE International Conference on Industrial Technology", March 17-19, 2015, Seville, Spain, on the topic of "When e-Transportation Meets Distributed Renewable Energy Resources".
- [2] 2016 – present, IEEE IES “Resilience and Security for Industrial Applications (ReSia)” Technical Committee Chair
- [3] Co-Editor-in-Chief, IEEE Transactions on Industrial Informatics, 2014-present.
- [4] IEEE Fellow, 2007.
- [5] IEEE Region 3 Joseph M. Biedebach Outstanding Engineering Educator Award, 2003.

Collaborators & Other Affiliations:*International:*

Federico Baronti (University of Pisa, Italy), Jiming Chen (Zhejiang University, China), Juan Jose Rodriguez-Andina (University of Vigo, Spain), Valeriy Vyatkin (Luleå University of Technology, Sweden), Zaiyue Yang (Zhejiang University, China)

National:

Chris Edrington (Florida State University), Gerald Heydt (Arizona State University), Bruce McMillin (Missouri Science and Technology University), Mischa Steurer (Florida State University)

North Carolina State University:

David Lubkemen (ECE), Ning Lu (ECE)

Graduate and Post-Doctoral Advisors:

Ph.D. Thesis advisor: Robert J. Thomas, Cornell University.

Thesis Advisor and Postgraduate-Scholar Sponsor:*Thesis students in progress:*

Yuan Zhang (PhD), Bharat Balagopal (PhD), Jie Duan (PhD), Alberto Castelo (PhD), Cong-Sheng Huang (PhD), Hamed Mohammadbagherpoor (PhD)

Postgraduate-Scholars in progress:

Habiballah Rahimi Eichi

Thesis students graduated in the last five years:

Navid Rahbari-Asr, „Cooperative Distributed Energy Scheduling in Smart Grids,“ PhD Thesis, Summer 2015.

Habiballah Rahimi Eichi, “Online Adaptive Battery Parameters Identification, and State of Charge (SOC) and State of Health (SOH) Co-Estimation”, PhD Thesis, Spring 2014.

Unnati Ojha, “A Lego-NXT Based Fast Prototyping Platform for Distributed Energy Management in Smart Grid”, PhD Thesis, Fall 2013.

Wente Zeng, “Secure Distributed Control Methodologies with Built-in Defense in Distributed Networked Control Systems”, PhD Thesis, Fall 2013.

Ziang (John) Zhang, “Time-Sensitive Cooperative Distributed Energy Management on Cyber-Physical Energy Systems”, PhD Thesis, Fall 2013.

YiXin Cai, “Small World Strategification for Power Distribution Fault Cause Identifications,” PhD Thesis, Fall 2010.

Rachana Gupta, “Vision based Control for Autonomous Vehicle Navigation,” PhD Thesis, Fall 2010.

Cameron Lynch, “Implementation and Sensitivity Analysis of a Task-Capability Interface Model for Automobile Driver Safety”, MS Thesis, Spring 2011.

Total number of graduate students advised: 45

Total number of post-doc scholars sponsored: 2

MARIESA LOUISE CROW
F. Finley Distinguished Professor of Electrical Engineering
233 Emerson Hall
Missouri University of Science & Technology, Rolla, MO 65409-0040
Phone: (573) 341-6305; FAX: (573) 341-6671

PROFESSIONAL PREPARATION:

B.S.E. (E.E.) University of Michigan in Ann Arbor, 1985
M.S. (E.E.) University of Illinois at Urbana-Champaign, 1986
Ph.D. (E.E.) University of Illinois at Urbana-Champaign, 1989

APPOINTMENTS:

2006-present, F. Finley Distinguished Professor of Electrical Engineering
2007-2012, Director, Energy Research and Development Center
2003-2007, Dean, School of Materials, Energy, and Earth Resources
2001-2003, Associate Dean for Research and Graduate Affairs, School of Engineering
2000-2006, Professor of Electrical and Computer Engineering, University of Missouri - Rolla
1996-2000, Associate Professor of Electrical Engineering, University of Missouri-Rolla
1991-1996, Assistant Professor of Electrical Engineering, University of Missouri-Rolla

PUBLICATIONS (RECENT) (* denotes graduate student)

- [1] Tu A. Nguyen* and M. L. Crow, "Stochastic Optimization of Renewable-Based Microgrid Operation Incorporating Battery Operating Cost," *IEEE Transactions on Power Systems*, (to appear).
- [2] Xin Qiu*, Tu Nguyen*, and M. L. Crow, "Heterogeneous Energy Storage Optimization for Microgrids" *IEEE Transactions on Smart Grid*, (to appear).
- [3] D. G. Shah* and M. L. Crow, "Online Volt-Var Control for Distribution Systems With Solid State Transformers," *IEEE Transactions on Power Delivery*, vol. 31, no. 1, February 2016.
- [4] Wei Wu*, Keyou Wang, Guojie Li, Mariesa L. Crow, "A Versatile Probability Model of Photovoltaic Generation Using Pair Copula Construction," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, October 2015.
- [5] Tu Nguyen*, M. L. Crow, and A. C. Elmore, "Optimal Sizing of a Vanadium Redox Battery System for Microgrid Systems," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 729 – 737, July 2015
- [6] D. Shah* and M. L. Crow, "Stability Assessment Extensions for Single Phase Distribution Solid State Transformers," *IEEE Transactions on Power Delivery*, vol. 30, no. 3, June 2015.
- [7] T. Gamage*, Y. Liu*, T. A. Nguyen*, X. Qiu*, B. McMillin, M. L. Crow, "A Novel Flow Invariants-based Approach to Microgrid Management," *IEEE Transactions on Smart Grid*, vol. 6, no. 2, March 2015.
- [8] D. Somayajula* and M. L. Crow, "An Integrated Dynamic Voltage Restorer – Ultracapacitor Design for Improving the Power Quality of the Distribution grid," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, April 2015.
- [9] X. Qiu*, M. L. Crow, and A. C. Elmore, "A Balance-of-Plant Vanadium Redox Battery System Model," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, April 2015.
- [10] D. Shah* and M. L. Crow, "Stability Design Criteria for Distribution Systems with Solid State Transformers," *IEEE Transactions on Power Delivery*, vol. 29, no. 6, December 2014.

SYNERGISTIC ACTIVITIES

Expanding Your Horizons, Girls Go Green summer camp, Faculty Advisor for Women in Nuclear Engineering, MS&T Faculty Recruitment and Retention Committee

BIOGRAPHICAL SKETCH
CHRIS S. EDRINGTON, PhD, PE, SMIEEE

PROFESSIONAL PREPARATION

Institution	Major/Area	Degree & Year
Arkansas State University	Engineering	B.S., 1999
University of Missouri-Rolla	Electrical Engineering	M.S., 2001
University of Missouri-Rolla	Electrical Engineering	Ph.D., 2004

APPOINTMENTS

<i>2012 – present</i>	<u>Associate Professor</u> , College of Engineering, Florida State University
<i>2013 – 2015</i>	<u>Associate Director</u> , Center for Advanced Power Systems, Florida State University,
<i>2014 (March – July)</i>	<u>Interim Director</u> , Center for Advanced Power Systems, Florida State University,
<i>2007 – 2012</i>	<u>Assistant Professor</u> , College of Engineering, and Florida State University
<i>2004 – 2007</i>	<u>Assistant Professor</u> , College of Engineering, Arkansas State University

PUBLICATIONS

5 MOST RELEVANT PUBLICATIONS

- [1] Salmani, A., **C. S. Edrington**, Real-time Small Signal Stability Analysis of the Power Electronic-based Components in Contemporary Distribution Systems, *Electric Power Systems Research*, Vol. 117, pp. 47 – 58, 2014.
- [2] M. Cupelli, F. Ponci, G. Sulligoi, Andrea Vicenzutti, **C. S. Edrington**, T. El-Mezyani, A. Monti, Power Flow Control and Network Stability in and All Electric Ship, *Proceedings of the IEEE*, Vol. 103, Issue 12, pp. 2355 – 2380, 2016.
- [3] **C. S. Edrington**, M. Steurer, J. Langston, K. Schoeder, and T. El-Mezyani, Role of Power Hardware in the Loop in Modeling and Simulation for Experimentation in Power and Energy Systems for *Proceedings of the IEEE*, Vol. 103, Issue 12, pp. 2401 – 2409, 2015.
- [4] A. Salmani, N. Asr, **C. S. Edrington** and M. Chow (2015). Online and Offline Stability Analysis Methods for the Power Electronic-based Components in Design and Operational Stages, *IEEE Transactions on Power Electronics*, Vol. 31, Issue 4, pp. 3151 – 3164, 2016.
- [5] Soto, D., **C. S. Edrington**, S. Balathandayuthapani, , and S. Ryster, Voltage Balancing of Islanded Microgrids using a Time-domain Technique,” *Electric Power Systems Research*, Vol. 84, Issue 1, pp. 214 – 223, 2012.

5 OTHER PUBLICATIONS

- [1] Vu, T., S. Paran, F. Diaz , T. El Mezyani, and **C.S. Edrington**,. Model Predictive Control for Power Control in Islanded DC Microgrids. In *IEEE Industrial Electronics Conference*, Yokagama, Japan. 2015.
- [2] Vodyakho O., M. Steurer, D. Neumayr, **C. S. Edrington**, G. Karady, and S. Bhattacharyya, Solid-State Fault Isolation Devices: Application to Future Power Electronics-based Distribution Systems, *IET Electric Power Applications*, Vol. 5, Issue 6, pp. 521 – 528, 2011.
- [3] Ramachandran, B., S. K. Srivastava, D. A. Cartes, and **C. S. Edrington**, An Intelligent Auction Scheme for Smart Grid Market Using a Hybrid Immune Algorithm, *IEEE Transactions on Industrial Electronics*, Vol.58, Issue 10, pp. 4603 – 4612, 2011.
- [4] Paran, S., T. Vu, T. El Mezyani, and **C. S. Edrington**, MPC-based Power Management in the Shipboard Power System, In *IEEE Electric Ship Technology Symposium*, Alexandria, VA, 2015. Soto, D., **C. S. Edrington**, and S. Balathandayuthapani, Grid Connected PV-APF System with Anti-islanding Protection, *European Transactions on Electric Power*, Vol. 23, Issue 7, pp. 1049–1070, 2013.
- [5] Hasanzadeh, A., **Edrington, C. S.**, and Mokhtari, H., “Optimal Tuning of Linear Controllers for Power Electronics/Power Systems Applications,” *Electric Power Systems Research*, Vol. 81, Issue 12, pp. 2188 – 2197, 2011.

SYNERGISTIC ACTIVITIES

1. Florida State University Campus Director for NSF FREEDM Systems Center since 2012. Lead a Young Scholars program during the summer.

2. Co-editor in 2013 for the Special Issue on Advanced Modeling, Simulation, Control, and Optimization Paradigms for Vehicular Power Systems, *IEEE Transactions on Vehicular Technology*.
3. Co-editor in 2013 for the Special Issue on Distributed Decision-making in Energy Conversion Systems. *IEEE Transactions on Energy Conversion*
4. Co-editor in 2011 for the Special Issue on Electric Vehicle *Journal of Power Electronics*.
5. Technical Co-Chair for the 2014 IEEE Industrial Electronics Conference.

COLLABORATORS AND CO-EDITORS

Subhashish Battacharya, NCSU; Herb Ginn, MSU; Alex Huang, NCSU; Jonathan Kimball, MS&T; Mahesh Krishnamurthy, IIT; Ned Mohan, UMN; Mischa Steurer, FSU; Sanjeev Srivastava, Siemens; Jay

GRADUATE ADVISORS AND POSTDOCTORAL SPONSORS

Babak Fahimi, UT-Dallas	Steve Pekarek, Purdue	Cihan Dagli, MS&T
Mariesa Crow, MS&T	Levant Acar, MS&T	

THESIS ADVISOR AND POSTGRADUATE-SCHOLAR SPONSOR

Thesis Advisor

Jabid Quiroga, MS, 2008, Columbia	Yusi Liu, MS, 2011, University of Arkansas – Fayetteville	Kavya Rentachinthala, MS, 2012, Intel Inc.	Sanaz Paran, MS, 2013, FSU	Lee Griffin, MS, 2014, Robins Airforce Base
Dorca Lee, MS, 2010, NMSU	Jianwu Cao, MS, 2011, FSU	Troy Bevis, MS, 2012, Amazon Inc.	Fletcher Fleming, MS, 2010, PhD, 2013, FSU	Venkata Pothavajhala, MS, 2014, Elutions Inc.
Brian Hacker, MS, 2010, L3	Parikshit Patil, MS, 2011, Doosan HydroTechnology	Siyu Leng, PhD, 2012, University of Alberta	Dionne Soto, MS, 2013, FSU	Amin Salmani, PhD, 2014, FSU
Diomar Infante, MS, 2010, ConverTeam	Thabendra Thevarajan, MS, 2011, N/A	Nicholas Stroupe, MS, 2012, Naval Surface Warfare Center	Chris Widener, MS, 2014, FSU	
Michael Sattler, MS, 2011, General Atomics	Furkan Akar, MS, 2012, Yildiz University	Yaw Nyanteh, PhD, 2013, University of Houston	Jesse Leonard, PhD, 2014, FSU	

Postdoctoral Scholars

Sardis Azongha, USPTO	Amin Hasanzadeh, University of Maryland
Shawn Henry, XoRail Inc.	Bulent Vural, Yildiz University
Saritha Balathandayuthapani, IIT	Danielle Li, John Deere Inc.

Theses Advised = 24, Postdoctoral Scholars Advised = 6

Mehdi Ferdowsi

Electrical and Computer Engineering Department
Missouri University of Science and Technology¹
234 EECH; 301 W. 16th Street; Rolla, MO 65409
Tel: (573) 341-4552; Fax: (573) 341-6671
Email: ferdowsi@mst.edu

Education:

• University of Tehran	Electrical Engineering	B.Sc. 1997
• Sharif University of Technology	Electrical Engineering	M.Sc. 1999
• Illinois Institute of Technology	Electrical Engineering	Ph.D. 2004

Relevant Experience:

- 2015-present Professor, ECE Department, Missouri University of Science and Technology.
- 2010-2015: Associate Professor, ECE Department, Missouri University of Science and Technology.
- 2004-2010: Assistant Professor, ECE Department, Missouri University of Science and Technology.
- 2002-2004: Ph.D. Research Assistant, Grainger Power Electronics and Motor Drives Laboratory, Illinois Institute of Technology.
- 2000-2002: Ph.D. Research Assistant, Center for Power Electronics Systems (CPES), North Carolina A&T State University.

Products:

A. Products that are most closely related to this proposal

- R. Ahmadi and M. Ferdowsi, "Double-input converters based on H-bridge cells: derivation, small-signal modeling, and power sharing analysis," *IEEE Trans. Circuits and Systems I*, vol. 59, no. 4, pp. 875-888, April 2012.
- L. Shi, B. Baddipadiga, M. Ferdowsi, and M. Crow, "Improving the dynamic response of a flying-capacitor three-level buck converter," *IEEE Trans. Power Electronics*, vol. 28, no. 5, pp. 2356-2365, May 2013.
- K. Gummi and M. Ferdowsi, "Double-input dc-dc power electronic converters for electric-drive vehicles—topology exploration and synthesis using a single-pole triple-throw switch," *IEEE Trans. Industrial Electronics*, vol. 57, no. 2, pp. 617-623, February 2010.
- A. C. Baughman and M. Ferdowsi, "Double-tiered switched-capacitor battery charge equalization technique" *IEEE Trans. Industrial Electronics*, vol. 55, no. 6, pp. 2277-2285, June 2008.
- R. Ahmadi and M. Ferdowsi, "Improving performance of a dc-dc cascaded converter system using an extra feedback loop," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Denver, CO, Sept. 2013, pp. 5511-5517.

B. Other products

- R. Ahmadi, P. Fajri, and M. Ferdowsi, "Performance improvement of a dc-dc converter feeding a telecommunication specific distributed power system using dynamic decoupling design," in *Proc. IEEE International Telecommunications Energy Conference (INTELEC)*, Scottsdale, AZ, Sept. 2012, pp. 1-7.

¹ Formerly University of Missouri-Rolla (UMR)

- Z. Darabi and M. Ferdowsi, “Aggregated impact of plug-in hybrid electric vehicles on electricity demand profile,” *IEEE Trans. Sustainable Energy*, vol. 2, no. 4, pp. 501-508, October 2011.
- M. Khazraei, H. Sepahvand, M. Ferdowsi, and K. Corzine, “Hysteresis-based control of a single-phase multilevel flying capacitor active rectifier,” *IEEE Trans. Power Electronics*, vol. 28, no. 1, pp. 154-164, January 2013.
- M. Khazraei and M. Ferdowsi, “Modeling and analysis of Projected Cross Point Control—a new current mode control approach,” *IEEE Trans. Industrial Electronics*, vol. 60, no. 8, pp. 3272-3282, August 2013.
- H. Sepahvand, J. Liao, and M. Ferdowsi, “Capacitor voltage regulation in single-dc-source cascaded H-bridge multilevel converters using phase-shift modulation,” *IEEE Trans. Industrial Electronics*, vol. 60, no. 9, pp. 3619-3626, September 2013.

Synergistic Activities:

- Development of three new courses in the EE curriculum (EE 309, EE 409, and EE 453).
- Associate Editor, IEEE Transactions on Power Electronics since 2005.
- Technical advisor for the EcoCAR the NeXt Challenge team at Missouri S&T.
- Collaboration with the St. Louis Science on the development of an Energy exhibit.
- Chair, IEEE Rolla Subsection of the St. Louis Section (2010-11).

Collaborators:

Total number of collaborators: 13

Mesut Baran (N.C. State University), Stuart Baur (Missouri S&T), Subhashish Bhattacharya (N.C. State University), Joel Burken (Missouri S&T), Badrul Chowdhury (University of North Carolina-Charlotte), Keith Corzine (Clemson University), Mariesa Crow (Missouri S&T), Chris Edrington (Florida State University), Kurt Elmore (Missouri S&T), George Karady (Arizona State University), Jonathan Kimball (Missouri S&T), Robert Landers (Missouri S&T), Bruce McMillin (Missouri S&T)

Graduate Advisor:

Total number of advisors: 1

Ali Emadi, McMaster University

Thesis Advisor, 9 M.Sc., 13 Ph.D.:

M.Sc. Advisees: Omkar Ghatpande (ABB), Nishant Chouhan (Danfoss), Vennela Yadhati (Smith Electric Vehicles), Shweta Neglur (employer unknown), Deepak Somayajula, (looking for a job), Karteek Gummi (Bechtel), Ashaben Patel (Dow Chemical), Krishna Yalamanchili (Laramore, Douglass and Popham Consulting Engineers), Andrew Baughman (General Motors)

Ph.D. Advisees: Bhanu Baddipadiaga (InnoCit), Sangin Lee, Poriya Fajri(Toyota), Darren Paschedag (Boeing), Anand Prabhala (IR), Reza Ahmadi (Southern Illinois University Carbondale), Zahra Darabi (SNC-Lavalin), Hossein Sepahvand (Petra Solar), Mostafa Khazraei (Solectria Renewables), Andrew Meintz (NREL), Lisheng Shi (Cree), Jingsheng Liao (GE Aviation), Kai Wan (Cirrus Logic)

Gerald T. Heydt

Regents' Professor, Professor of Advanced Technology, PhD, Purdue University
heydt@asu.edu; (480) 965-8307

Research Expertise: Power engineering, electric power quality, distribution engineering, transmission engineering, computer applications in power engineering, power engineering education, power system sensors and instrumentation.

Gerald Thomas Heydt is from Las Vegas, NV. He holds a BEEE degree from the Cooper Union in New York and MSEE and PhD. degrees from Purdue University. He spent approximately 25 years as a faculty member at Purdue, and in 1994, he took the position of site director of the NSF and industrially supported Power Systems Research Center at ASU. He has industrial experience with the Commonwealth Edison Company in Chicago, E.G. & G. in Mercury, NV, and with the United Nations Development Program. In 1990, he served as the program manager of the National Science Foundation program in power systems engineering. He is the author of two books in the area of power engineering. Professor Heydt is a Regents' Professor and Professor of Advanced Technology at ASU; he is a member of the National Academy of Engineering, and a Life Fellow of the IEEE.

Honors and Distinctions: Life Fellow, IEEE; Member, U.S. National Academy of Engineering; Edison Electric Institute Power Engineering Educator Award, 1989; IEEE Power Engineering Society Power Engineering Educator of the Year, 1995; IEEE Kaufmann Award, 2010.

Selected Publications:

Sara Eftekharnajad, G. Heydt, V. Vittal, "Optimal generation dispatch with high penetration of photovoltaic generation," *IEEE Transactions on Sustainability*, Paper TSTE-00422-2013, July, 2015, v. 6, No. 3, pp. 1013 – 1020.

S. Eftekharnajad, V. Vittal, G. Heydt, B. Keel, J. Loehr, "Small signal stability assessment of power systems with increased penetration of photovoltaic generation: a case study," *IEEE Transactions on Sustainable Energy*, v. 4, No. 4, October 2013, pp. 960 – 967.

F. Meng, D. Haughton, B. Chowdhury, M. Crow, G. Heydt, "Distributed generation and storage optimal control with state estimation," *IEEE Transactions on Smart Grid*, v. 4, No. 4, December 2013, pp. 2266-2273.

Y. Chakhchoukh, V. Vittal, G. T. Heydt, "PMU based state estimation by integrating correlation," *IEEE Transactions on Power Systems*, v. 29, No. 2, March 2014, pp. 617 – 626.

M. Al-Muhaini, G. T. Heydt, "Evaluating future power distribution system reliability including distributed generation," *IEEE Transactions on Power Delivery*, v. 28, No 4, October 2013, pp. 2264 – 2272.

Keith E. Holbert, Ph.D., P.E.
Associate Professor, Fulton School of Engineering
Arizona State University, Tempe, AZ 85287-5706
Phone: (480) 965-8594 Email: holbert@asu.edu

PROFESSIONAL PREPARATION

University of Tennessee	Nuclear Engineering	B.S. 1984
University of Tennessee	Nuclear Engineering	M.S. 1986
University of Tennessee	Nuclear Engineering	Ph.D. 1989

APPOINTMENTS

1995-Present	<i>Associate Professor</i>	Arizona State University
2004-2005	<i>Visiting Staff Member</i>	Los Alamos National Laboratory
1997-2004	<i>Associate Chair (Undergraduate Studies)</i>	Arizona State University
1996	<i>Faculty Sabbatical</i>	Motorola, Space and Systems Technology
1989-1995	<i>Asst. Professor (Electrical Engineering)</i>	Arizona State University
1991	<i>Faculty Research Appointment</i>	Battelle, Pacific Northwest Laboratory
1983-1988	<i>Field Test Engineer</i>	Analysis and Measurement Services Corp.

RELEVANT PUBLICATIONS

1. K. E. Holbert, L. L. Grable, A. Overbay, B. Nzekwe, "FREEDM Precollege Programs: Inspiring Generation Y to Pursue Careers in the Electric Power Industry," *IEEE Transactions on Power Systems*, vol. 29, no. 4, July 2014, pp. 1888-1895.
2. K. E. Holbert, "Online Multidisciplinary Nuclear Power Generation Graduate Certificate Program," *Transactions of the American Nuclear Society*, vol. 110, Reno, NV, June 2014, pp. 21-22.
3. K. E. Holbert, L. L. Grable, A. Overbay, B. Nzekwe, "FREEDM ERC Precollege Programs: Motivating Careers in the Electric Power Industry," *IEEE Power & Energy Society General Meeting*, Vancouver, BC, July 21-25, 2013, 5 pp.
4. L. L. Grable, A. Overbay, M. Bosworth, "Enhancing Teaching and Learning with an Immersion Research Experience: Project Updates from an Engineering Precollege Program," *Proceedings of Society for Information Technology & Teacher Education International Conference*, New Orleans, LA, March 25-29, 2013, pp. 4585-4591.
5. L. Grable, M. Rickard, K. Holbert, K. Molyneaux, B. Nzekwe, "Renewable Energy as a STEM Interest Motivator: Project updates from an engineering precollege program," *Proceedings of Society for Information Technology & Teacher Education International Conference*, Austin, TX, March 5-9, 2012, pp. 1801-1805.
6. K. E. Holbert, K. Molyneaux, L. L. Grable and P. Dixon, "Multi-university Precollege Outreach from a Renewable Energy Focused Engineering Research Center," *41st ASEE/IEEE Frontiers in Education Conference*, Rapid City, SD, October 12-15, 2011.
7. L. L. Grable, K. Molyneaux, P. Dixon, K. Holbert, "STEM and TPACK in Renewable Energy for Middle and High School: Building a Learning Community through Teacher Professional Development," *Proc. of Society for Information Technology & Teacher Education International Conference*, Nashville, TN, March 7-11, 2011, pp. 2480-2485.
8. K. Holbert, L. Grable, P. Dixon, S. Schulze, "Precollege Outreach within the FREEDM Systems Center," *Proceedings of the 2010 American Society for Engineering Education Annual Conference & Exposition*, Louisville, KY, June 20-24, 2010, 10 pp.

9. K. E. Holbert, G. G. Karady, "Strategies, Challenges and Prospects for Active Learning in the Computer-Based Classroom," *IEEE Transactions on Education*, vol. 52, no. 1, pp. 31-38, Feb. 2009.
10. G. G. Karady, K. E. Holbert, "Novel Technique to Improve Power Engineering Education Through Computer-Assisted Interactive Learning," *IEEE Transactions on Power Systems*, vol. 19, no. 1, pp. 81-87, February 2004.

SYNERGISTIC ACTIVITIES

- Lead-PI on an NSF Research Experience for Undergraduates (REU) program that was funded for three summers (1999, 2000 and 2001). The REU was designed to facilitate the involvement of American Indian students on energy engineering related topics, which were taken from research projects and applied to problems unique to rural, reservation regions.
- Actively engaged in education-related research that is directly tied to instrumentation issues and emerging Internet-based delivery of courses.
- Conducted workshops/laboratories in the summers of 1998-2003 for teachers and counselors from secondary schools, and community college faculty attending the Women in Science and Engineering (WISE) Investments program at ASU.
- Co-PI of a three-year, multi-university, NSF-sponsored Combined Research and Curriculum Development (CRCD) project aimed at improving electric power industry competitiveness through the application of artificial intelligence. Drawing from my fuzzy logic based instrumentation research, I developed a fuzzy logic educational module for use in graduate and upper-division undergraduate courses.
- Honors and Achievements
 - IEEE Transactions on Education* Best Paper award for 2010
 - IEEE Phoenix Section *Outstanding Faculty Award*, 2007
 - ASU Engineering College *Teaching Excellence Award*, 1996-1997
 - Registered Professional Engineer (P.E.)
- Professional and Scientific Service
 - IEEE Phoenix Area Student Activities Chair, 2001-2005
 - American Society for Engineering Education (ASEE) Member, 1992-present
 - IEEE, Senior Member, 1996-present, Member, 1988-1996

COLLABORATORS AND OTHER AFFILIATIONS

- Collaborators and Co-Editors: P. Adell (Jet Propulsion Laboratory), D. R. Alexander (AFRL/RVSE), A. Amort (Boeing Phantom Works), M. Baze (Boeing Phantom Works), G. Dunham (NAVSEA Crane), D. M. Fleetwood (Vanderbilt), F. M. Guerra (Los Alamos National Lab), H. P. Hjalmarson (Sandia National Labs), A. S. Heger (Los Alamos National Lab), K. C. Kelley (Los Alamos National Lab), S. McClure (Jet Propulsion Laboratory), S. S. McCreedy (Los Alamos National Lab), L. Mili (VA Tech), A. Mishra (VA Tech), S. T. Pantelides (Vanderbilt), D. G. Platteter (NAVSEA Crane), B. G. Rax (Jet Propulsion Laboratory), R. D. Schrimpf (Vanderbilt), J. Seiler (NAVSEA Crane), M. R. Shaneyfelt (Sandia National Labs), W. M. Shedd (AFRL/RVSE), J. Wert (Boeing Phantom Works)
- Graduate Advisors: Profs. T. Kerlin and B. Upadhyaya, University of Tennessee
- Thesis Advisor: Kang Lin, Sanket Adhikari, Anand Swaminathan, Sriram Sankaranarayanan, Sandeep Borkar, Avinash Padmanbh, Vidhyas Ananthanarayanan, James Nessel. Twenty-five graduate students advised.

Dr. Alex Q. Huang

Department of Electrical and Computer Engineering, North Carolina State University
aquang@ncsu.edu, <http://www.ece.ncsu.edu/people/aquang>

Professional Preparation:

Institution	Location	Major	Degree/Year
Zhejiang University	Hangzhou, China	Electrical Engineering	B.S. 1983
Chengdu Institute of Radio Engineering	Chengdu, China	Electrical Engineering	M.S. 1986
Cambridge University	Cambridge, UK	Electrical Engineering	Ph.D. 1992

Appointments:

2007-present	Progress Energy Distinguished Professor of Electrical and Computer Engineering, NCSU
2008-2014	Founding Director, NSF Engineering Research Center FREEDM Systems Center
2008-2014	Founding Director, Advanced Transportation Energy Center, NC State University
2004-2007	Alcoa Professor of Electrical Engineering, Dept. of Electrical Engineering, NCSU
1994-2004	Professor, Center for Power Electronics System and the Bradley Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA
1992-1994	Research Fellow, Magdalene College, Cambridge, United Kingdom
1992-1994	Research Associate, Department of Engineering, Cambridge University
1989-1992	Research Student, Department of Engineering, Cambridge University
1988-1989	Marketing Manager, XiNi Technology Company, China
1986-1988	Assistant Lecturer, Chengdu Institute of Radio Engineering, China

Five Products Relevant to Proposal:

- Huang, A.Q.; Crow, M.L.; Heydt, G.T.; Zheng, J.P.; Dale, S.J.; , "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet," Proceedings of the IEEE , vol.99, no.1, pp.133-148, Jan. 2011
- Huang, Alex; Yu, Xunwei; She, Xu; Rezaei, Mohammad Ali; Chen, Dong "Autonomous Control, Operation, and Protection of the FREEDM System", pp. 969-974, Proceedings of the 19th IFAC World Congress, 2014
- Mohammad Ali Rezaei and Alex Huang, "Ultra Fast Protection of Radial and Looped Electric Power Grid using a Novel Solid-State Protection Device", ENERGY CONVERSION CONGRESS AND EXPOSITION (ECCE), 2012 IEEE , pp. 610
- She, X.; Yu, X.; Wang, F.; Huang, A.Q., "Design and Demonstration of a 3.6KV-120V/10KVA Solid State Transformer for Smart Grid Application," Power Electronics, IEEE Transactions on , vol.29, no.8, pp.3982
- Wang, Fei; Wang, Gangyao; Huang, Alex; Yu, Wensong; Ni, Xijun, "Design and operation of A 3.6kV high performance solid state transformer based on 13kV SiC MOSFET and JBS diode," Energy Conversion Congress and Exposition (ECCE), 2014 IEEE , vol., no., pp.4553,4560, 14-18 Sept. 2014

Five Other Selected Products:

- Huang, A.Q., "Renewable energy system research and education at the NSF FREEDM systems center," Proc. IEEE PES GM 2009, vol., no., pp.1-6, 26-30 July 2009
- Huang, A.Q.; Baliga, J., "FREEDM System: Role of power electronics and power semiconductors in developing an energy internet," Proceeding of IEEE ISPSD 2009, pp.9-12, 14-18 June 2009
- Huang, Alex; , "FREEDM system - a vision for the future grid," Power and Energy Society General Meeting, 2010 IEEE , vol., no., pp.1-4, 25-29 July 2010
- Xu She, Alex Q. Huang, Rolando Burgos, "Review of Solid-State Transformer Technologies and Their Application in Power Distribution Systems", IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. I, No.3, September 2013, pp. 186-197
- Karady, G.G.; Huang, A.Q.; Baran, M., "FREEDM system: An electronic smart distribution grid for the Future," Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES , vol., no., pp.1,6, 7-10 May 2012

Synergistic Activities:

- Research & Education Productivity: \$220m+ external funding, 70+ graduated Ph.D. and master students, 106 Journal papers, 343 Conference papers, 21 US Patents; 30+ Invention Disclosures
- Professional Society Membership:
 - Fellow, IEEE since 2005
- Professional Services:
 - 2015-Vice Chair, IEEE WBG Workshop
 - 2013-Honorary Chair, IEEE WBG Workshop, Columbus, Ohio
 - 2012-General Chair, IEEE ECCE 2012, Raleigh, North Carolina
 - 1994-now Various Executive Committee, Technical Committee, Session Chair and Short Course Chair role in IEEE ISPSD, APEC, ECCE, PESC, IPEMC, IAS, IECON
 - 1994-now – Reviewers for various journals and government agencies
 - 2004- Associated Editor, IEEE Transaction on Power Electronics Special Issue on Integrated Power Electronics;;

Collaborators:

Mesut Baran (NCSU), Jay Baliga (NCSU), Subhashish Bhattacharya (NCSU), Aranya Chakraborty (NCSU), Moyuen Chow (NCSU), Mariesa Crow (MST), Chris Edrington (FSU), Gerald Heydt (ASU), Iqbal Husain (NCSU), Srdjan Lukic (NCSU), Veena Misra (NCSU), Ning Lu (NCSU), Mischa Steurer (FSU), Wencong Su (Univ. of Mich.), Wenye Wang (NCSU), Mengqi Wang (Univ. of Mich.), Qingan Zeng (NCAT), Xiangwu Zhang (NCSU), Jim Zheng (FAMU)

Graduate and Post-Doctoral Advisors:

Dr. Gehan Amaratunga, Department of Engineering, Cambridge University, United Kingdom

Thesis Advisor and Sponsor for Various Researchers:

Graduated Masters (27): Julie Dong (1997), Josh Hawley (2004), Mohammed Islam (1998), Ding Li (2006), YuanZhu Li (2001), Wei Liu (2005), Yin Liu (2001), Yan Ma (2004), Kevin Motto (2000), Karan Tewari (2006), Zhaoning Yang (2006), Budong You (1997), Jifeng Qi(2008), Ning Zhu (2007), Shoubhik Doss (2008) , Sameer Mundkur (2008) Ryan Meitl (2011) Phillip Funderburk (2011) Jiadi Jiang (2011) Yaling Wang(2011) Xing Huang (2011) Jerry Hu (2013) Bharadwaj Vasudevan (2013), Jai Wang (2013), Yi Wang (2014), Yuling Zhao(2014), Yaser Naeimi(2014)

Graduated Ph.D. (50): Budong You (1999), Yuming Bai (2003), Haifei Deng (2005), Xiaoming Duan (2006), Chong Han (2006), Yuxin Li (2000), Siriroj Sirisukprasert (2004), Zhenxue Xu (2003), Bin Zhang (2005), Xin Zhang (2005), Xigen Zhou (2005), Yan Gao (2007), Bin Chen(2008), Mohamed Maharsi(2009), Xiaojun Xu (2008), Jinseok Park (2009), Jeeseung Jung (2009), Yu Liu (2009), Jun Wang (2009), JieWei Fan(2010), LiYu Yang (2010), Wenchao Song (2010), Xiaopeng Wang (2010), Jingzhen Hu (2010), Jun Li (2010) Tiefu Zhao (2010) Xin Zhou (2010) Sungkeun Lim (2010) Rong Guo (2010) Xiaohu Zhou (2011) Zhigang Liang (2011) Woongje Sung (2011) Yu Du (2011) Qian Chen(2012) Pochi Lin (2012) Edward Van Brunt (2012) Wencong Su(2013) Xu She(2013), Gurava Bawa(2013) Gangyao Wang (2013), Yenmo Chen(2013), Xunwei Yu (2014), Xing Huang(2014), Changjian(Jared) Hu(2014), Falahi Ghazal(2014), Mengqi Wang(2014), Fei Wang (2014), Mohammad Ali Rezaei(2015), Elie Njam (2015), Meng-Chia Lee(2015)

Visiting Scholars/Professors (23): Mr. Bo Zhang (1998), Dr. John Li (2003), Dr. Zhong Du (2005-2006), Prof. G. Tan (2007), Mr. Jei Zeng (2008), Mr. Wei Jing (2009), Mr. Yang Liu (2011), Dr. J. Shi, (2009-2010), Prof. Lamine Thiaw (2009-2010), Dr. Wenxi Yao (2010-2011), Chushan Li (2011), Dr. Junho Bang (2011), Dr. Doon-Chong Lee (2011-2012), Dr. In-dong Kim(2012-), YiYi Zhang(2012-2013) Yanlei Zhao (2013-2014) Lijun Zheng (2013-2014) Qiwen Lu (2013-2014) Xuan Li (2013-2015) Song Zong (2013-2014) Lin Liang(2014-2015), Siyang Liu(2015-), Ma Lan(2015-)

Postdoctoral Researchers (9): Dr. Seou Ju Ahn (2010-2011), Dr. Wu Chen (2010-2011), Dr. Young-Hwan Choi (2010-2012), Dr. Xijun Ni (2011-2015), Dr. Sherwin Yang (2012-2014), Kuijun Lee(2012-2014) Ruiyu Yang (2013-) Dong Chen(2013-) Hwan Ji (2013-).

Hiring and Mentoring of Tenure Track Faculty (5): Dr. Subhashish Bhattacharya, Dr. Srdjan Lukic, Dr. Aranya Chakraborty, Dr. Ning Lu, Dr. Iqbal Husain.

Hiring and Mentoring of Research Professors (5): Dr. Woongje Sung (2012-now), Dr. Wensong Yu (2013-now), Dr. Doug Hopkins (2012-2014), Dr. David Lubkeman (2011-2014), Dr. Len White (2011-2014).

Current Students:

Masters (1): Pengkun Liu; **Ph.D. (23):** Liqi Zhang, Chang Peng, Kai Tan, Suxuan Guo, Xiaoqing Song, Xiaomin Li, Yasher Naeimi, Dharma Kadam, Qi Tian, Sizhen Wang, Yizhi Xu, Li Wang, Sarah Hambridge, Lei Yang, Fei Xue, Zhiping Chen, Qianlai Zhu, Qingyun Huang, Hanning Tang, Kristen Garcia, Atsushi Shimbori, Yifan Jiang

Iqbal Husain
 ABB Distinguished Professor, Electrical and Computer Engineering
 North Carolina State University

A. Professional Preparation

Bangladesh Univ. of Eng. and Technology	Electrical Engineering	BS, 1987
Texas A&M University	Electrical Engineering	MS, 1989
Texas A&M University	Electrical Engineering	PhD, 1993

B. Appointments

3/2014-Present	Director, FREEDM Systems Center, NC State University	
8/2011-Present	ABB Distinguished Professor, Department of ECE, NC State University	
8/2003-8/2011	Professor, University of Akron, Dept. of Electrical & Computer Eng.	
8/1999-7/2003	Associate Professor, University of Akron, Dept. of Electrical Eng.	
1/2002-3/2002	Visiting Professor, Oregon State University, Dept. of Elec. and Comp. Eng.	
7/1994-7/1999	Assistant Professor, University of Akron, Dept. of Electrical Eng.	
5/1996-8/1996	Summer Faculty Fellow, Wright-Patterson AFB, Dayton, Ohio.	
9/1993-6/1994	Assistant Lecturer, Texas A&M University, Dept. of Electrical Eng.	
1/1988-8/1993	Research Assistant, Texas A&M University, Dept. of Electrical Eng.	
Consulting	ITT Automotive, Dayton, Ohio	Delphi Automotive, Indianapolis, IN
Appointments	Graphic Enterprises, Canton, OH	Goodyear Tire & Rubber, Akron, OH
	Hi-Tech Inc., Cleveland, OH	Caterpillar, Inc., Peoria, IL
	Wright Patterson AFB, Dayton, OH	Winston Group, Chicago, IL
	Honeybee Robotics, New York, NY	Infineon, Livonia, MI

C. Publications

Relevant Publications

1. C. Peng, I. Husain, A. Huang, B. Lequesne, and R. Briggs, "A fast mechanical switch for medium voltage hybrid DC and AC circuit breakers," Energy Conversion Congress & Expo (ECCE2015), pp. 5211-5218, Montreal, Canada, Sept. 2015.
2. Z. Yu, R. Ayannar, and I. Husain, "A Detailed Model of a Solid State Transformer," Energy Conversion Congress & Expo (ECCE2015), pp. 723-729, Montreal, Canada, Sept. 2015.
3. M.A. Khan, I. Husain, Y. Sozer, "A Bidirectional DC-DC Converter With Overlapping Input and Output Voltage Ranges and Vehicle to Grid Energy Transfer Capability," IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 2, No. 3, pp.507-516, 2014.
4. A. Elrayyah, A. Safayet, Y. Sozer, I. Husain and M. Elbuluk, "Novel Harmonic and Phase Estimator for Grid-Connected Renewable Energy Systems," *IEEE Transactions on Industry Applications*, Vol. 50, No. 1, pp. 620-630, Jan/Feb 2014.
5. M. N. Arafat, S. Palle, Y. Sozer and I. Husain, "Transition Control Strategy between Standalone and Grid Connected Operation of Voltage Source Inverters," *IEEE Transactions on Industry Applications*, Vol. 48, No. 5, pp. 1516-1525, 2012.

Other Significant Publications

1. Y. Sozer, I. Husain, and D.A. Torrey, "Guidance in Selecting Advanced, Control Techniques for Switched Reluctance Machine Drives in Emerging Applications," IEEE Transactions on Industry Applications, Vol. 51, No. 6, pp. 4505-4515, 2015.
2. C. Sikder, I. Husain, and W. Ouyang, "Cogging Torque Reduction in Flux-Switching Permanent Magnet Machines by Rotor Pole Shaping," IEEE Transactions on Industry Applications, Vol. 51, No. 5, pp. 3609-3619, 2015.

3. A. Elrayyah, K. Namburi, Y. Sozer, and I. Husain, "A Novel Dithering Algorithm to Reduce the Electro-Magnetic Interference (EMI) in DC/AC Inverters," *IEEE Trans. on Power Electronics*, Vol. 29, No. 6, pp. 2798-2806, 2014.
4. S. Underwood and I. Husain, "On-line Parameter Estimation and Adaptive Control of Permanent Magnet Synchronous Machines," *IEEE Transactions on Industrial Electronics*, Vol. 57, No. 7, pp. 2335-2343, July 2010.
5. N. Hasan and I. Husain, "A Luenberger-Sliding Mode Observer for On-line Parameter Estimation and Adaptation in High-Performance Induction Motor Drives," *IEEE Trans. on Industry Applications*, Vol. 45, No. 2, pp. 772-781, March-April 2009.

Total Journal Papers: 72; Total Conference Papers: 85; Patents and Invention Disclosures: 7

D. Synergistic Activities

1. **Power Electronics and Electric Machines Design and Modeling:** Research on power electronics electric machines allowed unique contributions in design, control, acoustic noise prediction, and parameter identification methods. Research applied to develop sensors. Honored with the IEEE Fellow Award in 2009 for contributions in SRM research.
2. **Course Development:** Developed the course on electric and hybrid vehicles course in Akron (first offered in 1996). Subsequently, wrote the textbook *Electric and Hybrid Vehicles: Design Fundamentals*, which has been adopted by many Universities around the globe. Developed the course on Dynamics & Control of Electric Machines at NC State.
3. **IEEE-IAS Distinguished Lecturer, 2012-2013:** Delivers guest lectures in Electric Machines drives, and electric and hybrid vehicles around the world.
4. **Service to Professional Society:** IEEE-IAS Board Member and Education Chair. Plenary Chair, ECCE 2016. General Co-Chair, Energy Conv. Congress & Expo (ECCE) in 2012, and Tech. Program Co-Chair of ECCE 2011. Chairman, IEEE-IAS Electric Machines Committee, 2009-2010. Chairman, IEEE-IAS Transportation Systems Committee, IEEE – Akron Student Section Advisor. 1995-2011. Received IEEE Third Millennium Medal, 2000.
5. **High School and Middle School Activity:** Ran several Science Olympiad (SO) regional competitions. Offers coaching to students on several SO events. Developed story boards and presentations for Environmental Education Center at Cuyahoga Valley National Park.

E. Collaborators & Other Affiliations

Collaborators and Co-Editors

A. Huang (NC State), S. Lukic (NC State), R. Aynnar (Arizona), A. Chakraborty (NC State), Y. Sozer (Univ. of Akron), A. Radun (General Electric), T. Sebastian (Halla), M. Islam (Halla), R. Islam (Nexteer), B. Lequesne (Consultant), R. Briggs (Consultant)

Graduate Advisor

M. Ehsani, Texas A&M University, College Station, TX

Recent Graduate Advisees and Current Students

A. Safayet (PhD 2015; Halla Mechatronics)	M. A. Khan (PhD 2015; NC State)
R. Mikail (PhD 2013; ABB, Inc.)	J. Wang (MS 2013; Power Integrations)
J. Markijohn (MS 2013, NavAir)	B. Mularcik (MS 2012; Diebold)
R. Islam (PhD 2009; Nexteer Automotive)	K. Pavan (MS 2012; Kinetec Controls, OH)
N. Hasan (PhD 2008 General Motors)	S. Underwood (PhD 2006; Aerovironment)
A. Khalil (PhD 2005 Caterpillar)	G. Pasquesoone (MS 2011; Magna)
S. Yarlagadda (MS 2011; Omron Automotive)	S. Narla (MS 2010; US Hybrid)
C. Salgues (MS 2008; US Hybrid)	S. Chanda (MS 2008; FEV Transmission)
N. Picot (MS 2007; General Motors)	R. Paciotti (MS 2007; General Motors)

Total Ph.D.: 14; Total M.S.: 25.

George G. Karady

School of Electrical, Computer and Energy Engineering
Arizona State University

Professional Preparation:

Technical University of Budapest	Electrical Engineering	Diploma in Electrical Engineering
Hungarian Academy of Science	Electrical Engineering	Candidate of Technical Sciences
Technical University of Budapest	Electrical Engineering	Doctorate

Appointments:

1986 - Present	Power System Engineering Chair Professor, Arizona State University
1977 -1986	Chief Consulting Electrical Engineer, Chief Engineer of Computer Technologies, and Manager of Electrical Systems, EBASCO Services
1969 - 1977	Member of Research Staff, Program Manager, and IREQ Fellow, Hydro Quebec Institute of Research
1952 - 1969	Teaching Assistant, Associate Professor, and Deputy Department Head, Technical University of Budapest

Relevant Publications:

Dr. Karady coauthored a book, which second edition will be published in this year. He also authored several book chapters. He published more than 130 Journal and over 210 conference papers.

- Sadik Kucuksari, George. G. Karady: "Complete Model Development for an Optical Current Transformer"; IEEE Transaction on. Power Delivery; Vol. 27, No 4, pp 1755-1762, October 2012.
- S. Kucuksari, G. G. Karady, "Experimental Comparison of Conventional and Optical VTs and Circuit Model for Optical VT," IEEE Trans. on Power Delivery, Vol. 26, No.3., pp:1571-1579; July 2011
- Xianjun Zhang, George G. Karady and Yonggang Guan, "Design methods investigations for residential microgrid infrastructure"; European Transaction on Electrical Power; Vol. 21, Issue 8, pp. 21520-2141 On line publication 24 Nov 2011.
- B. L. Kokanos and G. G. Karady: "Associate Hermite Expansion Small Signal Mode Estimation". Transaction on Power Systems; Vol. 25, No 2, pp 999-1007, May 2010
- E. A. Al-Ammar, G.G Karady, and H. J. Sim: "Novel Technique to Improve the Fault Detection Sensitivity in Transformer Maintenance Test" European Transaction on Electrical Power; On line May 2009, paper: Vol. 20,No: 4, pp: 438-449, May 2010.
- K.E. Holbert, G.G Karady: "Strategies, Challenges and Prospects for Active Learning in the Computer Based Classroom"; IEEE Transaction on Education, Vol.52, No 1, pp. 31-38, February 2009. Award winning paper: 2010 Best Transaction on Education Paper Award

Other Significant Publications:

- Xianjun Zhang, George G Karady, Kalyan R. Piratla, Samuel T Ariarataam: "*Nexus between Distributed Generation and Urban Water Infrastructure*". Paper no:1469; IEEE-PES General Meeting in San Diego; CA. pp:8, July 22-26, 2012
- G. Karady ,A.Q. Hua, B. Mesut: "FREEDM System: An Electronic Smart Distribution Grid" 2012TD0211, Transmission and Distribution Conference, Orlando FL. P:1-7, May 7-10 2012
- George G. Karady, Jay R. Prigmore, Jorge A. Mendoza,: *A Neodymium Permanent Magnet Fault Current Limiter for Use in the FREEDM Project*"; Paper No 180, pp:1-7; 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin Oct 14-17; 2012
- George G Karady, Essam Al-Ammar, Baozhuang Shi, Monty W. Tuominen: "Experimental Verification of the Proposed IEEE Performance and Testing Standard for ADSS Fiber Optic Cable for Use on Electric Utility Lines". IEEE Transaction Power Delivery, Vol: 21, No. 1, pp: 450-455, January 2006

G. Karady, K. Holbert, Electric Energy Conversion and Transport using an Interactive Computer-Based Approach, John Wiley and Sons Inc. ISBN 0-471-47652-8, 2005. **Book**

Synergistic Activities:

- Dr. Karady is working on the NSF sponsored FREEDM project, which developing an micro-grid with electronic circuit breakers and solid-state transformers.
- He also works on the NSF sponsored RESIN project, which investigates interaction of the distributed generation supported distribution grid and the local gas and water supply.
- Dr. Karady and his student investigated the effect of voltage injection by FACT device in a feeder. This study resulted in the PhD degree for the student and two transactions publications.
- Dr. Karady developed four (4) graduate courses and serves as the chair of the power group area committee. He graduated 23 Doctor of Philosophy (PhD) and 48 Master of Science (MS) students.
- Dr. Karady is active in IEEE (Institute of Electrical and Electronic Engineers). He was chair of Subcommittee on I0 Power Electronics, Substations and WG I1 Power Electronic Equipment. He also serves as an editor for the Transaction on Power Delivery.
- Dr. Karady also worked in CIGRE, (International Conference on Large High Voltage Electric Systems); there he has served as Vice President and Treasurer/Secretary of the US National Committee and as a member of the US Technical Committee
- Dr. Karady has received several awards and honors including: Honorary Doctorate from The Technical University of Budapest, Hungary 1996; IEEE Fellow, 1978; IEEE Third Millennium Medal, 2000; Acknowledgement of Contribution to the development of “1623 IEEE Guide for the Functional Specification of Medium Voltage (1-35kV) Electronic Shunt Devices for Dynamic Voltage Compensation”. IEEE-SA Standard Board, May 2005, IEEE Phoenix Section “In Recognition and Appreciation of Your Valued Services and Contribution as Chairman. 2004’ Attwood Associate Award. CIGRE US National Committee 2004, IEEE Membership Chapter Activities Award. “Outstanding Services and contribution to the PES Membership and Chapters activities”. 2004; IEEE PES Distinguished Service Award 2009; IEEE PES Certificate of Appreciation, For Dedicated Service as Chair of the High Voltage Power Electronics Stations Subcommittee IO 2009

Collaborators & Other Affiliations:

Collaborators and Co-Editors:

Dr. Baj Agrawal, Arizona Public Service; Dr. Anjan Bose, Professor and Dean, Washington State University; Bryce Corderoy, CIGRE, Australia; Mike Dyer, Salt River Project; Dr. Hamid Elahi, Manager, General Electric Company; William M. Frix, Department of Defense, Washington DC; Dr. Byung Moon Han, Professor and chair, Myongji University, Korea;

Graduate and Post-Doctoral Advisors:

Thesis Advisor and Postgraduate-Scholar Sponsor: Total number of Students Graduated: **PhD: 23, MS 47; Graduated in last 5 years: PhD:** Essam Al-Ammar PhD07, Mehmet Argin PhD07, Sadik Kucuksari PhD10, Barrie L. Kokanos PhD10: Xianjun Zhang **PhD 13, Jay Prigmore PhD 13. Graduated in last 5 years MS:** Surendra R. Puchalapalli MS07, Jeffrey Irving MS08, Linh Dam MS10, Hui Zhang MS10, Seshank Malap MS 10, Arvind Thirumalai MS 11, Kumaraguru Prabakar MS 2011, Xing Liu MS 12, Yan Ma MS 12.

Presently advised graduate students: Matthew Rhodes PhD; Varun Iyengar MS; Jicheng Yu MS; Ashish Makthal MS; Sachin Gopal Soni MS; Krutak Kamdar MS; Akhil Mandadi;

Postgraduate –Scholar Sponsor:

Ibrahim Gunes, Visiting Researcher, Istanbul University, Turkey, 2007-2008; Prof Dr. Mustafa Ugur Unver, Sakarya University, Turkey, 2008; Mingrui Zhang, Tongji University, China, 2009-2010; Yonggang Guan, Tsinghua University, 2009-2010. Mustafa Ugur Unver, Meylana, Turkey 2012

Jonathan W. Kimball

Associate Professor, Missouri University of Science and Technology

Professional Preparation

Carnegie Mellon University	Electrical and Computer Engineering	BS, 1994
University of Illinois at Urbana-Champaign	Electrical Engineering	MS, 1996
University of Illinois at Urbana-Champaign	Electrical and Computer Engineering	PhD, 2007

Appointments

Missouri University of Science and Technology: Assistant Professor, Jan. 2008-Aug. 2014; Associate Professor (with tenure), Sep. 2014-present
SmartSpark Energy Systems, Inc.: Co-Founder; Senior Engineer, Dec. 2007-2009; VP of Engineering, 2003-2007
University of Illinois at Urbana-Champaign: Senior Research Engineer, 2006-07; Research Engineer, 2003-2006; Visiting Lecturer for five semesters
Baldor Electric (Fort Smith, AR): Senior Design Engineer, 1998-2003
Motorola (Semiconductor Products Sector, Phoenix, AZ): Systems Design Engineer, 1996-1998

Five Closely Related Products

M. M. Baggu, B. H. Chowdhury, **J. W. Kimball**, "Comparison of Advanced Control Techniques for Grid Side Converter of Doubly-Fed Induction Generator Back-to-Back Converters to Improve Power Quality Performance during Unbalanced Voltage Dips," *IEEE Journal on Emerging and Selected Topics in Power Electronics*, vol. 3, pp. 516-524, June 2015.

J. A. Mueller, M. Rasheduzzaman, and **J. W. Kimball**, "A Model Modification Process for Grid-Connected Inverters Used in Islanded Microgrids," *IEEE Transactions on Energy Conversion*, vol. PP, in press.

T. Paul, **J. W. Kimball**, M. Zawodniok, T. P. Roth, B. McMillin, S. Chellappan, "Unified invariants for cyber-physical switched system stability," *IEEE Transactions on Smart Grid*, vol. 5, pp. 112-120, Jan. 2014.

A. Alzahrani, **J. W. Kimball**, and C. Dagli, "Predicting solar irradiance using time series neural networks," presented at Complex Adaptive Systems, in *Procedia Computer Science*, 2014, vol. 36, pp. 623-628.

Md. Rasheduzzaman, J. A. Mueller, **J. W. Kimball**, "An accurate small-signal model of inverter-dominated islanded microgrids using dq reference frame," *IEEE Journal on Emerging and Selected Topics in Power Electronics*, vol. 2, pp. 1070-1080, Dec. 2014.

Five Additional Products

M. Rasheduzzaman, J. A. Mueller, and **J. W. Kimball**, “Reduced order small-signal model of microgrid systems,” *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1292–1305, Oct. 2015.

A. Choudhary, H. Ramaprasad, T. Paul, **J. W. Kimball**, M. Zawodniok, B. McMillin, S. Chellappan, “Stability of a cyber-physical smart grid system using cooperating invariants,” in *Proc. IEEE Intl. Computer Software & Applications Conference (COMPSAC)*, 2013.

H. Qin, **J. W. Kimball**, “Solid state transformer architecture using ac-ac dual active bridge converter,” *IEEE Transactions on Industrial Electronics*, vol. 60, pp. 3720–3730, Sept. 2013.

M. Rasheduzzaman, T. Paul, **J. W. Kimball**, “Markov jump linear system analysis of microgrid stability,” in *Proc. American Control Conference*, 2014, pp. 5062–5066.

J. W. Kimball and M. Zawodniok, “Reducing Common-Mode Voltage in Three-Phase Sine-Triangle PWM with Interleaved Carriers,” *IEEE Transactions on Power Electronics*, vol. 26, pp. 2229–2236, Aug. 2011.

Synergistic Activities

Co-founder, SmartSpark Energy Systems, Inc., 2003. SmartSpark was founded to commercialize power electronics research from the University of Illinois.

Technical advisor, Solar House Team, Missouri S&T, Jan. 2010-present.

Technical advisor, MSAT (satellite) team, Missouri S&T, May 2015-present.

Collaborators (outside Missouri S&T)

Murali Baggu (NREL), Mesut Baran (North Carolina State), Subhashish Bhattacharya (North Carolina State), Patrick Chapman (SunPower), Mo-Yuen Chow (North Carolina State), Keith Corzine (Clemson), Chris Edrington (Florida State University), Touria El-Mezyani (Florida State), Jordan Henry (Sandia National Laboratory), Iqbal Husain (NC State), Brian Kuhn (SunPower), Harini Ramaprasad (University of North Carolina-Charlotte), Sanjeev Srivastava (Siemens), Mischa Steurer (Florida State University), Luke Watson (Sandia)

Graduate Students Advised (23 total): Majed Al-Abbass (M.S. 2013), Sami Alalwani, Ahmad Al-Zahrani, Murali Baggu (Ph.D. 2009), Anupama Balakrishnan (M.S. 2013), Jacob Delaney, Faris al-Faris (M.S. 2012), Jordan Henry (M.S. 2010), Seyed Hesam Jafari (M.S. 2013), Zachary Johnson (M.S. 2012), Amshumaan Kashyap (M.S. 2013), Nickolas McFowland (M.S. 2012), Jacob Mueller (M.S. 2014), Lukas Müller (M.S. 2014), Nisha Nagarajan (M.S. 2010), Tamal Paul (M.S. 2012, Ph.D. 2015), Hengsi Qin (Ph.D. 2012), Md. Rasheduzzaman (Ph.D. 2015), Amir Saad (M.S. 2012), Luke Watson (Ph.D. 2013), Beth Yount (M.S. 2010), Jie Zhao (M.S. 2012), Hailong Zhou (M.S. 2012)

Postdoctoral Scholars Advised: None

Thesis Advisor: Philip Krein (University of Illinois at Urbana-Champaign)

Hui Li

Professional Preparation:

Institution	Major/Area	Degree, Year
Huazhong University of Science & Technology, China	Electrical Engineering	B.S., 1992
Huazhong University of Science & Technology, China	Electrical Engineering	M.S., 1995
The University of Tennessee, Knoxville, TN	Electrical Engineering	Ph.D., 2000

Appointments:

- *Professor*, August 2013 – present
Florida State University, Tallahassee, FL
Department of Electrical and Computer Engineering
- *Associate Professor*, August 2008 – July 2013
Florida State University, Tallahassee, FL
Department of Electrical and Computer Engineering
- *Assistant Professor*, August 2002 – July 2008
Florida State University, Tallahassee, FL
Department of Electrical and Computer Engineering
- *Member of Technical Staff*, Jan 2001- May 2002
Tyco Electronics, Power Systems, Mesquite, Texas
- *Research Associate*, May 1999- December 2000
Engineering Technology Division, Power Electronics & Electric Machinery Research Center
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Products:

- Zhou, Y., Li, H. B., & Li, H. (2016). A Single-Phase PV Quasi-Z-Source Inverter with Reduced Capacitance Using Modified Modulation and Double-Frequency Ripple Suppression Control. *IEEE Transaction on Power Electronics*, 31, 2166-2173.
- Shi, Y., Li, R., Xue, Y., & Li, H. (2016). High-Frequency-Link Based Grid-tied PV System with Small DC-link Capacitor and Low-frequency Ripple-free Maximum Power Point Tracking. *IEEE transaction on Power Electronics*, 31, 328-339.
- Liu, L., Li, H., Xue, Y., & Liu, W. (2015). Decoupled Active and Reactive Power Control for Large Scale Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters. *IEEE Transaction in Power Electronics*, 30, no. 1, 176-187.
- Liu, X., & Li, H. (2015). An Electrolytic-Capacitor-Free Single-Phase High-Power Fuel Cell Converter with Direct Double-Frequency Ripple Current Control. *IEEE Transaction on Industrial Applications*, 51, no.1, 297-308.
- Greenleaf, M., Li, H., & Zheng, J. P. (2014). Application of Physical Electric Circuit Modeling to Characterize Li-ion Battery Electrochemical Processes. *Journal of Power Sources (ELS)*, 270, 113-120.
- Zhou, Y., & Li, H. (2014). Analysis and Suppression of Leakage Current in Cascaded-Multilevel-Inverter based PV systems. *IEEE Transaction on Power Electronics*, 29, no.10, 5265-5277.
- Yang, Y., Li, H., Zheng, J., & Aichhorn, A. (2014). Sizing Strategy of Distributed Battery Storage System with High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving. *IEEE Transaction on Smart Grid*, Vol. 5, issue 2, 982-991.
- Liu, X., Li, H., & Wang, Z. (2014). "A Fuel Cell Power Conditioning System with Low-frequency Ripple Free Input Current Using a Control-oriented Power Pulsation Decoupling Strategy". *IEEE Transaction on Power Electronics*, vol.29, no.1, 159-169.

Synergistic Activity:

My research interest is to develop new generations of power electronics converters for renewable energy and energy storage applications. I have developed a multi-port current-fed DAB soft-switching converter in the several kW range for fuel cell vehicle, hybrid electric vehicle and PV applications in the past. I have also developed a control system for distributed PV generation systems to solve the system voltage issues and unintentional islanding problems. My recent research interest includes developing power converters using SiC and GaN device to achieve high efficiency and high power density. As PI, I have received research funding from Department of Energy, National Science Foundation, Office of Naval Research (ONR), and Industry.

The research work has made measurable impacts to the power electronics industry, such as the high power density and high efficiency WBG converters, leakage current suppression method for transformerless PV converters and multiport low power current-fed soft-switching dc-dc converters. The research work has resulted in over 100 journal and conference publications including two prestigious IEEE paper prize award in 2014, 4 issued and 3 pending patents. I have developed a regularly offered course “renewable energy generation” for graduate students and senior undergraduate students at FAMU-FSU college of Engineering to equip them with the cutting-edge knowledge of smart grid, PV, energy storage and electric vehicle. I have supervised 12 Ph.D. students to degree completion. I am associate editor of IEEE Transactions on Power Electronics, and the elected member of Administrative Committee of IEEE Power Electronics Committee. I served as the education subcommittee chair, power electronics society from 2008 -2010. I also served the technical committee and session chairs for several conferences.

Collaborators & Other Affiliations:

Collaborators and Co-Editors (12):

R. Ayyanar, Arizona State University; S. Bhattacharya, North Carolina State University; D. Boroyevich, Virginia Tech University; A. Chakraborty North Carolina State University; C. Edrington, Florida State University; A. Huang, North Carolina State University; I. Husain, North Carolina State University; L. Liu, ABB Corporate Research; W. Liu, Lehigh University; S. Lukic, North Carolina State University; M. Steurer, Florida State University; J. Zheng, Florida State University.

Graduate Advisors and Postdoctoral sponsors (1):

Dr. Jack Lawler, University of Tennessee, Knoxville.

Thesis Advisors and Postgraduate-Scholar Sponsors (15):

S. Azongha, United States Patent and Trademark Office; Y. Deng, GE Power Electronics, Inc.; H. Fan, Intersil Corp.; S. Hwang, Kyungnam University; H. Li, unknown; R. Li, Shanghai Jiaotong University; X. Liu, GE Global Research; B. Mirtalebi, Rockwell Automation; Y. Shi, Center for Advanced Power Systems; P. Tatcho, unknown; L. Wang, Dell, Inc.; L. Wang, ABB, Inc.; Z. Wang, Transphorm, Inc.; Y. Yang, Dynapower Company, LLC; Y. Zhou, Ford Motor Company.

Ning Lu, Ph.D.

Associate Professor
Dept. of Electrical and Computer Engineering
North Carolina State University
Raleigh, NC 27695-7911
Email Address: nl2@ncsu.edu
Phone: (509) 554-0678(Cell)

EDUCATION

Ph.D. in Electric Power Engineering at Rensselaer Polytechnic Institute, Troy, New York; December 2002.

Ph.D. dissertation: *Power System Modeling Using Petri Nets*
Advisors: Prof. Alan A Desrochers and Prof. Joe H. Chow

M.S. in Electric Power Engineering at Rensselaer Polytechnic Institute, Troy, New York; December 1999.

B.Eng. in Electrical Engineering at Harbin Institute of Technology, Harbin, Heilongjiang, China; July 1993.

PROFESSIONAL AFFILIATIONS

Senior Member, Institute of Electrical and Electronics Engineers (IEEE), 2005

Editor, IEEE Transactions on Smart Grid, 2013-present

Chair, Climate Change Technology Subcommittee, Energy Development & Power Generation Committee, Power and Energy Society, 2014 - present

Secretary, Climate Change Technology Subcommittee, Energy Development & Power Generation Committee, 2008 - 2014

Secretary, System Economic Subcommittee, Power System Analysis, Computing, and Economics Committee, Power and Energy Society, 2009 - present

Chair, Demand Response Working Group, System Economic Subcommittee, Power System Analysis, Computing, and Economics Committee, Power and Energy Society, 2014 - present

President, North American Chinese Power Professional Association, 2011 - 2013

Chair, Business Models for Energy Storage Applications Working Group, System Economic Subcommittee, Power System Analysis, Computing, and Economics Committee, Power and Energy Society, 2011 - 2014

Guest Editor, special Issues on Energy Storage, IEEE Transactions on Smart Grid, 2012 - 2013

Guest Editor, Special Issue on Control Theory and Technology, IEEE Transactions on Smart Grid, 2013

Guest Editor, special Issues on Big Data Analytics for Grid Modernization, IEEE Transactions on Smart Grid, 2015-2016

Member, American Society for Engineering Education (ASSE), 2013

PROFESSIONAL EXPERIENCE

Jan. 2013– Electrical and Computer Engineering Dept., North Carolina State University, Raleigh, NC

Associate Professor

Research Interests: load modeling and control, wide-area energy storage applications, renewable integration, smart grid data analytics, microgrid modeling and control.

2003– 2012 Pacific Northwest National Laboratory, Richland, WA

Senior Research Engineer

1993– 1998 Shenyang Electric Bureau, Shenyang City, Liaoning Province, P. R. China

Substation Design Engineer

- Developed an Auto-CAD based distribution substation design system.
- Designed substations and distribution networks.

PUBLICATIONS

US Patent

- 1) Jin, Chunlian, **Ning Lu**, Shuai Lu, and Yuri V. Makarov. "Controller for hybrid energy storage." Publication number: US8754547 B2, filed November 17, 2010. Description available online at: <http://www.google.com/patents/US8754547>

Pending US Patents

- 1) **Lu, Ning**, Pengwei DU, Xinxin GUO, Robert PRATT, and Donald Hammerstrom. "Scheduling and modeling the operation of controllable and non-controllable electronic devices." Publication number: US20110270452 A, filed May 3, 2010. Description available online at: <https://www.google.com/patents/US20110270452>
- 2) **Lu, Ning**, Yu Zhang, Pengwei Du, and Yuri V. Makarov. "Controller for thermostatically controlled loads." Publication number: US20130282181 A1, filed April 20, 2012. Description available online at: <http://www.google.com/patents/US20130282181>

Books and Book Chapters:

Pengwei Du and **Ning Lu**, Energy Storage for Smart Grids: Planning and Operation for Renewable and Variable Energy Resources, Elsevier. 2014. <http://store.elsevier.com/Energy-Storage-for-Smart-Grids/Pengwei-Du/isbn-9780124095434/>

Journal and Conference Publications can be found online at:

<http://scholar.google.com/citations?user=J6pQoxIAAAJ&hl=en>

David L. Lubkeman, PhD, P.E., IEEE Fellow

Education and Training

- ◆ Licensed Professional Engineer
- ◆ Ph.D., Electrical Engineering, Purdue University
- ◆ M.S.E.E., Electrical Engineering, Purdue University (power systems focus)
- ◆ B.S.E.E., Electrical Engineering, Purdue University

Professional Experience

Research Professor, North Carolina State University, FREEDM Systems Center: 2012 to Present

Faculty associated with NSF FREEDM Systems Center and Instructor for Electric Power Systems Engineering (EPSE) Master's degree program.

Senior Product Line Manager – Distribution Automation, Sensus, Raleigh, North Carolina: 2011 - 2012

Responsible for management of Sensus distribution automation product portfolio. This includes development of product strategy and roadmap, setting investment direction, establishing partnering relationships, setting product pricing and developing sales support material.

Principal Consultant, KEMA, Raleigh, North Carolina: 2008 - 2010

Consulting in the areas of distribution system modeling, reliability, analytics and smart grid automation. Project tasks included modeling the impact of distributed generation/storage devices on electric distribution grids, characterizing the performance of a large-scale battery storage system and providing expertise on Smart Grid applications for medium-voltage distribution systems.

Senior Principal Scientist, Asea Brown Boveri (ABB), Raleigh, NC: 1999 - 2007

Directed internal R&D projects to support ABB business unit needs. Developed prototypes for new hardware and software products. Participated in field pilots with customers. Lead R&D consultant for distribution automation and reliability.

Associate Professor, Electrical and Computer Engineering Department, Clemson University, Clemson, SC: 1989 - 1999

Course instructor for various classes in power systems analysis, supervised graduate students and conducted R&D projects with electric utilities. Topics of projects included: distribution circuit measurement estimation, distribution circuit fault location for crew direction, industrial power quality modeling, and new techniques for electric circuit disturbance classification.

Research Interests

Electric power distribution system analysis, distribution automation, distribution management systems, microgrid applications, equipment asset management.

Publications and Reports

Singh, U.; Baran, M.; Lubkeman, D., "Performance Metrics for Assessment of Distribution System Protection Schemes," 2014 IEEE Conference and Exposition, PESGM.2014.6938879.

Baran, M.E.; Carpenter, P.P; Borbye, L. ; Lubkeman, D.L. ; Ligett, M. ; Covington, D.H. ; "A New Professional Master Program for Electric Power Systems Engineering," *IEEE Transactions on Power Systems*, Volume 29, Issue 4, July 2014, Page(s):1903 – 1910.

Khan, M.T.A. ; Husain, I. ; Lubkeman, D.L. ; "Power Electronic Components and System Installation for Plug-and-Play Residential Solar PV," *2014 Energy Conversion Congress and Exposition (ECCE)*, Page(s):3272-3278.

Lubkeman, D.; Leufkens, P.; Feldman A.; "Battery Energy Storage System Testing for Grid Standard Compliance and Application Performance," *CIGRE 2011 Conference Proceedings*, Frankfurt, Germany, Paper 0674.

Pan, J.; Wang, Z.; Lubkeman, D.; "Condition based failure rate modeling for electric network components," *IEEE PES Power Systems Conference and Exposition 2009*, 2009, Page(s) :1-6.

Patents (14 total)

US Patent 7,272,516 Failure rate adjustment for electric power network reliability analysis

US Patent 7,751,166 Advanced feeder architecture with automated power restoration

US Patent 7,725,295 and 7,672,812 Cable fault detection

US Patent 7,558,703 Electrical substation monitoring and diagnostics

US Patent 8,621,117 Intelligent configuration system for power distribution feeder reclosers and switches

Srdjan Lukic
Biographical Sketch

I. Professional Preparation

Illinois Institute of Technology	Electrical Engineering	BS 2002
Illinois Institute of Technology	Electrical Engineering	MS 2004
Illinois Institute of Technology	Electrical Engineering	PhD 2008

II. Appointments

2014 - Present	Associate Professor, Electrical and Computer Engineering Department, North Carolina State University
2008 - 2014	Assistant Professor, Electrical and Computer Engineering Department, North Carolina State University
2006 – 2008	Graduate Research Assistant, Electrical and Computer Engineering Department, Illinois Institute of Technology
2004 - 2006	Senior Electrical Development Engineer, Firefly Energy Inc, Peoria, IL
2002 – 2004	Graduate Research Assistant, Electrical and Computer Engineering Department, Illinois Institute of Technology

III. Publications

a. Selected Relevant Publications (5):

1. D. Hong, S. Bai, and S.M. Lukic “Closed Form Expressions for Minimizing Total Harmonic Distortion in 3-Phase Multilevel Converters” *IEEE Transactions on Power Electronics*, vol.29, no.10, pp.5229-5241, Oct. 2014
2. S. Bai and S.M. Lukic “Unified Active Filter and Energy Storage System for a MW Electric Vehicle Charging Station,” *IEEE Transactions on Power Electronics*, vol.28, no.12, pp.5793-5803, Dec. 2013
3. Y. Du, S. M. Lukic, B. S. Jacobson, and A.Q. Huang, “Modulation Technique to Reverse Power Flow for the Isolated Series Resonant DC-DC Converter with Clamped Capacitor Voltage,” *IEEE Transactions on Industrial Electronics*, vol.59, no.12, pp.4617-4628, Dec. 2012
4. S. Bai and S.M. Lukic, "Modular design of cascaded H-bridge for community energy storage systems by using secondary traction batteries," in *Proc. IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp.3297-3304, March 2014
5. S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, “Energy storage systems for automotive applications” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2258-2267, June 2008

b. Other Significant Publications (5):

6. Z. Pantic and S. M. Lukic “Framework and Topology for Active Tuning of Parallel Compensated Receivers in Wireless Power Transfer Systems” *IEEE Transactions on Power Electronics*, vol.27, no.11, pp.4503-3513, Nov. 2012

7. X. She, A. Q. Huang, S.M. Lukic, M. Baran "On integration of solid state transformer with zonal DC micro-grid," *IEEE Transactions on Smart Grid*, vol.3, no. 2, pp.975-985, June. 2012
8. Z. Pantic, S. Bai, S.M. Lukic, "ZCS LCC-Compensated Resonant Inverter for Inductive-Power-Transfer Application," *IEEE Transactions on Industrial Electronics*, vol.58, no.8, pp.3500-3510, Aug. 2011
9. S. Vasquez, S.M. Lukic, E. Galvan, L.G. Franquelo, J.M. Carrasco "Energy storage systems for transport and grid application" *IEEE Transactions on Industrial Electronics*, vol.57, no.12, pp.3881-2895, Dec. 2010
10. S. M. Lukic and A. Emadi. *Power Management for Multi-Module Energy Storage Systems in Electric, Hybrid Electric and Fuel Cell Vehicles*. US Patent #7,859,202. Issued December 28, 2010.

IV. Synergistic Activities

- IEEE Vehicular Technology Society Distinguished Lecturer 2011-2017,
- Associate Editor, IEEE Transactions on Industry Applications. 2012-present; Guest Associate Editor, IEEE Trans. on Industrial Electronics, Special Section on Energy Storage, Dec. 2010; Served on the Technical Program Committees of ECCE, ITEC and IEVC Conferences.
- Subthrust Leader: Distributed Energy Storage Devices – NSF Future Renewable Electric Energy Delivery and Management System (FREEDM) ERC
- REU student advisor for FREEDM (a total of 10 students);
- North Carolina State University ECE senior design project advisor (30 students total)
- Member, Power Electronics Technical Committee of the Industrial Electronics Society and SAE J2836™/J2847 Task Force for communication between Plug-In Vehicles and the Utility Grid

V. Collaborators & Other Affiliations

a. Collaborators and Co-Editors (9)

Subhashish Bhatacharya (NCSU); Abhishek Dubey (Vanderbilt University); Mo-Yuen Chow (NCSU); Alex Huang (NCSU); Iqbal Husain (NCSU); Gabor Karsai (Vanderbilt University); Ning Lu (NCSU); David Lukeman (NCSU); Anurag Srivastava (Washington State University).

b. Graduate Advisor (1)

Ali Emadi, (PhD Advisor, Illinois Institute of Technology, Chicago, IL)

c. PhD thesis advisor (3 graduated; 6 current)

Zeljko Pantic (Assistant Professor, Utah State University);
Rui Wang (Ford Motor Co);
Sanzhong Bai (Eaton);

Bruce M. McMillin
Professor of Computer Science
Missouri University of Science and Technology (Missouri S&T)
(Formerly the University of Missouri-Rolla),
Rolla, MO 65409-0350

Education:

B.S. (E.E.)	Michigan Technological University, Houghton, MI, 1979.
M.S. (C.S.)	Michigan Technological University, Houghton, MI, 1985.
Ph.D. (C.S.)	Michigan State University, East Lansing, MI, 1988.

Academic Experience :

2014-	Associate Dean of the College of Engineering and Computing, Missouri S&T
2001-	Professor of Computer Science, & Director of Center of Information Assurance, Missouri S&T
1993-2001	Associate Professor of Computer Science & Director of Experimental Computation Laboratory, University of Missouri-Rolla
1988-1993	Assistant Professor of Computer Science & Director of Experimental Computation Laboratory, University of Missouri-Rolla
2001 -2011	Graduate Coordinator, Department of Computer Science
1990-Present	Research Investigator/Senior Investigator - Intelligent Systems Center, Missouri S&T
1994-1995	Visiting Associate Professor of Computer Science, State University of New York at Stony Brook

Thesis Supervised (Completed): Ph.D. = 13, M.S. = 13

Related & Significant Products:

Tamal Paul, J. W. Kimball, M. Zawodniok, Tom Roth, Bruce McMillin, and Sriram Chellappan, Unified Invariants for Cyber-Physical Switched System Stability, *IEEE Transactions on Smart Grid*, Vol. 5, No. 1, January 2014, pp. 112-120, [DOI:10.1109/TSG.2013.2283171](https://doi.org/10.1109/TSG.2013.2283171)

Thoshitha Gamage, Thomas Roth, Bruce McMillin and Mariesa Crow, “Mitigating Event Confidentiality Violations in Smart Grids: An Information Flow Security-based Approach,” *IEEE Transactions on Smart Grid*, Vol. 4, No. 3, September 2013, pp. 1227-1234, DOI: [10.1109/TSG.2013.2243924](https://doi.org/10.1109/TSG.2013.2243924)

Gerry Howser and Bruce McMillin, “Modeling and reasoning about the security of drive-by-wire automobile systems,” *International Journal of Critical Infrastructure Protection*, Elsevier 2012, DOI: [10.1016/j.ijcip.2012.09.001](https://doi.org/10.1016/j.ijcip.2012.09.001).

Dale Fitch, Sahra Sedigh, Bruce McMillin, and Ravi Akella “CPS-CSH Cyber-Physical Analysis and Design,” *Seventh CRITIS Conference on Critical Information Infrastructures Security*, [10.1007/978-3-642-41485-5_9](https://doi.org/10.1007/978-3-642-41485-5_9), Springer, LNCS 7722, Hämmerli, Bernhard; Kalstad Svendsen, Nils; Lopez, Javier (Eds.), Lillehammer, Norway, September 17-18, 2012, Published 2013, pp. 92-105.

Hu Chun, Wei Jiang and Bruce McMillin, “Privacy-Preserving Power Usage Control in the Smart Grid,” *Proceedings of the Sixth IFIP WG 11.10 International Conference on Critical Infrastructure Protection*, Washington, DC, March 18-21, 2012, pp/ 127-138.

Ravi Akella and Bruce McMillin, “Verification and Protection of Confidentiality in an Advanced Smart Grid,” *Proceedings of the 45th Hawaii Conference on System Sciences*, pp 2169 – 2175, January, 2012, DOI: [10.1109/HICSS.2012.634](https://doi.org/10.1109/HICSS.2012.634)

Ravi Akella, Han Tang, Bruce M. McMillin, "Analysis of Information Flow Security in Cyber-Physical Systems," *International Journal of Critical Infrastructure Protection*, Elsevier, Vol 3-4, pp. 157-173, December 2010, DOI: [10.1016/j.ijcip.2010.09.001](https://doi.org/10.1016/j.ijcip.2010.09.001)

Keyou Wang, Mariesa Crow, Bruce McMillin, and Stan Attcity "A Novel Real-Time Approach to Unified Power Flow Controller Validation," *IEEE Transactions on Power Systems*, Vol 25, Issue 4, pp. 1892-1901. DOI: [10.1109/TPWRS.2010.2045664](https://doi.org/10.1109/TPWRS.2010.2045664).

Ravi Akella and Bruce McMillin, "Information Flow Analysis of Energy Management in a Smart Grid," *The 29th International Conference on Computer Safety, Reliability and Security (SAFECOMP '10)*, Springer-Verlag, Berlin, Heidelberg, Vienna, Austria, pp. 263-276

Ayman Z. Faza, Sahra Sedigh, and Bruce M. McMillin, "Reliability analysis for the advanced electric power grid: from cyber control and communication to physical manifestations of failure," *The 28th International Conference on Computer Safety, Reliability and Security (SAFECOMP '09)*, (Hamburg, Germany, September 15 - 18, 2009, LNCS, vol. 5775. Springer-Verlag, Berlin, Heidelberg, pp. 257-269 (Best Paper Award).

Synergistic Activities

McMillin's primary research focus is on development of run-time assurance and security for distributed computing systems. This work has led to grants from NSF, AFOSR, and state agencies and yielded a number of Ph.D. and M.S. theses.

Several synergistic activities have been undertaken with industry and national labs including safe railroad interlockings, and protection of the national electric power grid.

In the area of professional service, McMillin serves as an ABET/CSAB program evaluator. This process involves examining individual computer science programs to determine if they meet accreditation criteria. He has also been on many NSF panels within CISE and Engineering. He was the Program co-Chair for IEEE COMPSAC 2007 in Beijing and General Chair for IEEE COMPSAC 2011 in Munich. He currently serves on the Board of Governors of the IEEE Computer Society (2016-2018).

McMillin has been the co-PI on several NSF REU grants for introducing students from non-research oriented schools to research activities in parallel computing (1990-1994) and more recently in 2009.

To encourage women to seek advanced degrees in computer science, McMillin obtained an AFOSR-sponsored grant to fund American women in graduate study and led a capacity building proposal to encourage traditionally under-represented groups to pursue advanced education in Information Assurance.

13 Former Ph.D. students and affiliations: Ravi Akella, LoadIQ Systems; David A. Cape; Thoshitha Gamage, Southern Illinois University (also as postdoc); Li Feng; Chul-Eui Hong, ETRI Korea; Gerry Howser, U. of Kalamazoo; Pei-yu Li; Jun-Lin Liu, ITRI; Taiwan; Jui-Lin Lu, National Chung Hsing University, Taiwan; Hanan Lutfiyya, University of Western Ontario; Thomas P. Roth (NIST), Martina Schollmeyer, BMW; Cristina Serban, AT&T; Aggie Sun, AT&T; Su-Mei Tsai, Fairleigh Dickinson University

1 Graduate Advisor: L. Ni, Michigan State University/Hong Kong U. of Science & Technology, no postdoctoral sponsors.

EWAN G. D. PRITCHARD, PHD, P.E.

Ewan G. D. Pritchard received Ph.D., M.S. and B.S. degrees in mechanical engineering from NC State University in Raleigh, NC, in 2010, 2003, and 1997 respectively. Ewan is the Associate Director of the National Science Foundation, Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Engineering Research Center and the Advanced Transportation Energy Center (ATEC), at NC State University. Dr. Pritchard is best known for his work to bring plug-in hybrid school buses to the market. Ewan has been involved with the transportation industry since 1997 with his work on electric vehicles at Advanced Energy Corporation. He began the program to transform the school bus industry to plug-in hybrids in 2002. Since then he has worked with numerous vehicle companies and organizations to develop and commercialize electric and plug-in platforms to reduce environmental emissions and fuel consumption.

EDUCATION

Ph.D., Mechanical Engineering

North Carolina State University (NCSU), Raleigh, NC, December 2010

Dissertation Title: “Torque Converter Interactions in a Parallel Post Transmission Hybrid Driveline”

Advisor: Dr. Richard Gould

M.S. Mechanical Engineering

North Carolina State University (NCSU), Raleigh, NC, May 2004

Thesis title: “Performance Modeling of Hybrid and Plug-In Hybrid Electric School Buses using ADVISOR”

Advisor: Dr. Richard Johnson

B. S. Mechanical Engineering

North Carolina State University (NCSU), Raleigh, NC, May 1997

PROFESSIONAL EXPERIENCE

Associate Director, Advanced Transportation Energy Center and Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center, North Carolina State University 2012 – Present

- Work with Program Partners to Build Research and Funding Profile
- Establish and Set-up Center Facilities Including Use Agreements and Funding Plans
- Develop and Establish Center’s Sustainability Plan
- Seek long term center funding through strategic partnerships and grants
- Establish a long term center vision that can sustain beyond seed funding

Director of Industry, Collaboration and Innovation, Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center, North Carolina State University 2010-2012

- Interact with industrial members of the center to ensure clear communication between
- Manage and facilitate the Industrial Advisory Board for the center
- Present to the National Science Foundation on the industry and innovation programs within the center
- Work with industrial members, center faculty, students and staff to create innovation programs to quickly bring ideas to programs and programs to products

Program Manager, Advanced Transportation Energy Center, North Carolina State University 2009-2012

- Serve as the Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center Plug-in Hybrid (PHEV) and Plug-in Electric Vehicle (PEV) test bed leader for the NSF funded Engineering Research Center
- Manage the proposal and implementation of center grant programs
- Industrial liaison between automotive members of ATEC and center researchers
- Perform system level vehicle modeling research on behalf of the center
- Serve as guest lecturer for the center on vehicle related matters
- Manage the image of ATEC within the research and vehicle community
- Work with center directors to effectively manage the center funding and workload

Hybrid Program Manager, Advanced Energy, 2002-2008

- Investigated the technical benefits and feasibility of plug-in hybrid technology for school buses and developed the Plug-In Hybrid School Bus program at Advanced Energy

- Assembled a group of potential purchasers, the Hybrid School Bus Buyers Consortium, which pools over 10% of North American demand for school buses, and worked to build a national purchase
- Secured over \$4 million in grants and funding for the purchase of up to 20 plug-in hybrid school buses
- Established as an industry leader in plug-in hybrid technology
- Facilitated the contract and purchase of plug-in hybrid school buses from International Truck and Engine to be delivered February 2007

NC GreenPower Resource Manager, Advanced Energy, 2005-2008

- Coordinated over 40 million kWh per year of solar, wind, hydroelectric, and landfill methane energy being added to the utility grid through the NC GreenPower program
- Provide recommendations to the resource committee based on review of proposed suppliers
- Primary technical resource for interconnection and renewables in day to day operation of the program

Energy Consultant and Trainer, Advanced Energy, 1997-2008

- Conducted energy audits and analyses in the commercial sector to determine opportunities for significant operational savings with minimal investment cost
- Primary areas of expertise in lighting, daylighting, HVAC and building envelope
- Certified Building Commissioning Professional through the Association of Energy Engineers
- Created training and presentations on various energy topics for utility and energy professionals
- Primary presenter on renewables and energy efficiency including lighting, process heating, solar photovoltaic, wind, and landfill gas
- Consulted with both utilities and industry across the county about process heating solutions
- Increased energy efficiency for manufacturing lines with the use of electric process heating technologies by using analytical skill and creativity to increase quality while reducing cost
- Specific technology expertise in infrared, radio frequency, induction and microwave heating

SELECT PUBLICATIONS

1. **E. Pritchard**, R. Johnson, R. Gould, "A Fluid Model Extension of the Torque Converter into the Overrunning Regime," SAE 2014 World Congress & Exhibition; Detroit, Michigan, April 2014
2. **E. Pritchard**, R. Johnson, R. Gould, "Torque Converter Interactions in a Parallel Post Transmission Hybrid Driveline," IEEE Vehicle Power and Propulsion Conference; Chicago, Illinois, September 2011
3. S. Sadiq, A. Emadi, **E. Pritchard**, "Plug-In Hybrid Market Transformation by Leveraging a Niche Market: School Buses," IEEE Vehicle Power and Propulsion Conference; Arlington, Texas, September 2007
4. **E. Pritchard**, R. Johnson, "Technical Performance Modeling of Hybrid and Plug-In Hybrid Electric School Buses Using ADVISOR," IMECE2005-79530, International Mechanical Engineering Conference & Exhibition; Orlando, Florida, November 2005
5. **E. Pritchard**, R. Johnson, "Hybrid Electric School Bus Technical Feasibility," 05CV9, SAE Commercial Vehicle Exhibition; Chicago, Illinois, November 2005

INVITED TALKS AND TUTORIALS

1. **E. Pritchard**, "Smart Grid, Smarter Grid" Invited Speaker, Siemens Solar Exchange East; Raleigh, NC, September 2011
2. **E. Pritchard**, "Smart Grid, Smarter Grid" Invited Speaker, North Carolina Smart Grid Leadership Forum; Chapel Hill, NC, August 2011
3. **E. Pritchard**, "Wheels in Motion: The promise of Plug-In Hybrid Vehicles," Invited Speaker, Alternate Fuels and Vehicles 2009; Orlando, Florida, April 2009
4. **E. Pritchard**, "Heavy Duty Plug-In Programs," Invited Speaker, Plug-In 2008; San Jose, California, July 2008
5. **E. Pritchard**, "The Marketplace for Plug-In Hybrid Vehicles," Invited Speaker, Alternate Fuel Vehicle Institute; Las Vegas, Nevada, May 2008
6. **E. Pritchard**, "Plug-In Hybrid School Bus Performance," Invited Speaker, Power-Up Conference; Wenatchee, Washington, May 2008
7. **E. Pritchard**, "Plug-In Hybrid Market Transformation," Invited Speaker, EVS 23; Anaheim, California, December 2007
8. **E. Pritchard**, "PHEV's, How to Transform a Marketplace," Keynote Speaker, PHEV-2007; Winnipeg, Canada, November 2007

9. **E. Pritchard**, “Nationwide Hybrid Electric School Bus Commercialization,” Invited Speaker, Transportation Research Board; Washington, DC, January 2005
10. **E. Pritchard**, “Plug-In Hybrid Electric School Buses,” Invited Speaker, DOE 21st Century Truck Group; Golden, Colorado, July 2004

BIOGRAPHICAL SKETCH: Michael “Mischa” Steurer

PROFESSIONAL PREPARATION

Institution	Location	Major/Area	Degree, Year
University of Technology	Vienna, Austria	EE (Power Systems)	Dipl.Ing (BS/MS), 1994
Swiss Federal Institute of Technology (ETH)	Zürich, Switzerland	EE (High Voltage Technology)	Dr. Tech. (PhD), 2001

APPOINTMENTS

2006-present	<i>Research Faculty III, Leader of the Power Systems Research Group, Center for Advanced Power Systems (CAPS), Florida State University. Principal investigator on several research projects in the field of electric power systems transient simulations, particularly hardware-in-the-loop real time simulations, and testing of power apparatus.</i>
2005-2006	<i>Assistant Professor, Florida State University. Assistant Professor at the FAMU-FSU College of Engineering, EE-Department, affiliated with the Center for Advanced Power Systems (CAPS).</i>
2001-2005	<i>Assistant Scholar Scientist, Center for Advanced Power Systems (CAPS), Florida State University. PI on several research projects in the field of electric power systems transient simulations, particularly hardware-in-the-loop real time simulations, and testing of power apparatus.</i>
1995-2000	<i>Assistant in Research and Teaching, Swiss Federal Institute of Technology (ETH). Assistant in Research and Teaching at the High Voltage Laboratory, Swiss Federal Institute of Technology, Zurich, Switzerland (before May 1997 at the Institute of Switching Devices and High Voltage Technology, Vienna University of Technology, Vienna, Austria).</i>

PUBLICATIONS

1. K. Schoder, Z. Cai, S. Sundararajan, M. Yu, M. Sloderbeck, I. Leonard, **M. Steurer**, “Real-Time Simulation of Communications and Power Systems for Testing Distributed Embedded Controls”, Engineering & Technology Reference, 10.1049/etr.2015.0022, ISSN 2056-4007, www.ietdl.org
2. **M. Steurer**, F. Bogdan, M. Bosworth, O. Faruque, J. Hauer, K. Schoder, M. Sloderbeck, D. Soto, K. Sun, M. Winkelkemper, L. Schwager, P. Blaszczyk, “Multifunctional Megawatt Scale Medium Voltage DC Test Bed based on Modular Multilevel Converter (MMC) Technology”, in Proc. of the ESARS 2015 International Conference, March 4-5, 2015 Aachen, Germany
3. Z. Cai, M. Yu, **M. Steurer**, H. Li, Y. Dong, “Network Modeling for A Real-time Hardware-in-the-loop Prototype of Smart Grid Distributed System”, Journal of Network and Computer Applications, Volume 59, January 2016, Pages 264-273, ISSN 1084-8045
4. C. Schacherer, J. Langston, **M. Steurer**, M. Noe, “Power Hardware-in-the-Loop Testing of a YBCO Coated Conductor Fault Current Limiting Module”, IEEE Trans. on Applied Superconductivity, Volume 19, Issue 3, Part 2, June 2009 Page(s):1801 – 1805
5. W. Ren, **M. Steurer**, T. L. Baldwin, “Improve the Stability of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithm”, IEEE Transactions on Industry Applications, Volume 44, Issue 4, July-Aug. 2008 Page(s):1286 - 1294

SYNERGISTIC ACTIVITIES

1. IEEE Standards Committees; Member, IEEE PES
2. Chairman, IEEE WG PC37.302 on "Fault Current Limiter Testing"

OBJECTIVE

I am an enthusiastic control engineer focusing on power electronics and power systems with advanced degree (PhD Candidate) in Electrical Engineering. Skilled at controls and automation for power electronics based systems, I am seeking a position in control of power electronics, microgrids, power systems, and motor drives

SUMMARY OF QUALIFICATIONS

- PhD Candidate in Electrical Engineering with focus on Adaptive Control for Microgrids
- 5 years working in the power conversion applications, control and automation engineering
- Power electronic converters troubleshooting skill using data measurements and analysis
- Power converters mechanical, thermal design; integration, control; and hardware implementation

EXPERIENCE

Center for Advanced Power Systems, Tallahassee, FL Aug 2013 - Present
Graduate Research Assistant; Grant: Office of Naval Research

- Project: Distributed Control for DC Microgrids
 - Implemented 400VDC/10 kW interconnection between two systems of power electronic converters (two-level rectifier, inverter, and three-level rectifier), battery (NHR9200), and loads (BK Precision, and NHR46000) with CAN communication establishment
 - Designed a control algorithm for a two-node distributed system with voltage and current information exchange between two DSP controllers of two 5 kW power electronic rectifiers via CAN to stabilize the 400VDC bus voltage, and share the power between converters delivered to the NHR9200 and BK Precision
 - Led a team to implement a 5 kVA three-phase inverter for NHR4600 to represent propulsion load
 - Detected problems and conducted solutions for the failure in sensors, cables, PCB boards, and power electronic components of active rectifiers and inverters
- Project: Fault Management, Protection and Reconfiguration
 - Created a Java-based program for natural language processing using text recognition for functional faults detection in MVDC ship power systems

NSF FREEDM Systems Center, Raleigh, NC Aug 2014 - Present
Graduate Research Assistant; Grant: National Science Foundation

- Project: MPC-based Distributed Control for Intelligent Energy Management of FREEDM Systems
 - Developed an energy prediction model for a 20 kW interconnected renewable energy system
 - Optimized the power flows in the renewable energy system utilizing economic Model Predictive Control for the demand response problem which helps to reduce the customers' electric bill by 20%

Samsung Vietnam Mobile R&D Center, Hanoi, Vietnam June - Sep 2012
Hardware Engineer

- Supported the production engineers in mobile faults detection in the Application and Radio parts
- Analyzed the power amplifier circuits inside mobile phones, collaborated with system team in firmware design

Center for Technology Innovation, Hanoi, Vietnam June 2010 - June 2012
Undergraduate Research Assistant

- Achieved 50% electromagnetic torque ripple reduction in BLDC motor using a new control method
- Extended the BLDC maximum speed up to 1.47 times compared with the conventional method

EDUCATION

Florida State University, Tallahassee, FL April 2016

- PhD in Electrical Engineering; GPA: 4.0/4.0 (Expected)
- *Dissertation topic:* Adaptive Secondary Droop Control for DC Microgrids
A robust advanced adaptive control with high performance in transient response is developed for adapting the droop constants to overcome the restriction of the conventional droop control in DC Microgrids, which is the tradeoff between current share among distributed energy resources and BUS voltage stability

Hanoi University of Science and Technology, Hanoi, Vietnam June 2012

- *Bachelor's Thesis:* Improved Pseudo Vector Control for Brushless DC Motor Drives
BLDC has high torque density but possesses large electromagnetic torque ripple with conventional control method. Thus, an alternative control (Pseudo-vector Control) is investigated to improve the torque's quality

TECHNICAL SKILLS

Languages: C, C++, Java, PLC Programming, Latex

Software: MATLAB, Simulink, PLECS, PSIM, dSPACE, Altium, Maxwell, TI Code Composer

Technology: Power electronics and PCB implementation, filters design, embedded DSP programming, numerical methods, modeling real-time simulators, hardware-in-the-loop

HONORS/AWARDS

- FREEDM research assistantship: NSF grant (2014 - Present)
- ESRDC research assistantship: ONR grant (2013 - Present)
- US government fellowship (VEF): Awarded \$54000, (2013)
- Samsung Scholarship: Awarded \$1000, (2012)

SELECTED PUBLICATIONS AND PRESENTATIONS

- Adaptive Droop Secondary Control for DC Microgrids, *IEEE Trans on Control Systems Technology*, to be submitted in September 2015
- Improvement in Transient Response for Distributed Secondary Control of DC Microgrids, *IEEE Trans on Control Systems Technology*, to be submitted in July 2015
- Model Predictive Control for Power Control in Islanded DC Microgrids, in *Industrial Electronics Society, IECON 2015*, Submitted
- MPC-based Distributed Control for Intelligent Energy Management, *FREEDM Annual Industry Conference*, 2015
- Real-time Distributed Power Optimization in the DC Microgrids of Shipboard Power Systems, *IEEE Electric Ship Technologies Symposium*, 2015

SYNERGISTIC ACTIVITIES

- Reviewed 1 technical article for *IEEE Trans on Energy Conversion* (2014)
- Mentor: *FREEDM Pre-college Education Program* (2015)
- IEEE, *Student Member*, since 2014

Mark H. Weatherspoon, Ph.D.

Professor and Associate Chair
Department of Electrical and Computer Engineering
Florida A&M University and Florida State University
Tallahassee, FL 32310

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Emails: weathers@eng.fsu.edu
mark.weatherspoon@famuedu

A. Professional Preparation

PhD, 2002, University of South Florida, Tampa, Electrical Engineering
MS, 1994, Florida State University, Electrical Engineering
BS, 1992, Florida State University, Electrical Engineering

B. Appointments

2015-present, Associate Department Chair, Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL

2014-present, Professor, Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL

2008-present, Director, NSF FREEDM Systems Center Research + Education Program (REP), FAMU-FSU College of Engineering, Tallahassee, FL

2009-2014, Associate Professor, Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL

2002-2009, Assistant Professor, Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL

2000, Contractor, Raytheon RF Components, Andover, MA

1998, 2001, Research Associate, National Institute of Standards and Technology, Microwave Metrology Laboratory, Boulder, CO

1995-1996, Engineer II, Raytheon Systems-ECI Division, St. Petersburg, FL

C. Recent Publications

1. E. N. Moss, Jr., R. Nelson, L. Morris, Jr., **M. H. Weatherspoon**, and P. L. Moss, "Lithium-Ion Battery Degradation in Energy Storage Systems for Grid Applications", *ECS Transactions*, vol. 66, no. 39, pp. 39-45, 2015.
2. R. Nelson, A. Flores-Nigaglioni, and **M. H. Weatherspoon**, "Analysis of Warburg Impedance in a Li-O₂ Cell Featuring a Porous Binder-free Cathode Via Impedance Spectroscopy and Equivalent Circuits", *Proceedings of the FREEDM Systems Center Annual Conference*, Raleigh, NC, January 2015.
3. E. N. Moss Jr., R. Nelson, **M. H. Weatherspoon**, and P. L. Moss, "Multi-Electrode Characterization of Various Electrode Material Using Cyclic Voltammetry and Electrochemical Impedance Spectroscopy", *Proceedings of the FREEDM Systems Center Annual Conference*, Raleigh, NC, January 2015.
4. R. C. Aarons and **M. H. Weatherspoon**, "Noise Diode Calibration Using Receiver Noise Parameters", 83rd ARFTG Microwave Measurement Conference, Tampa, FL, June 2014.
5. R. Nelson, J. Kosivi, **M. H. Weatherspoon**, E. E. Kalu, and J. P. Zheng, "Impedance Behavior of Binderless Ni-Mo Composite Oxide Cathode for a Li-O₂ Battery via Impedance Spectroscopy", *ECS Transactions*, vol. 58, no. 22, pp. 15-20, 2014.

6. T. Bull, R. Nelson, and **M. H. Weatherspoon**, “Computational Analysis of Interfacial Capacitance of a Li-O₂ Cell Using Electrochemical Impedance Spectroscopy”, *Proceedings of the FREEDM Systems Center Annual Conference*, Raleigh, NC, January 2014. (*Best Paper Presentation Award*)
7. R. Nelson and **M. H. Weatherspoon**, “Investigation of Kinetic Behaviors of a Lithium Oxygen Cell with a Binder-Free Cathode via Electrochemical Impedance Spectroscopy and Equivalent Circuit Modeling”, *Proceedings of the FREEDM Systems Center Annual Conference*, Raleigh, NC, January 2014.
8. C. Oladimeji, P. L. Moss, and **M. H. Weatherspoon**, “Characterization of Lithium Phosphate Battery Material”, *Proceedings of the FREEDM Systems Center Annual Conference*, Raleigh, NC, January 2014.
9. **M. H. Weatherspoon**, J. D. Connor, and S. Y. Foo, “Shaped Beam Synthesis of Phased Arrays Using the Cross Entropy Method”, *International Journal of Numerical Modeling*, vol. 26, no. 6, pp. 630–642, 2013.
10. R. Nelson, **M. H. Weatherspoon**, J. Gomez, E. E. Kalu, and J. P. Zheng, “Investigation of a Li-O₂ Cell Featuring Binder-Free Cathodes via Impedance Spectroscopy and Equivalent Circuit Model Analysis,” *Electrochemistry Communications*, vol. 34, no. 9, pp. 77–80, 2013.
11. J. Gomez, E. E. Kalu, R. Nelson, **M. H. Weatherspoon**, and J. P. Zheng, “Binderless Co-Mn Composite Oxide Electrode for Li-Air Battery Application,” *Journal of Materials Chemistry A*, vol. 1, no. 10, pp. 3287–3294, 2013.
12. J. R. Gomez, , E. E. Kalu, R. Nelson, **M. H. Weatherspoon**, and J. P. Zheng, “Thin Film Co-MnO₂ by Combined Electroless-Electrolytic Techniques for Ultracapacitor and Li-Air Battery Applications”, *ECS Transactions*, vol. 45, no. 18, pp. 1-13, 2013.
13. J. Gomez, E. E. Kalu, R. Nelson, C. Akpovo, **M. H. Weatherspoon**, and J. P. Zheng, “Binder-free Electrode Fabrication by Electroless-Electrolytic Method,” *ECS Electrochemistry Letters*, vol. 1, no. 6, pp. D25–D28, 2012.

D. Synergistic Activities

- PI of NSF ERC FREEDM “Battery Degradation and Cost Analysis Modeling” 2014-16 (\$145k)
- PI of NSF ERC FREEDM “College Education Grant” 2014-16 (\$57.4k)
- Co-PI of NSF ERC FREEDM “Development of Adv. Energy Storage Devices” 2008-18 (\$2.835m)
- Measurement, modeling, and simulation of the behavior of devices such as batteries and supercapacitors for integration into sustainable electric energy systems.
- Developed three new courses in lithium battery technology and sustainable energy systems.
- Completed a one-week advanced electrochemical measurements workshop at the Ernest B. Yeager Center for Electrochemical Sciences at Case Western Reserve University in August 2013.

E. Collaborators and Other Affiliations

- Collaborators: E. Kalu (FAMU-FSU), J. Zheng (FAMU-FSU), P. Moss (FAMU-FSU).
- Current Advisees: 3 PhD: R. Nelson, L. Morris, and R. Aarons and 2 MS: J. Stephens and D. Queen.
- Past Advisees: (graduated) 2 PhD: J. Connor (Argon ST, VA), D. Langoni (Naval Surface Warfare Center, Panama City, FL), and 6 MS: H. Martinez (HNTB Corporation, FL), D. Langoni, R. Aarons (PhD candidate), R.J. Smith (Lockheed Martin, FL), T. Moses (RCC Consultants, FL), S. Sagaram.
- Current Service on Other Advisory Committees: 1 PhD: S. Saddique.
- Past Service on Other Advisory Committees: 4 PhD, 11 MS, and 1 BS (Honors Thesis).

BIOGRAPHICAL SKETCH

Ming Yu

CONTACT INFORMATION

Position/Title: Professor

Department: Electrical and Computer Engineering

Organization: FAMU – FSU College of Engineering

Address: 2525 Pottsdamer St., Tallahassee,
FL 32312, USA.

Phone: (850) 410-6263 Fax: (850) 410-6479

Email: mingyu@eng.fsu.edu

EDUCATION & TRAINING

Institution	Major/Area	Degree, Year
Rutgers University, New Brunswick, NJ	Electrical & Computer Engineering	Ph.D., 2002
Rutgers University, New Brunswick, NJ	Graduate Study	1994-1997
Tsinghua University, Beijing	Electrical & Computer Engineering	Doctor, 1994
Huazhong Uni. of Sci. & Tech., Wuhan, China	Electrical & Computer Engineering	M.S., 1987
Hubei Inst. of Auto Tech., Hubei, China	Electrical & Computer Engineering	B.S., 1984

APPOINTMENTS

08/2015 – Present	<i>Professor</i> , Dept. of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL 32310.
08/2009 – 07/2015	<i>Associate Professor</i> , Dept. of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL 32310.
08/2006 – 07/2009	<i>Assistant Professor</i> , Dept. of Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL 32310.
09/2003 – 08/2006	<i>Assistant Professor</i> , Dept. of Electrical and Computer Engineering, State University of New York (SUNY) at Binghamton, NY 13902.
11/2002 – 08/2003	<i>System Engineer</i> , Dept. of IP/Data NMS, AT&T Labs, Middletown, NJ 07748.
10/2000 – 10/2002	<i>Senior Software Engineer</i> , Jedai Networks, Red Bank, NJ 07733.
07/1997 – 09/2000	<i>Senior Technical Staff Member</i> , Dept. of ATM Networking, AT&T Labs, Middletown, NJ 07748.

PUBLICATIONS

Related Publications:

1. **M. Yu** and N. Ansari, "Smart grid communications: modeling and validation by test-bed," Journal of Network and Computer Applications, (Elsevier), Jan. 2016.
2. Z. Cai, Y. Dong, **M. Yu**, M. Steurer, and H. Li, "Modeling of a real-time hardware-in-the-loop prototype of a smart grid distributed system," Journal of Network and Computers Applications, (Elsevier), Jan. 2016.
3. K. Schoder, Z. Cai, **M. Yu**, M. Steurer, and M. Sloderbeck, "Real-time emulation of the communication layer for microgrids using hardware-in-the-loop (HIL) simulations," IET Engineering and Technology Reference, Nov. 2015. (Note: doi: 10.1049/etr.2015.0022)
4. W. Liu and **M. Yu**, "Anonymous secure routing for trustworthiness-based wireless sensor networks in adversarial environment," IEEE Trans. on Vehicular Tech., vol. 63, no. 9, pp. 4585-4593, Nov. 2014.
5. **M. Yu**, X. Ma, and M. Zhou, "An optimal radio channel assignment using simulated annealing and Gibbs sampling," IEEE Trans. on Vehicular Tech., vol. 63, no. 9, pp. 4670-4680, Nov. 2014.

Other Publications:

6. **M. Yu** and K. Leung, "A trustworthiness-based QoS routing protocol for ad hoc networks," IEEE Trans. on Wireless Comms., vol. 8, No. 4, pp. 1888-1898, April 2009.
7. **M. Yu** and M. C. Zhou, "A secure routing protocol against Byzantine attacks for MANETs in

- adversarial environment*,” *IEEE Trans. on Vehicular Tech.*, vol. 58, no. 1, pp. 449-460, Jan. 2009
8. **M. Yu** and M. C. Zhou, “A performance modeling scheme for multistage switch networks with phase-type and bursty traffic,” *IEEE/ACM Trans. on Networking*, vol. 18, no. 4, pp. 1091-1104, Aug. 2010.
 9. **M. Yu**, A. Malvankar, and W. Su, “A distributed radio channel allocation scheme for WLANs with multiple data rates,” *IEEE Trans. on Comms.*, vol. 56, no. 3, pp. 454-465, March 2008.
 10. **M. Yu**, K. Leung, and A. Malvankar, “Dynamic clustering and energy-efficient routing technique for sensor networks,” *IEEE Trans. on Wireless Comms.*, vol. 6, no. 8, pp. 3069-3079, Aug. 2007.
 11. **M. Yu**, H. Luo, and K. Leung, “A dynamic radio resource management technique for multiple APs in WLANs,” *IEEE Trans. on Wireless Comms.*, vol. 5, no. 7, pp. 1910-1920, July 2006.

SYNERGISTIC ACTIVITIES

1. Finance chair of IEEE ICNSC 2014, Miami, FL, April 6-9, 2014; co-chair, IEEE SMC 2011 Int. Workshop on *System Safety and Security*, Anchorage, Alaska, Oct. 9-12, 2011; co-chair, IEEE Int. Workshop on *Recent Advance in Cognitive Communications and Networking* (RACCN), Houston, TX, 5-9, Dec., 2011.
2. Served as NSF *IT Research Panelist* 2004 and NSF *Cyber Trust Panelist* in 2005.
3. Reviewer for *IEEE/ACM Trans. on Networking*, *IEEE Trans. on Communications*, *IEEE Trans. on Wireless Communications*, *IEEE Trans. on Mobile Computing*, *IEEE Trans. on Antenna and Propagations*, *IEEE GLOBECOM*, *ICC*, *WCNC*, and other conferences.
4. TPC members and session chairs for many IEEE conferences including *IEEE GLOBECOM*, *WCNC*, *ICC*, *ICNSC*, etc.
5. Serves as a guest editor for a special issue of the *Int. Journal of Wireless and Mobile Computing*.
6. Guest Editor, for Special Issue on “Smart Grid Communications and Validations” for *Journal of Networks and Computer Applications*, Elsevier, 2015.

COLLABORATORS & OTHER AFFILIATIONS

Collaborators in Recent Years

Li-Jin Chong (AT&T, NJ)	Wen-Jui Li (AT&T, NJ)
David G. Daut (Rutgers University, NJ)	Hui Luo (Broadcom, NJ)
Mischa Steurer (FSU, FL)	Wei Su (US Army Labs, MD)
Kin K. Leung (Imperial College, London, UK)	M. C. Zhou (NJIT, NJ)
Leonard Tung (FSU, FL)	Tian Xing (AT&T, FL)
Wei Liu (Huazhong U. of Sci. & Tech., China)	Xiuwen Liu (FSU, FL)
Mike Burmester (FSU, FL)	

Graduate Students in Recent Years

PhD Students

Xiaoguang Ma (ABB Research, PA)	Larry Morris (FAMU, FL)
Aniket Malvankar (Broadcom, CA)	Ting Zhu (SUNY Binghamton, NY)
Ziyuan Cai (FSU, FL)	Yizhou Dong (FSU, FL)
Xing Liu (FSU, FL)	Jianwu Cao (FSU, FL)

MS Students

Kiran Anand (SUNY Binghamton, NY)	Sandeep Menon (SUNY Binghamton, NY)
Meher Vinay Dheram (SUNY Binghamton, NY)	Tim Walton (FSU, FL)
Nachiket Kalmar (SUNY Binghamton, NY)	Kyle Washington (SUNY Binghamton, NY)
Srinivas Kulkarni (SUNY Binghamton, NY)	Haojun Yang (FSU, FL)

Thesis Advisors

David G. Daut (Rutgers University, NJ)
Cheng Wu (Tsinghua University, Beijing, China)

Wensong Yu

Department of Electrical and Computer Engineering
North Carolina State University

Education:

Ph.D. 2000	Electric and Mechanic Engineering	South China University of Technology
M.S. 1999	Electric and Mechanic Engineering	Center China University of Science and Technology
B.S. 1992	Mechanic Engineering	Hefei University of Industry

Appointments:

2013-present	Research Associate Professor, NSF Engineering Research Center FREEDM Systems Center, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC.
2010-2013	Research Assistant Professor, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA.
2006-2010	Research Scientist, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA.
2004-2006	Postdoctoral Researcher, School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China.
2000-2004	Senior Product Manager, Emerson Network Power Co., Ltd., Shenzhen, Guangzhou, China.
1995-1997	Lecturer, Department of Electric and Mechanic Engineering, Center China University of Science and Technology, Wuhan, Hubei, China.

Selected Awards:

2015	2015 IEEE Power Electronics Society Transactions Second Prize Paper Award

Selected Five Relevant Publications (out of 70+):

1. Mengqi Wang, Qingyun Huang, Wensong Yu, A.Q. Huang, "An isolated bi-directional soft-switched DC-AC converter using wide-band-gap devices with novel carrier-based unipolar modulation technique under synchronous rectification," in *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp.2317-2324, March 2015
2. LaBella, T.; Wensong Yu; Jih-Sheng Lai; Senesky, M.; Anderson, D., "A Bidirectional-Switch-Based Wide-Input Range High-Efficiency Isolated Resonant Converter for Photovoltaic Applications," *IEEE Transactions on Power Electronics*, vol.29, no.7, pp.3473-3484, July 2014
3. York, B., Wensong Yu, Jih-Sheng Lai, "An Integrated Boost Resonant Converter for Photovoltaic Applications," *IEEE Transactions on Power Electronics*, vol.28, no.3, pp.1199-1207, March 2013.
4. Wensong Yu, Jih-Sheng Lai, Wei-Han Lai, Hongmei Wan, "Hybrid Resonant and PWM Converter With High Efficiency and Full Soft-Switching Range," *IEEE Transactions on Power Electronics*, vol.27, no.12, pp.4925-4933, Dec. 2012.
5. Wensong Yu, Jih-Sheng Lai, Hao Qian, C. Hutchens, G. Lisi, and A. Djabbari, "High efficiency MOSFET inverter with H6-type configuration for non-isolated photovoltaic AC module applications," *IEEE Transactions*

on *Power Electronics*, vol.26, no.4, pp.1253-1260, April 2011.

Selected Five Other Significant Publications:

1. Fei Xue, Ruiyang Yu, Wensong Yu, A.Q. Huang, Yu Du, "A novel bi-directional DC-DC converter for distributed energy storage device," in *Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE*, pp.1126-1130, 15-19 March 2015
2. York, B., Wensong Yu, Jih-Sheng Lai, "Hybrid-Frequency Modulation for PWM-Integrated Resonant Converters", *IEEE Transactions on Power Electronics*, vol.28, no.2, pp.985,994, Feb. 2013.
3. Wensong Yu, Jih-Sheng Lai, Hongbo Ma, and Cong Zheng, "High Efficiency DC-DC Converter with Twin-Bus for Dimmable LED Lighting", *IEEE Transactions on Power Electronics*, vol.26, no.8, pp.2095-2100, Aug. 2011.
4. Wensong Yu, Jih-Sheng Lai, and Sun-Yan Park, "An Improved Zero-Voltage-Switching Inverter Using Two Coupled Magnetics in One Resonant Pole," *IEEE Transactions on Power Electronics*, vol.25, no. 4, pp. 952-961, Apr. 2010.
5. Wensong Yu, Hao Qian, Jih-Sheng Lai, "Design of High-Efficiency Bidirectional DC-DC Converter and High-Precision Efficiency Measurement," *IEEE Transactions on Power Electronics*, vol.25, no. 3, pp. 650-658, Mar. 2010.

Relevant Activities:

1. SiC Inverter for Electric Vehicle Traction Drive, granted by the U.S Department of Energy, PowerAmerica Institute, 2015-2019
2. Medium Voltage SiC Fast Charger, granted by the U.S Department of Energy, PowerAmerica Institute, 2015-2019
3. Development of Gen III Solid State Transformer based on 15kV SiC Power Devices, granted by National Science Foundation, 2014-2017
4. Development of an Innovative Plug and Play PV Electrical System, granted by the U.S Department of Energy, 2014-2015
5. DOE High Penetration Solar Deployment, granted by the U.S Department of Energy, 2010-2014
6. Intelligent Universal Transformer for Electrical Vehicle Charging Station, granted by Electric Power Research Institute (EPRI), 2011-2013
7. 55 kW high-efficiency soft-switching inverter for electrical vehicle application, granted by Department of Energy, U.S.A., 2008-2012
8. Electrolytic-capacitor-free photovoltaic micro-inverter, granted by National Semiconductor Co., U.S.A., 2008-2009
9. Digital uninterruptible power supply, working at Emerson Network Power Co., 2000-2004

Patents: 4 were submitted to Technique Transfer Office at NC State University

Jim P. Zheng

Department of Electrical and Computer Engineering, Florida A&M University and Florida State University

Aero-Propulsion, Mechatronics and Energy Center and Center for Advanced Power Systems,
Florida State University, Tallahassee, FL 32310

Email: zheng@eng.fsu.edu; Phone: (850) 410-6464/645-0103; Fax: (850) 410-6479

A. Professional Preparation

PhD, 1990, State University of New York-Buffalo, Electrical Engineering

MS, 1986, State University of New York-Buffalo, Electrical Engineering

BS, 1982, Fudan University, Shanghai, China, Physics

B. Appointments

2013-present, Sprint Eminent Scholar Chair Professor, 2003-present, Professor, 1997-2003, Associate Professor, Electrical and Computer Engineering, FAMU-FSU College of Engineering, Tallahassee, FL

1995-1997, Electrical Engineer and Research Scientist, General Technical Service/Army Research Lab (ARL), Wall Township, NJ

1993-1995, National Research Council Fellow, ARL, Fort Monmouth, NJ

1990-1992, Research Associate & Research Assist. Prof, Electrical and Computer Engineering, UB, Buffalo, NY

C-1. Five Relevant Publications (113 refereed journal papers in total)

1. W.J. Cao, M. Greenleaf, Y.X. Li, D. Adams, M. Hagen, T. Doung, and J.P. Zheng, "The effect of lithium loadings on anode to the voltage drop during charge and discharge of Li-ion capacitors", *J. Power Sources*, **280**, 600 (2015).
2. W. Cao, J.S. Zheng, D. Adams, T. Doung, and J.P. Zheng, "Comparative Study of the Power and Cycling Performance for Advanced Lithium-Ion Capacitors with Various Carbon Anodes", *Journal of The Electrochemical Society*, **161**, A2087 (2014).
3. W. Cao, Y.X. Li, B. Fitch, J. Shih, T. Doung, and J.P. Zheng, "Strategies to optimize lithium-ion supercapacitors achieving highperformance: Cathode configurations, lithium loadings on anode, and types of separator", *Journal of Power Sources*, **268**, 841(2014).
4. W.J. Cao, J. Shih, J.P. Zheng, and T. Doung, "Development and characterization of Li-ion capacitor pouch cells", *Journal of Power Sources*, **257**, 388 (2014).
5. W.J. Cao and J.P. Zheng, "The Effect of Cathode and Anode Potentials on the Cycling Performance of Li-Ion Capacitors", *Journal of The Electrochemical Society*, **160**, A1572 (2013).

C-2. Other Five Recent Publications

1. M. Greenleaf, H. Li, and J.P. Zheng, "Application of physical electric circuit modeling to characterize Li-ion battery electrochemical processes", *Journal of Power Sources*, **270**, 113 (2014).
2. J.S. Zheng, T. Tian, Y. Gao, Q. Wu, J.X. Ma, and J.P. Zheng, "Ultra-low Pt loading catalytic layer based on buckypaper for oxygen reduction reaction", *International Journal of Hydrogen Energy*, **39**, 13816 (2014).
3. Y. Yang, H. Li, A. Aichhorn, J.P. Zheng, and M. Greenleaf, "Sizing Strategy of Distributed Battery Storage System With High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving", *IEEE Transactions on Smart Grid*, **Vol. 5**, 982 (2014).

4. M. Mehta, G. Mixon, J.P. Zheng, and P. Andrei, “Analytical Electrochemical Impedance Modeling of Li-Air Batteries under D.C. Discharge”, *Journal of The Electrochemical Society*, **160**, A2033 (2013).
5. X.J. Chen, A. Shellikeri, Q. Wu, J.P. Zheng, M. Hendrickson, and E.J. Plichta, “A High-Rate Rechargeable Li-Air Flow Battery”, *Journal of The Electrochemical Society*, **160**, A1619 (2013).

D. Synergistic Activities

1. Research Highlight:

- A. Discovered a novel Li-ion capacitor with energy density of 5 times of that of conventional supercapacitor.
 - B. Explored and developed ultra-low platinum loading and high performance PEMFCs using buckypaper supported catalytic electrodes.
 - C. Discovered a new electrode material of $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ nanoparticles for ultracapacitors, with charge storage density at least two times greater than that of any other electrode materials.
 - D. Developed a novel monolithic hybrid fuel cell configuration, which demonstrated significantly performance improvement in response of transient and pulse current.
 - E. Developed the energy density theories for a number of electrochemical energy storage systems including ultracapacitors, battery-ultracapacitor hybrid cells, and Li-air batteries.
 - F. Explored and developed highly sensitive chemical sensors based on single SnO_2 nanobelts.
 - G. Explored and developed and studied a highly sensitive and fast nanostructural porous silicon photodiode.
2. **Innovation:** Awarded 12 US patents. More noticeably, 5 patents have been licensed by industries. Co-founder of Bing Energy Inc (BEI): BEI is a fuel cell company – based on breakthrough nano-technology, Founder of General Capacitor LLC-a company manufactures Li-ion capacitors.
 3. **Curriculum Development:** Developed 5 new courses including Engineering Optics (under/graduate), Solid State Sensors (graduate), Semiconductor Device Theory (graduate), Nanoscience and Nanotechnology (under/graduate), and Introductory Energy Storage (under/graduate). Initiated a proposal and started to offer the Electrical and Computer Engineering Graduate Seminar commencing fall 2002. The graduate seminar provides graduate students with information concerning current researches related to electrical and computer engineering and other engineering fields.

E. Collaborators and Other Affiliations

1. **Graduate Advisors:** MS & Ph.D. advisor: Prof. H.S. Kwok, (State University of New York at Buffalo)
2. **Collaborators:** E.J. Plichta and M.A. Hendrickson (Army CERDEC), Jeffrey Read and Richard Jow (ARL), D.A. Evans (Evans Capacitor Company), S.M. Durbin, (New Zealand), P. Andrei, M. Zhang, and P. Xiong (FSU), Y. Xin and R.Q. Fu (NHMFL, FSU),
3. **Graduate Advisees:** 9 PhD+16 MS graduated: X. Wang (Microsoft, WA), A. Pun (Diverse Computing, NC), L.L. Fields (Corning, NY), Y. Wang, P. Moss (FAMU), Ben Cao (General Capacitor), M. Greenleaf (NRC), X. Chen (GC), A. Shellikeri (FSU).
4. **Currently Advising:** 2 Postdocs: Q. Wu and A. Shellikeri; 4 PhD students: M. Hagen, K. Yao, C. Shen, and A. Cappetto.

Current & Pending Support

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Petru Andrei		Other agencies (including NSF) to which this proposal has been/will be submitted.	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Experimental Centric Based Engineering Curriculum for HBCUs Source of Support: NSF-TUES Total Award Amount: \$240,000 Total Award Period Covered: 9/15/2013-8/31/2016 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Development of REU program, a sub-contract from the Center for Future Renewable Electric Energy Delivery and Management FREEDM) Systems Source of Support: NSF Total Award Amount: \$26,000 Total Award Period Covered: 9/1/2015-8/31/2016 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.25			
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Energy storage devices based on Li-air flow systems for electric grid applications Source of Support: NSF Total Award Amount: \$297,299 Total Award Period Covered: 04/1/2016-03/31/2019 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5			
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.			

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USE ADDITIONAL SHEETS AS NECESSARY

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Current & Pending Support

Aranya Chakraborty

1. **Current Support:** National Science Foundation - ECCS, Energy, Power and Adaptive Systems (EPAS)

Project Title: CAREER: Wide-Area Control of Large Power Systems Using Distributed Synchronphasors: Where Network Theory Meets Power System Dynamics

Total award amount (including indirect costs): \$ 400,000

Total award period: 5 years (2011-2016)

Average person-months per year: 1

Location -North Carolina State University

2. **Current Support:** National Science Foundation (ECCS)

Project Title: SEP Collaborative: Integrating Heterogeneous Energy Resources for Sustainable Power Networks - A Systems Approach

Total award amount (including indirect costs): \$ 374,619

Total award period: 4 years

Average person-months per year: 1

Location - North Carolina State University

3. **Current Support:** National Science Foundation (ECCS)

Project Title: CPS Synergy: Distributed Asynchronous Algorithms and Software Systems for Wide-Area Monitoring of Power Systems using Synchronphasors

Total award amount (including indirect costs): \$ 400,000

Total award period: 3 years

Average person-months per year: 0.1

Location - North Carolina State University

4. **Current Support:** National Science Foundation (CNS)

Project Title: CPS: TTP Option: Synergy: Collaborative Research: Hardening Network Infrastructures for Fast, Resilient and Cost-Optimal Wide-Area Control of Power Systems

Total award amount (including indirect costs): \$ 600,000

Total award period: 3 years

Average person-months per year: 0.1

Location - North Carolina State University

5. **Current Support:** National Science Foundation (CNS)

Project Title:US Ignite: Track 1: Collaborative Research: DISTINCT: A Distributed Multi-Loop Networked System for Wide-Area Control of Large Power Grids

Total award amount (including indirect costs): \$ 250,000

Total award period: 3 years

Average person-months per year: 0.1

Location - North Carolina State University

6. **Current Support:** National Science Foundation (ECCS)

Project Title: Collaborative Research: Computational Methods for Stability Assessment of Power Systems With High Penetration of Clean Renewable Energy

Total award amount (including indirect costs): \$ 170,038

Total award period: 2 years

Average person-months per year: 0.1

Location - North Carolina State University

7. **Current Support:** UK-USA-India Research Partnership Grant, British Council

Project Title: Smart grid that harness Satellite based Virtual Power Plants for energy sustenance
Total award amount (including indirect costs): \$ 20,000

Total award period: 2 years

Average person-months per year: 0.01

Location - North Carolina State University

8. **Pending Support:** National Science Foundation (CNS)

Project Title: TWC: Medium: Collaborative: Computational Certificates for Trustable Distributed Dynamic Infrastructures

Total award amount (including indirect costs): \$ 300,000

Total award period: 3 years

Average person-months per year: 1

Location - North Carolina State University

9. **Pending Support:** National Science Foundation (ENG)

Project Title: BIGDATA: Collaborative Research: IA: Macroscopic Modeling and Visualization of Power Systems Using Time-Critical Big Data Techniques.

Total award amount (including indirect costs): \$ 704,745

Total award period: 3 years

Average person-months per year: 1

Location - North Carolina State University

Current and Pending Support

Investigator: Ayyanar, Raja	Other agencies(including NSF) to which this proposal has been/will be submitted
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: PSERC ASU Center Account (Ayyanar) Source of Support: PSERC-ASU Total Award Amount: \$115,000.00 Total Award Period Covered: 6/1/2011 - 12/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.5	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ERC for Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Source of Support: NORTH CAROLINA STATE UNIV Total Award Amount: \$3,185,317.00 Total Award Period Covered: 9/1/2008 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.5 Sumr: 0.75	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Collaborative Research: PSERC Collaborative Proposal for a Phase III Industry University Cooperative Research Center Program Source of Support: NSF-ENG Total Award Amount: \$1,290,900.00 Total Award Period Covered: 3/1/2010 - 2/28/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.04 Sumr: 0	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Automotive High Frequency DC-DC Topologies Source of Support: TEXAS INSTRUMENTS Total Award Amount: \$150,000.00 Total Award Period Covered: 4/19/2013 - 4/18/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.04 Sumr: 0	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: GOALI: Intelligent Networked Solar Panel Array Management Source of Support: NSF-ECCS Total Award Amount: \$207,808.00 Total Award Period Covered: 9/15/2013 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.05	

Support:	☒ Current	☐ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Task 4_15: DOE "Next Generation Power Electronics Manufacturing Innovation Institute" (NGPEMII) - "PowerAmerica"			
Source of Support:	NORTH CAROLINA STATE UNIV			
Total Award Amount:	\$220,000.00	Total Award Period Covered: 2/1/2015 - 3/31/2016		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 1	Sumr: 0	

Support:	☒ Current	☐ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Task 5: DOE "Next Generation Power Electronics Manufacturing Innovation Institute" (NGPEMII) - "PowerAmerica"			
Source of Support:	NORTH CAROLINA STATE UNIV			
Total Award Amount:	\$30,063.00	Total Award Period Covered: 2/1/2015 - 3/31/2016		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0.5	Sumr: 0	

Support:	☒ Current	☐ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Phase 2: Module Level Power Electronics Reliability and Accelerated Testing Standards Development			
Source of Support:	SANDIA NATL LAB			
Total Award Amount:	\$115,000.00	Total Award Period Covered: 4/7/2015 - 4/6/2016		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0	Sumr: 0.94	

Support:	☒ Current	☐ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Power Factor Correction Circuit with an Auxiliary Circuit for Zero Voltage Transitions			
Source of Support:	PANASONIC INDUSTRIAL CO			
Total Award Amount:	\$60,000.00	Total Award Period Covered: 8/1/2015 - 3/31/2016		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0.41	Sumr: 0	

Support:	☐ Current	☒ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Arizona State University Site in an I/UCRC for Efficient Vehicles and Sustainable Transportation Systems			
Source of Support:	NSF			
Total Award Amount:	\$749,999.00	Total Award Period Covered: 7/1/2016 - 6/30/2021		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0	Sumr: 0.5	

Support:	☐ Current	☒ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Leveraging Industry Research to Educate a Future Electric Grid Workforce in the Western U.S.			
Source of Support:	ELECTRIC POWER RESEARCH INST (EPRI)			
Total Award Amount:	\$317,012.00	Total Award Period Covered: 1/1/2016 - 12/31/2018		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0	Sumr: 0.7	

Support:	☐ Current	☒ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	High Performance Solar PV String and Micro Inverters: DOE "Next Generation Power Electronics Manufacturing Innovation Institute" (NGPEMII) - "PowerAmerica"			
Source of Support:	NORTH CAROLINA STATE UNIV			
Total Award Amount:	\$200,000.00	Total Award Period Covered: 4/1/2016 - 3/31/2017		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0.83	Sumr: 0	

Support:	☐ Current	☒ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:	Design and Demonstration of a Fully Modular Power Conditioning System Block (PCSB) for Microgrid Applications: DOE "Next Generation Power Electronics Manufacturing Innovation Institute" (NGPEMII) - "PowerAmerica"			
Source of Support:	NORTH CAROLINA STATE UNIV			
Total Award Amount:	\$200,000.00	Total Award Period Covered: 4/1/2016 - 3/31/2017		
Location of Project:	Arizona State University			
Person-Months Per Year Committed to the Project.	Cal: 0	Acad: 0.5	Sumr: 0	

Current Support: B. Jayant Baliga

- (1) “Post Silicon Devices”, FREEDM Systems Center, \$ 250,000.
- (2) “1.2 kV SiC Power JBSFET”, PowerAmerica, \$ 400,000.

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.				
Investigator: Mesut Baran	Other agencies (including NSF) to which this proposal has been/will be submit-			
Support: X Current Pending Submission Planned in Near Future *Transfer of Support Project/Proposal Title: FREEDM System cost-benefit analysis Source of Support: NSF ERC - FREEDM Systems Center Total Award Amount: \$106,500 Total Award Period Covered: 09/2014-08/2016 Location of Project: NC State University Person-Months Per Year Committed to the Project. Cal: Acad: 0.25 Sumr: 0.				
Support: X Current Pending Submission Planned in Near Future *Transfer of Support Project/Proposal Title: Workforce Training for the Electric Power Sector Source of Support: Department of Energy Total Award Amount: \$3,403,458 Total Award Period Covered: 8/2010-7/2015 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: 2 Sumr: 2				
Support: X Current Pending Submission Planned in Near Future *Transfer of Support Project/Proposal Title: DGI: Volt-Var control in FREEDM Systems Source of Support: NSF ERC - FREEDM Systems Center Total Award Amount: \$76,000 Total Award Period Covered: 09/2014-8/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: 0.25 Sumr: 0.0				
Support: Pending Submission Planned in Near Future *Transfer of Support Project/Proposal Title: Source of Support: Total Award Amount: Total Award Period Covered: Location of Project: Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0				
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.				



Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Mo-Yuen Chow	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Cooperative Distributed Energy Management

Source of Support: **NSF - FREEDM Center**

Total Award Amount: **\$90,000**

Total Award Period Covered: **9/1/15 - 8/31/16**

Location of Project: **NC State University**

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: **0.5**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Cooperative Distributed Home Energy Management Systems

Source of Support: **Total SA Inc**

Total Award Amount: **\$791950**

Total Award Period Covered: **09/01/2015 - 8/31/18**

Location of Project: **NC State University**

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: **0.75**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Big Data based Adaptive Range Estimation

Source of Support: **Samsung SAIT**

Total Award Amount: **\$99,000**

Total Award Period Covered: **10/1/2015-9/31/2016**

Location of Project: **NC State University**

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: **0.5**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Prototyping a Smart Battery Gauge Technology for Stationary Energy Storage of Renewable Energy Resources

Source of Support: **NSF**

Total Award Amount: **\$200000.00**

Total Award Period Covered: **5/16/2015-11/15/2016**

Location of Project: **NCSU**

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: **0.5**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Collaborative Research: Breakthrough: Secure Algorithms for Cyber-Physical Systems

Source of Support: **NSF**

Total Award Amount: **\$166654.00**

Total Award Period Covered: **5/1/2015-4/30/2018**

Location of Project:

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: **0.05**

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

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Current and Pending Support**(See GPG Section II.D.8 for guidance on information to include on this form.)**

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Chris S. Edrington	Other agencies (including NSF) to which this proposal has been/will be submit-

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

NSF ERC-FREEDM Systems, Site at FSU: MPC-based Distributed Control for IEM, Real-Time Stability Analysis for the FREEDM System Utilizing Nonlinear Time-Series Analysis and Embedding Phase-Space Techniques, and Design of Distributed Resilient Sensing Systems

Source of Support: North Carolina State University / NSF Current: 2008-1015-02

Total Award Amount: \$190,000

Total Award Period Covered: 9/1/2015-8/31/16

Location of Project: Florida State University

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: 0.7

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Electric Ship Research and Development Consortium – Impedance-based Control and Control of Distributed Control of Energy Storage

Source of Support: Office of Naval Research Current: N00014-08-01-0080

Total Award Amount: \$220,000

Total Award Period Covered: 1/1/2014-1/14/2017

Location of Project: Florida State University

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: 0.7

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

RTDS Instantiation of an Electrolyzer/Fuel Cell Based Power Electronics-based Distribution System

Source of Support: Idaho National Laboratory

Total Award Amount: \$120,000

Total Award Period Covered: 5/5/2015 – 5/30/2016

Location of Project: Florida State University

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: 0.5

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Design and Analysis of a non-rare-earth Linear Machine for ICE Valve Control

Source of Support: Sentimetel Journey Inc.

Total Award Amount: \$79,993

Total Award Period Covered: 11/1/2015-2/1/16

Location of Project: Florida State University

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: 0.7

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Methodologies for Self-organization in Energy System using a Hybrid Systems-based Approach

Source of Support: National Science Foundation

Total Award Amount: \$284,703

Total Award Period Covered: 8/1/2016 -8/1/2019

Location of Project: Florida State University

Person-Months Per Year Committed to the Project.

Cal:

Acad:

Sumr: 0.7

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.



(See GPG Section II.C.2.h for guidance on information to include on this form.)

Other agencies (including NSF) to which this proposal has been/will be submitted.

Person-Months Per Year Committed to the Project. Cal:0.50 Acad: 0.00 Sumr: 0.50

Person-Months Per Year Committed to the Project. Cal:3.00 Acad: 0.00 Sumr: 3.00

Person-Months Per Year Committed to the Project.	Cal:3.00	Acad: 1.00	Sumr: 2.00

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

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USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

Investigator: Heydt, Gerald	Other agencies(including NSF) to which this proposal has been/will be submitted
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Collaborative Research: PSERC Collaborative Proposal for a Phase III Industry University Cooperative Research Center Program Source of Support: NSF Total Award Amount: \$1,290,900.00 Total Award Period Covered: 3/1/2010 - 2/28/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.04 Sumr: 0	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ACEPS: Center for the Advanced Control of Energy and Power Systems Source of Support: SRP-SALT RIVER PROJECT Total Award Amount: \$5,813,931.00 Total Award Period Covered: 7/1/1996 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.04 Sumr: 0	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ERC for Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Source of Support: NORTH CAROLINA STATE UNIV Total Award Amount: \$3,185,317.00 Total Award Period Covered: 9/1/2008 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.25 Sumr: 0.72	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: PSERC Faculty Project Account (Heydt) Source of Support: PSERC-ASU Total Award Amount: \$620,975.00 Total Award Period Covered: 1/1/2006 - 12/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.5 Sumr: 0	
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Leveraging Industry Research to Educate a Future Electric Grid Workforce in the Western U.S. Source of Support: ELECTRIC POWER RESEARCH INST (EPRI) Total Award Amount: \$250,000.00 Total Award Period Covered: 1/1/2016 - 12/31/2018 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.33	

Current and Pending Support

Investigator: Holbert, Keith Edwin	Other agencies(including NSF) to which this proposal has been/will be submitted
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: On-Site Radiological Research Support Source of Support: RADIATION SAFETY ENGINEERING Total Award Amount: \$41,469.00 Total Award Period Covered: 6/1/1993 - 5/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.04 Sumr: 0	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ERC for Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Source of Support: NORTH CAROLINA STATE UNIV Total Award Amount: \$3,185,317.00 Total Award Period Covered: 9/1/2008 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.75	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Basic Radiation Effects Mechanisms in Chalcogenide-Based Nanoionic Structures Source of Support: DOD-DTRA Total Award Amount: \$261,798.00 Total Award Period Covered: 8/15/2011 - 8/14/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 1.0 Sumr: 0	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Radiation Hardened Memristive Technologies for Space-Based Nonvolatile Memory Source of Support: DOD-AFRL Total Award Amount: \$449,998.00 Total Award Period Covered: 8/8/2015 - 8/7/2018 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.25	

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Alex Q. Huang	Other agencies (including NSF) to which this proposal has been/will be submitted. NONE		
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: FREEDM Systems Center Project: Solid State Transformer			
Source of Support: National Science Foundation/FREEDM Total Award Amount: \$100,000 Total Award Period Covered: 09/01/2015 - 08/31/2016 Location of Project: NC State Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: FREEDM Systems Center Project: Fault Isolation Device			
Source of Support: NSF/FREEDM Total Award Amount: \$50,000 Total Award Period Covered: 8/2015-8/2016 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: 0.0 Acad: Sumr: 0.0			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Testing, Characterization and Design Optimization of High Voltage SiC Gate Turn-off (GTO) Thyristors			
Source of Support: CREE/ARL Total Award Amount: \$254100 Total Award Period Covered: 01/13-01/17 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: 0.25 Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: FREEDM Systems Center Project: GEH/DESD/Post Silicon Power Devices			
Source of Support: NSF/FREEDM Total Award Amount: \$180000 Total Award Period Covered: 8/2015-08/2016 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Solid State Circuit Breaker Based on High Voltage SiC GTO			
Source of Support: ONR/ABB Total Award Amount: \$219,746 Total Award Period Covered: 8/2015-08/2016 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: 0. Acad: Sumr: 1			

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99)

USE ADDITIONAL SHEETS AS NECESSARY



Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Alex Q. Huang	Other agencies (including NSF) to which this proposal has been/will be submitted. NONE		
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Distributed, Scalable and Utility Friendly Reserves: Software Engine Development, Validation and Demo			
Source of Support: ARPA-E/Quanta Total Award Amount: \$632626 Total Award Period Covered: 01/01/2016 - 12/31/2018 Location of Project: NC State Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5			
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: T&D Nodal Location Marginal Cost Discovery for Efficient Demand-Side Provisioning of Reserves			
Source of Support: ARPA-E/Boston University Total Award Amount: \$516466 Total Award Period Covered: 2/2016-1/2019 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: 0.0 Acad: Sumr: 0.5			
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Collaborative Research: High Frequency AC Microgrid: Superior Power Delivery Architecture to Convent			
Source of Support: NSF Total Award Amount: \$199237 Total Award Period Covered: 9/1/2016-8/31/2019 Location of Project: Raleigh, NC Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.			
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: High Performance Chip-to-Chip Interconnect for Near-Zero Parasitic Inductance in GaN Power Module			
Source of Support: NSF/IIC LLC Total Award Amount: \$123401 Total Award Period Covered: 1/2016-12/2016 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5			
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: CPS: TTP Option: Frontiers: Collaborative Research: Distributed CPS Architecture for Demand-Side Res			
Source of Support: NSF/Boston University Total Award Amount: \$1140913 Total Award Period Covered: 1/2016-6/2020 Location of Project: NCSU Person-Months Per Year Committed to the Project. Cal: 0. Acad: Sumr: 1			

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.



Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Iqbal Husain	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Direct-drive Modular Transverse Flux Electric Machine without Using Rare-Earth Permanent Magnet Material for Alternative Energy Applications. Source of Support: National Science Foundation Total Award Amount: \$266,313 Total Award Period Covered: 9/1/2013-8/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.75

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: SiC Inverter for Electric Vehicle Traction Drive Collaborative Proposal: Source of Support: Power America: Prime –Department of Energy Total Award Amount: \$275,015 Total Award Period Covered: 1/1/2015-3/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 1.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Design and Analysis of Switched Reluctance and Flux Reversal Machines for Industrial Applications Source of Support: ABB Total Award Amount: \$200,566 Total Award Period Covered: 1/3/2012-12/31/2015 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Scalable, Low-Cost, High-Performance Non-Rare Earth PM Motor for Hybrid Vehicles Source of Support: General Electric Global Research Total Award Amount: \$262,423 Total Award Period Covered: 10/1/2011-1/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0.5

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Switched Reluctance Machine and Controller Development for Electric Power Steering Source of Support: Nexteer Power Steering Total Award Amount: \$150,736 Total Award Period Covered: 10/01/11-12/31/15 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 0

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.



Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support			
Project/Proposal Title: Development of Ocean Compressed Air Energy Storage Including Transmission and Distribution Off the North Carolina Coast Source of Support: Coastal Studies Institute- State of North Carolina Total Award Amount: \$256,532 Total Award Period Covered: 07/01/12-06/30/16 Location of Project: North Carolina State University Person-Months Per Year Committed to the Pro- Cal: Acad: Sumr: 0.25			
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.			

Current and Pending Support

Investigator: Karady, George G	Other agencies(including NSF) to which this proposal has been/will be submitted
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Main: US-Pakistan Centers for Advanced Studies in Energy (USPCASE) Source of Support: USAID Total Award Amount: \$3,734,865.00 Total Award Period Covered: 11/21/2014 - 11/20/2019 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.5	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ACEPS Projects: PI Karady (1998-2016) Source of Support: SRP-SALT RIVER PROJECT Total Award Amount: \$1,349,326.00 Total Award Period Covered: 7/1/1998 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0 Sumr: 0.78	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ERC for Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Source of Support: NORTH CAROLINA STATE UNIV Total Award Amount: \$3,185,317.00 Total Award Period Covered: 9/1/2008 - 8/31/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.75 Sumr: 0.5	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Study of Fiber Optic ADSS Cables Source of Support: Total Award Amount: \$11,108.00 Total Award Period Covered: 12/21/2015 - 6/20/2016 Location of Project: Arizona State University Person-Months Per Year Committed to the Project. Cal: 0 Acad: 0.04 Sumr: 0	

(See GPG Section II.C.2.h for guidance on information to include on this form.)

Investigator: Hui Li

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: WBG PV Converter Development

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Person-Months Per Year Committed to the Project.	Cal:0.00	Acad: 0.00	Sumr: 1.00

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Person-Months Per Year Committed to the Project.	Cal:0.00	Acad: 0.00	Sumr: 0.50

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

All current support which has a related or similar scope of work from whatever source (e.g., Federal, State, local or foreign government agencies, public or private foundations, industrial or other commercial organizations) must be listed.

Investigator: Ning Lu

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future

Contract Title & Description:

Cybersees Type 2: Cyber-Enabled Water and Energy Systems

Source of Support: National Science Foundation (NSF)

Total Award Amount: \$250,000

Total Award Period Covered: 8/16/2014 8/15/2017

Location of Project: Raleigh, NC

% Annual Time Commitment: 0.6 month

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future

Contract Title & Description:

Hydrological Model Integration for the Energy Operations Modeling Tool

Source of Support: Pacific Northwest National Laboratory

Total Award Amount: \$60,000

Total Award Period Covered: 9/1/2014 8/31/2015

Location of Project: Richland, WA

% Annual Time Commitment: 0.5 month

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future

Contract Title & Description:

Green Energy Hub

Source of Support: NSF

Total Award Amount: 50,000

Total Award Period Covered: 8/16/2014 8/15/2015

Location of Project: Raleigh, WA

% Annual Time Commitment: 0

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future

Contract Title & Description:

Distribution Planning Criteria and Tools for Future Distributed Energy Resource Penetration Scenarios using Probabilistic Approaches

Source of Support: CAPER operated by Clemson University

Total Award Amount: 20,000

Total Award Period Covered: 1/1/2015 12/31/2016

Location of Project: Raleigh

% Annual Time Commitment: 0

USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

All current support which has a related or similar scope of work from whatever source (e.g., Federal, State, local or foreign government agencies, public or private foundations, industrial or other commercial organizations) must be listed.

Investigator: Ning Lu - page 2

Support: ☒ Current ☐ Pending ☐ Submission Planned in
Near Future

Contract Title & Description:

Smart Home Energy Management System

Source of Support: Total Inc.

Total Award Amount: \$150,000

Total Award Period Covered: 1/1/2015 12/31/2017

Location of Project: Raleigh, NC

% Annual Time Commitment: 0

Support: ☒ Current ☐ Pending ☐ Submission Planned in
Near Future

Contract Title & Description:

The Olney Town Center Microgrid

Source of Support: DOE

Total Award Amount: \$100,000/\$374,615

Total Award Period Covered: 1/1/2015 12/31/2016

Location of Project: Raleigh, NC

% Annual Time Commitment: 1 month

Support: ☒ Current ☐ Pending ☐ Submission Planned in
Near Future

Contract Title & Description:

Solar Electric Home Energy Management Systems and Modeling Tools

Source of Support: Total Inc

Total Award Amount: \$385,597

Total Award Period Covered: 8/16/2015 8/15/2018

Location of Project: Raleigh

% Annual Time Commitment: 3 months

Support: ☒ Current ☐ Pending ☐ Submission Planned in
Near Future

Contract Title & Description:

Enabling high penetration of distributed PV through the optimization of sub-transmission voltage regulation

Source of Support: DOE

Total Award Amount: \$365,000

Total Award Period Covered: 10/1/2015 9/30/2018

Location of Project: Raleigh, NC

% Annual Time Commitment: 0.5 month

USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: David Lubkeman	Other agencies (including NSF) to which this proposal has been/will be submit-		
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Olney Town Center Microgrid Project Source of Support: Department of Energy (Burr Energy prime) Total Award Amount: \$374,615 Total Award Period Covered: 11/1/2014-10/31/2014 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: 1.2 Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Distribution Planning Criteria and Tools for Future Energy Resources Source of Support: Center for Advanced Power Engineering Research (Clemson University prime) Total Award Amount: \$50,000 Total Award Period Covered: 1/1/2015-12/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Project. Cal: 0.12 Acad: Sumr:			
Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Source of Support: Total Award Amount: \$ Total Award Period Covered: Location of Project: Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:			
Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Source of Support: Total Award Amount: \$ Total Award Period Covered: Location of Project: Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:			
Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Source of Support: Total Award Amount: \$ Total Award Period Covered: Location of Project: Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:			
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.			



Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Srdjan Lukic	Other agencies (including NSF) to which this proposal has		
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ERC for Future Renewable Electric Energy Distribution and Management (FREEDM) Systems Source of Support: National Science Foundation Total Award Amount: \$ 29,639,606 Total Award Period Covered: 09/01/2008 - 08/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Cal: Acad: 0.5 Sumr: 0.5			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: CPS: Synergy: Collaborative Research: Diagnostics and Prognostics Using Temporal Causal Models for Cyber Physical Systems – A case of Smart Grid Source of Support: National Science Foundation Total Award Amount: \$ 200,000 Total Award Period Covered: 10/01/2013 - 09/30/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Cal: Acad: 0.5 Sumr: 0.25			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Direct-drive Modular Transverse Flux Electric Machine without Using Rare-Earth Permanent Magnet Materials Source of Support: National Science Foundation Total Award Amount: \$ 266,135 Total Award Period Covered: 09/01/2013- 08/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: PowerAmerica: Next Generation Electronics Manufacturing Innovation Institute Source of Support: Department of Energy Total Award Amount: \$ 40,000,000 Total Award Period Covered: 12/01/2014 - 03/31/2016 Location of Project: North Carolina State University Person-Months Per Year Committed to the Cal: Acad: 1 Sumr: 0.5			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Resilient Information Architecture Platform for the Smart Grid (RIAPS) Source of Support: Department of Energy Total Award Amount: \$ 410,000 Total Award Period Covered: 02/01/2016- 01/31/2019 Location of Project: North Carolina State University Person-Months Per Year Committed to the Cal: 0.1 Acad: Sumr: 0			
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.			

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Srdjan Lukic		Other agencies (including NSF) to which this proposal has	
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support			
Project/Proposal Title: Collaborative Proposal: Modular Multilevel Converter with Parallel Connectivity—Novel Topology, Control, and Applications			
Source of Support: National Science Foundation			
Total Award Amount: \$ 291,189		Total Award Period Covered:	
Location of Project: North Carolina State University			
Person-Months Per Year Committed to the		Cal:	Acad: 0.1 Sumr: 0.25
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.			

NSF Form 1239 (10/99)

USE ADDITIONAL SHEETS AS
NECESSARY

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Bruce McMillin	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
 Project/Proposal Title: Collaborative Research:Breakthrough:Secure Algorithms for Cyber-Physical Systems

Source of Support: NSF

Total Award Amount: \$333,298 Total Award Period Covered: 5/1/2015-4/30/2018

Location of Project: Missouri University of Science and Technology

Person-Months Per Year Committed to the Pro- 0 Cal: Acad: Sumr: .15

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
 Project/Proposal Title: Future Renewable Electric Energy Delivery and Management Systems Center

Source of Support: NSF ERC Subcontract from NC State University

Total Award Amount: \$2,690,107 Total Award Period Covered: 9/1/13-8/31/18

Location of Project: Missouri University of Science and Technology

Person-Months Per Year Committed to the Project. 0 Cal: Acad: Sumr: 1.0

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
 Project/Proposal Title: Determining Security Threats Through Information Flow Analysis

Source of Support: National Institute of Standards and Technology (NIST)

Total Award Amount: \$199,457 Total Award Period Covered: 1/01/2016-12/31/2017

Location of Project: Missouri University of Science and Technology

Person-Months Per Year Committed to the Project. 0 Cal: Acad: Sumr: 0,75

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future
 Project/Proposal Title: MASTER: Missouri Advanced Security Training Education and Research

Source of Support: NSF

Total Award Amount: \$3,001,744 Total Award Period Covered: 8/15/2014-7/31/2019

Location of Project: Missouri University of Science and Technology

Person-Months Per Year Committed to the Project. 0 Cal: Acad: Sumr: 0.5

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

Investigator: Ewan Pritchard	Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: FREEDM Systems ERC	Source of Support: NSF Total Award Amount: \$40M Total Award Period Covered: 10 Years Location of Project: NC State University, Raleigh NC Person-Months Per Year Committed to the Project. Cal: 9.4 Acad: 9.0 Sumr: 0.4
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	Source of Support: Private/USTDA Total Award Amount: \$322,000 Total Award Period Covered: 2 Years Location of Project: NC State University, Raleigh NC Person-Months Per Year Committed to the Project. Cal: 2.6 Acad: 0 Sumr: 2.6
Support: ☐ Current ☐ Pending ☒ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Optimization of Electrification and Distributed Energy in the Republic of Ireland and Northern Ireland	Source of Support: NSF Total Award Amount: \$1.5M Total Award Period Covered: 3 Years Location of Project: NC State University, Raleigh NC Person-Months Per Year Committed to the Project. Cal: 2 Acad: 0 Sumr: 2
Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title:	Source of Support: Total Award Amount: \$ Total Award Period Covered: Location of Project: Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:
Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title:	Source of Support: Total Award Amount: \$ Total Award Period Covered: Location of Project: Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.



Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Michael "Mischa" Steurer		Other agencies (including NSF) to which this proposal has been/will be submitted.	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: FREEDM Y8 Hardware-in-the-Loop Testbed Source of Support: North Carolina State University Total Award Amount: \$ 209,939 Total Award Period Covered: 9/1/13 – 8/31/16 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: FREEDM Y8 Fault Isolation Device Development Source of Support: North Carolina State University Total Award Amount: \$ 200,000 Total Award Period Covered: 9/1/13 – 8/31/16 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ESRDC FY14 Power Systems Source of Support: Office of Naval Research Total Award Amount: \$ 542,400 Total Award Period Covered: 8/1/14 – 1/14/17 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: S-Parameter Based Framework... ("Grounding") Source of Support: Office of Naval Research Total Award Amount: \$ 347,000 Total Award Period Covered: 4/22/15 – 3/25/17 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: ESO TI3 Source of Support: Naval Sea Systems Command (NAVSEA) / US Navy Total Award Amount: \$ 350,000 Total Award Period Covered: 12/15/15 – 3/15/16 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:			
*If this project has previously been funded by another agency, please list and furnish information for immediately pre-ceding funding period.			

NSF Form 1239 (10/99)

USE ADDITIONAL SHEETS AS NECESSARY



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Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Mechanical Forces – Phase 2 Source of Support: Electric Power Research Institute Total Award Amount: \$ 105,000 Total Award Period Covered: 2/27/15 – 2/29/16 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Study of Potential Benefits from Integrating High Temperature Superconducting Energy Storage Devices and Transformers into SGCC's Electrical Transmission System Source of Support: SGRI North America (SGRINA) Total Award Amount: \$ 449,930 Total Award Period Covered: 10/1/15 – 11/31/16 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Test Laboratory and Services for Validating Performance of a Prototype SSCB Source of Support: Eaton Corporation Total Award Amount: \$ 281,805 Total Award Period Covered: 2/23/15 – 3/31/16 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: DURIP Source of Support: Office of Naval Research Total Award Amount: \$ 300,183 (base) Total Award Period Covered: 7/15/16 – 7/14/17 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: An Open-Source Distributed Control Platform for HIL-Based Testing and Demonstration of Advanced Ship Power Systems Source of Support: Office of Naval Research Total Award Amount: \$ 620,385 Total Award Period Covered: 7/1/16 – 7/14/17 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:
Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Medium Voltage Direct Current (MVDC) Fault Detection, Localization, and Isolation Source of Support: IAP Research, Inc Total Award Amount: \$ 65,646 Total Award Period Covered: 7/1/16 – 1/31/17 Location of Project: Florida State University Person-Months Per Year Committed to the Project Cal: Acad: Sumr:

Support:	☐ Current	☒ Pending	☐ Submission Planned in Near Future	☐ *Transfer of Support
Project/Proposal Title:				
Calnetix SUB-DOE-FOA001208				
Source of Support: Calnetix Technologies				
Total Award Amount: \$ 552,758		Total Award Period Covered: 1/1/18 – 12/31/18		
Location of Project: Florida State University				
Person-Months Per Year Committed to the Project	Cal:	Acad:	Sumr:	

Current and Pending Support

February, 2016

Investigator: Ming Yu
Support: Current Project/Proposal Title: Dynamic Real-time Threat Analysis for Electrical Grids Source of Support: National Security Agency Total Award Amount: \$291,000. Total Award Period Covered: 08/2015 – 07/2016 Location of Project: FAMU – FSU College of Engineering, Tallahassee, FL Person-Months Per year Committed to the Project: Cal Acad Summer: 1.0
Support: Current Project/Proposal Title: Reliable and Secure Communications for FREEDM Systems Source of Support: NSF Total Award Amount: \$60,000. Total Award Period Covered: 09/2015 – 08/2016 Location of Project: FAMU – FSU College of Engineering, Tallahassee, FL Person-Months Per year Committed to the Project: Cal Acad Summer: 1.0
Support: Current Project/Proposal Title: Electrical Ship Research and Development Consortium (ESRDC): Ultra-fast real-time networking protocols for the fault protection of all-electrical battle ships Source of Support: ONR Total Award Amount: \$55,000. Total Award Period Covered: Location of Project: FAMU – FSU College of Engineering, Tallahassee, FL Person-Months Per year Committed to the Project: Cal Acad Summer: 1.0
Support: Pending Project/Proposal Title: Development of Secure Communication Protocols for Wireless Traffic Detecting Devices Source of Support: Florida Dept. of Transportation Total Award Amount: \$154,900. Total Award Period Covered: 08/2016 – 07/2018 Location of Project: FAMU – FSU College of Engineering, Tallahassee, FL Person-Months Per year Committed to the Project: Cal Acad Summer: 1.0
Support: Pending Project/Proposal Title: Partitioning Power & Energy Management Control and Information Functions for Naval Shipboard Distribution Systems and Evaluating Control Performance using Hardware-in-the-Loop Methods Source of Support: ONR Total Award Amount: \$750,000. Total Award Period Covered: 08/2016 – 07/2018 Location of Project: FAMU – FSU College of Engineering, Tallahassee, FL Person-Months Per year Committed to the Project: Cal Acad Summer: 1.0

Current and Pending Support

(See GPG Section II.D.8 for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.			
Investigator: Jim P. Zheng		Other agencies (including NSF) to which this proposal has been/will be submitted.	
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Development of Advanced Energy Storage Devices a sub-contract from Center for Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Source of Support: National Science Foundation, Engineering Research Center Program Total Award Amount: \$2,000,000 Total Award Period Covered: 08/01/2008-07/31/2016 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: 1 Synergies/Overlaps with this application: No			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Investigation on the Effects of Porosity and Catalyst to the Cathode Performance in L-Air Batteries Source of Support: US Army Communications-Electronics Command Total Award Amount: \$700,000 Total Award Period Covered: 02/06/2013-01/31/2017 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: 1 Sumr: 1 Synergies/Overlaps with this application: No			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Investigation of Pre-Lithiated Anodes for Li-ion Source of Support: Department of Energy /PNNL Total Award Amount: \$450,000 Total Award Period Covered: 01/01/2013-03/31/2016 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: 1 Sumr: 1 Synergies/Overlaps with this application: No			
Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Development and Characterization of Li-ion Capacitor Electrodes and Cells Source of Support: General Capacitor Total Award Amount \$513,030 Total Award Period Covered: 01/01/2014-12/31/2016 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: Acad: Sumr: Synergies/Overlaps with this application: No			
Support: ☒ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Project/Proposal Title: Monolithic Li-Ion Battery and Li-Ion Capacitor Hybrid Cells for Brigade, Soldier and Small Unit Power Source of Support: Army Research Laboratory Total Award Amount: \$1,215,441 Total Award Period Covered: 08/18/2015-8/17/2017 Location of Project: FAMU-FSU College of Engineering Person-Months Per Year Committed to the Project. Cal: 0 Acad: 2 Sumr: Synergies/Overlaps with this application: No			
*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.			

ERC Web Project and Personnel Data

Volume II: Project Personnel Data												
Project Name	Project Leader	Project Investigator	Project Role	Title	First Name	Middle Initial	Last Name	Suffix	Institution	Title Within Institution	Department Within Institution	Personnel Types Within Institution
Analysis of Practical Microgrid Stability in the Presence of Random Events	No	No			Weichao		Zhang		Missouri University of Science and Technology			Research - Master's Student
Analysis of Practical Microgrid Stability in the Presence of Random Events	Yes	Yes		Dr.	Jonathan	W	Kimball		Missouri University of Science and Technology			Research - Senior Faculty
Analysis of Practical Microgrid Stability in the Presence of Random Events	No	No			Jacob		Mueller		Missouri University of Science and Technology			Research - Master's Student
Collaborative Research: Computational Methods for Stability Assessment of Power Systems With High Penetration of Clean Renewable Energy	Yes	Yes		Dr.	Aranya		Chakraborty		NC State University	Associate Professor	Electrical and Computer Engineering	Research - Junior Faculty
Cooperative Distributed Home Energy Management Systems	Yes	Yes		Dr.	Mo-Yuen		Chow		NC State University	Professor	Electrical and Computer Engineering	Research - Senior Faculty
CPS: Breakthrough: Collaborative Research: Securing Smart Grid by Understanding Communications Infrastructure Dependencies	No	No			Weichao		Zhang		Missouri University of Science and Technology			Research - Master's Student
CPS: Breakthrough: Collaborative Research: Securing Smart Grid by Understanding Communications Infrastructure Dependencies	No	Yes		Dr.	Jonathan	W	Kimball		Missouri University of Science and Technology			Research - Senior Faculty
CPS: Breakthrough: Collaborative Research: Securing Smart Grid by Understanding Communications Infrastructure Dependencies	No	Yes		Dr.	Bruce	M	McMillin		Missouri University of Science and Technology	Professor	Computer Science	Research - Senior Faculty
CPS: Breakthrough: Collaborative Research: Securing Smart Grid by Understanding Communications Infrastructure Dependencies	Yes	Yes		Dr.	Mariesa		Crow		Missouri University of Science and Technology	F. Finley Distinguished Professor of Electrical Engineering	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
CPS: Synergy: Collaborative Research: Diagnostics and Prognostics Using Temporal Causal Models for Cyber Physical Systems- A case of Smart Electric Grid	No	No			Yuhua		Du		NC State University			Research - Doctoral Student
CPS: Synergy: Collaborative Research: Diagnostics and Prognostics Using Temporal Causal Models for Cyber Physical Systems- A case of Smart Electric Grid	Yes	Yes		Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
CPS: Synergy: Collaborative Research: Diagnostics and Prognostics Using Temporal Causal Models for Cyber Physical Systems- A case of Smart Electric Grid	No	No			Rishabh		Jain		NC State University			Research - Doctoral Student
CPS: TTP Option: Synergy: Collaborative Research: Hardening Network Infrastructures for Fast Resilient and Cost-Optimal Wide-Area Control of Power Systems	Yes	Yes		Dr.	Aranya		Chakraborty		NC State University	Associate Professor	Electrical and Computer Engineering	Research - Junior Faculty
CPS: TTP Option: Synergy: Collaborative Research: Hardening Network Infrastructures for Fast Resilient and Cost-Optimal Wide-Area Control of Power Systems	No	No			Mang		Liao		NC State University			Research - Doctoral Student
Design and Analysis of Switched Reluctance and Flux Switching Permanent Magnet (FSPM) Machines for Industrial Applications	No	No			Chandan		Sikder		NC State University			Research - Doctoral Student
Design and Analysis of Switched Reluctance and Flux Switching Permanent Magnet (FSPM) Machines for Industrial Applications	Yes	Yes		Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Design of High Performance Low-cost Non-rare Earth Electric Machines Meeting IE4/IE5 Efficiency Requirements	Yes	Yes		Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Design of High Performance Low-cost Non-rare Earth Electric Machines Meeting IE4/IE5 Efficiency Requirements	No	No			Md Ashfanoo		Kabir		NC State University			Research - Doctoral Student
Determining Security Threats Through Information Flow Analysis	Yes	Yes		Dr.	Bruce	M	McMillin		Missouri University of Science and Technology	Professor	Computer Science	Research - Senior Faculty
Development and Characterization of Li-ion Capacitor Electrodes and Cells	Yes	Yes		Dr.	Jim	P	Zheng		Florida A & M University	Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Development and Testing of Silicon Carbide Gate Turn-Off Thyristor Based High Power Solid State Circuit Breaker (SSCB) for DC Power Distribution System	No	No			Richard		Woodley		NC State University			Research - Master's Student Curriculum - Master's Student
Development and Testing of Silicon Carbide Gate Turn-Off Thyristor Based High Power Solid State Circuit Breaker (SSCB) for DC Power Distribution System	Yes	Yes		Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	No	Yes		Dr.	David		Lubkerman		NC State University	Research Professor	Electrical and Computer Engineering	Research - Research Staff
Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	No	No			Landon		Mackey		NC State University			Research - Master's Student
Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	No	No			Di		Zhu		NC State University			Research - Doctoral Student
Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	No	No			Eric		Green		NC State University			Research - Doctoral Student
Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	Yes	Yes		Dr.	Ewan		Pritchard		NC State University	Director of Industry Collaboration & Innovation	FREEDM	Research - Senior Faculty Leadership/Administration - Industrial Liaison Officer (ILO)
Development of a Mobile Energy Generator for use in Microgrids in the Dominican Republic	No	No			Taha		Arif		NC State University			Research - Undergraduate Student Curriculum - Undergraduate Student
Development of Stationary DESDS	No	No			Lakshita		Ravuri		NC State University			Research - Master's Student
Development of Stationary DESDS	No	Yes		Dr.	Jim	P	Zheng		Florida A & M University	Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Development of Stationary DESDS	Yes	Yes		Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Development of Stationary DESDS	No	No			Fei		Xue		NC State University			Research - Doctoral Student
Development of Stationary DESDS	No	Yes		Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
Development of the Electrical Distribution for Windlift Airborne Wind Turbines	No	No			Kibok		Lee		NC State University			Research - Doctoral Student
Development of the Electrical Distribution for Windlift Airborne Wind Turbines	Yes	Yes		Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
DGI/RSC	No	Yes		Dr.	Mesut		Baran		NC State University	Professor	Electrical and Computer Engineering	Leadership/Administration - Thrust Leader Research - Senior Faculty

DGI/RSC	No	Yes		Dr.	Mo-Yuen		Chow		NC State University	Professor	Electrical and Computer Engineering	Research - Senior Faculty
DGI/RSC	No	Yes		Dr.	Chris		Edrington		Florida State University	Associate Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
DGI/RSC	No	No			Yue		Shi		NC State University			Research - Doctoral Student
DGI/RSC	No	No			Sukhmaan		Rathore		Missouri University of Science and Technology			Research - Master's Student Curriculum - Master's Student
DGI/RSC	No	No			Tom		Roth		Missouri University of Science and Technology			Research - Doctoral Student
DGI/RSC	No	No			Huawei		Yang		Florida State University			Research - Doctoral Student
DGI/RSC	No	No		Ms	Li		Feng		Missouri University of Science and Technology			Research - Doctoral Student
DGI/RSC	No	No			Touria		El Mezayani		Florida State University			Research - Postdoc
DGI/RSC	No	Yes		Dr.	Jonathan	W	Kimball		Missouri University of Science and Technology			Research - Senior Faculty
DGI/RSC	Yes	Yes		Dr.	Bruce	M	McMillin		Missouri University of Science and Technology	Professor	Computer Science	Research - Senior Faculty
ELECTROCORE Distributed Power System Training	Yes	Yes		Dr.	George		Karady		Arizona State University	Power System Chair Professor	School of Electrical Computer and Energy engineering	Research - Senior Faculty Leadership/Administration - Education Program Leader
ELECTROCORE Distributed Power System Training	No	No			Qiushi		Wang		Arizona State University			Research - Master's Student Curriculum - Master's Student
Enabling high penetration of distributed PV through the optimization of si transmission voltage regulation	No	Yes		Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
Enabling high penetration of distributed PV through the optimization of si transmission voltage regulation	Yes	Yes		Dr. Ning	Ning		Lu		NC State University			Research - Senior Faculty
EOM Development	Yes	Yes		Dr. Ning	Ning		Lu		NC State University			Research - Senior Faculty
EOM Development	No	No			Xinda		Ke		NC State University			Research - Doctoral Student
Fabrication of Lithium-Sulfur Pouch Cell Batteries	Yes	Yes		Dr.	Jim	P	Zheng		Florida A & M University	Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Fast Electromechanical Disconnect Switching Chamber with Integrated Drive Mechanism	Yes	Yes		Dr.	Michael		Steurer		Florida State University	Scholar Scientist	Center for Advanced Power Systems - CAPS	Leadership/Administration - Thrust Leader Research - Senior Faculty
Fast Electromechanical Disconnect Switching Chamber with Integrated Drive Mechanism	No	No			James		Owens		Florida State University			Research - Undergraduate Student
FID Development	No	No			James		Owens		Florida State University			Research - Undergraduate Student
FID Development	No	Yes		Dr.	Gerald	T	Heydt		Arizona State University	Regents' Professor	Electrical Computer and Energy Engineering	Research - Senior Faculty Leadership/Administration - Director Curriculum - Undergraduate Student
FID Development	No	No			Joshua		Roybal		Florida State University			Curriculum - Undergraduate Student
FID Development	No	No			Odoi		Ali		Florida State University			Curriculum - Undergraduate Student
FID Development	No	Yes		Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
FID Development	No	No			Xiaoping		Song		NC State University			Research - Doctoral Student
FID Development	Yes	Yes		Dr.	Michael		Steurer		Florida State University	Scholar Scientist	Center for Advanced Power Systems - CAPS	Leadership/Administration - Thrust Leader Research - Senior Faculty
FREEDM System Demonstration: Green Energy Hub	No	No			Jiahong		Yan		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Green Energy Hub	No	No			Ankan		De		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Green Energy Hub	No	No			Richard		Beddingfield		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Green Energy Hub	Yes	Yes		Dr.	David		Lubkeman		NC State University	Research Professor	Electrical and Computer Engineering	Research - Research Staff
FREEDM System Demonstration: Green Energy Hub	No	Yes		Dr. Ning	Ning		Lu		NC State University			Research - Senior Faculty
FREEDM System Demonstration: Green Energy Hub	No	Yes		Dr	Subhashish		Bhattacharya		NC State University	Dr.	Electrical and Computer Engineering	Research - Senior Faculty
FREEDM System Demonstration: Green Energy Hub	No	No			Yonghwan		Cho		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Green Energy Hub	No	No			Rui		Gao		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Green Energy Hub	No	No			Thomas		Dotson		NC State University			Research - Master's Student Curriculum - Master's Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Diandra		Prioleau		Florida State University			Research - Undergraduate Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Melanie		Gonzalez		Florida State University			Research - Undergraduate Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Touria		El Mezayani		Florida State University			Research - Postdoc
FREEDM System Demonstration: Hardware in the Loop	No	No		Ms	Li		Feng		Missouri University of Science and Technology			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr.	Jonathan	W	Kimball		Missouri University of Science and Technology			Research - Senior Faculty
FREEDM System Demonstration: Hardware in the Loop	No	No			Tom		Roth		Missouri University of Science and Technology			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Youyuan		Jiang		Arizona State University			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	Yes			Rajapandian		Ayyanar		Arizona State University			Research - Senior Faculty
FREEDM System Demonstration: Hardware in the Loop	No	No			Sindhu Jas		Sundararajan		Florida State University			Research - Master's Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Ziyuan		Cai		Florida State University			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Farzad		Ferdowzi		Florida State University			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr.	Bruce	M	McMillin		Missouri University of Science and Technology	Professor	Computer Science	Research - Senior Faculty
FREEDM System Demonstration: Hardware in the Loop	No	No			Yuan		Zhang		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	No			Jie		Duan		NC State University			Research - Doctoral Student
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr.	David		Lubkeman		NC State University	Research Professor	Electrical and Computer Engineering	Research - Research Staff
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr.	Mesut		Baran		NC State University	Professor	Electrical and Computer Engineering	Leadership/Administration - Thrust Leader Research - Senior Faculty
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr.	Mo-Yuen		Chow		NC State University	Professor	Electrical and Computer Engineering	Research - Senior Faculty
FREEDM System Demonstration: Hardware in the Loop	No	Yes		Dr	Ming		Yu		Florida State University			Research - Senior Faculty
FREEDM System Demonstration: Hardware in the Loop	Yes	Yes	Testbed Leader	Dr.	Michael		Steurer		Florida State University	Scholar Scientist	Center for Advanced Power Systems - CAPS	Leadership/Administration - Thrust Leader Research - Senior Faculty

FREEDM System Demonstration: Large Scale System Simulation	No	Yes		Dr.	George		Karady		Arizona State University	Power System Chair Professor	School of Electrical Computer and Energy engineering	Research - Senior Faculty Leadership/Administration - Education Program Leader
FREEDM System Demonstration: Large Scale System Simulation	Yes	Yes		Dr.	Mariesa		Crow		Missouri University of Science and Technology	F. Finley Distinguished Professor of Electrical Engineering	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
FREEDM System Demonstration: Large Scale System Simulation	No	No			Darshit		Shah		Missouri University of Science and Technology			Research - Doctoral Student
FREEDM System Demonstration: Large Scale System Simulation	No	No			Tamral		Paul		Missouri University of Science and Technology			Research - Doctoral Student
GEH Industry	No	No			Bramhasamudra	M	Pratheek		NC State University			Curriculum - Master's Student
GEH Industry	No	No			Sarah		Hambridge		NC State University			Research - Doctoral Student
GEH Industry	Yes	Yes		Dr.	David		Lubkeman		NC State University	Research Professor	Electrical and Computer Engineering	Research - Research Staff
										Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	
GEH Industry	No	Yes		Dr.	Alex	Q	Huang		NC State University			Research - Senior Faculty Leadership/Administration - Director
GEH Industry	No	No			Daili		Li		NC State University			Research - Master's Student
GEH Industry	No	No			Lisha		Sun		NC State University			Research - Master's Student
Investigation of Pre-Lithiated Anodes for Li-Ion batteries and Li-Ion capacitors	Yes	Yes		Dr.	Jim	P	Zheng		Florida A & M University	Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Li-Ion Battery and Li-Ion Capacitor Hybrid Energy Storage Devices	Yes	Yes		Dr.	Jim	P	Zheng		Florida A & M University	Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Load Regulation with PV-Storage and Electric Vehicle with Dynamic Programming	Yes	Yes		Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Load Regulation with PV-Storage and Electric Vehicle with Dynamic Programming	No	No			Faeza		Halfiz		NC State University			Research - Doctoral Student
Medium Voltage Fast Charger	No	No			Xinyu		Liang		NC State University			Research - Master's Student
Medium Voltage Fast Charger	No	No			Chi		Zhang		NC State University			Research - Doctoral Student
Medium Voltage Fast Charger	Yes	Yes		Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Missouri Advanced Security Training Education and Research	Yes	Yes		Dr.	Bruce	M	McMillin		Missouri University of Science and Technology	Professor	Computer Science	Research - Senior Faculty
Monolithic Li-Ion Battery and Li-Ion Capacitor Hybrid Cells for Brigade Soldier and Small Unit Power	Yes	Yes		Dr.	Jim	P	Zheng		Florida A & M University	Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Ocean Energy: Assessment of Energy Storage Aspects Including Control and Grid Connection off the North Carolina Coast	Yes	Yes		Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Ocean Energy: Assessment of Energy Storage Aspects Including Control and Grid Connection off the North Carolina Coast	No	No			Ali		Safayet		NC State University			Research - Doctoral Student
										Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	
Ocean Energy: Assessment of Energy Storage Aspects Including Control and Grid Connection off the North Carolina Coast	No	Yes		Dr.	Alex	Q	Huang		NC State University			Research - Senior Faculty Leadership/Administration - Director
Ocean Energy: Assessment of Energy Storage Aspects Including Control and Grid Connection off the North Carolina Coast	No	No			Chang		Peng		NC State University			Research - Doctoral Student
Olney Town Center Microgrid Project	Yes	Yes		Dr.	David		Lubkeman		NC State University	Research Professor	Electrical and Computer Engineering	Research - Research Staff
Olney Town Center Microgrid Project	No	Yes		Dr. Ning	Ning		Lu		NC State University			Research - Senior Faculty
Olney Town Center Microgrid Project	No	No			Jian		Lu		NC State University			Research - Doctoral Student
Olney Town Center Microgrid Project	No	Yes		Dr.	Aranya		Chakraborty		NC State University	Associate Professor	Electrical and Computer Engineering	Research - Junior Faculty
Olney Town Center Microgrid Project	No	Yes		Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Olney Town Center Microgrid Project	No	No			Xiangji		Zhu		NC State University			Research - Doctoral Student
Permanent Magnet Transverse Flux Electric Machine with Flux Focusing Technique for Direct Drive Applications	No	No			Zhao		Wan		NC State University			Research - Doctoral Student
Permanent Magnet Transverse Flux Electric Machine with Flux Focusing Technique for Direct Drive Applications	Yes	Yes		Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Permanent Magnet Transverse Flux Electric Machine with Flux Focusing Technique for Direct Drive Applications	No	Yes		Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Permanent Magnet Transverse Flux Electric Machine with Flux Focusing Technique for Direct Drive Applications	No	No			Adeeb		Ahmed		NC State University			Research - Doctoral Student
Post Silicon Devices	No	No			Haotao		Ke		NC State University			Research - Doctoral Student
Post Silicon Devices	No	No			Yang		Xu		NC State University			Research - Doctoral Student
Post Silicon Devices	No	No			Sizhen		Wang		NC State University			Curriculum - Doctoral Student Research - Doctoral Student
										Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	
Post Silicon Devices	No	Yes		Dr.	Alex	Q	Huang		NC State University			Research - Senior Faculty Leadership/Administration - Director
Post Silicon Devices	Yes	Yes		Dr.	Jay		Balliga		NC State University	Distinguished University Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Post Silicon Devices	No	Yes		Dr.	Viena		Misra		NC State University	Dr.	Electrical and Computer Engineering	Research - Senior Faculty
Post Silicon Devices	No	Yes		Dr.	Douglas		Hopkins		NC State University			Research - Senior Faculty
Post Silicon Devices	No	No			In-Hwan		Ji		NC State University			Research - Postdoc
Post Silicon Devices	No	No		Dr.	Woongje		Sung		NC State University	Assistant Research Professor	FREEDM	Research - Research Staff
Post Silicon Devices	No	No			Faisal		Azam		NC State University	PhD student	Electrical and Computer Engineering	Curriculum - Doctoral Student
Post Silicon Devices	No	No			Yifan		Jiang		NC State University			Research - Doctoral Student
Power America: Development of SiC/GaN Based High Performance PV String Inverters and Micro Inverters	No	No			Yinglai		Xia		Arizona State University			Research - Doctoral Student
Power America: Development of SiC/GaN Based High Performance PV String Inverters and Micro Inverters	Yes	Yes			Rajapandian		Ayyanar		Arizona State University			Curriculum - Junior Faculty Research - Senior Faculty
Power America: Medium Voltage Gate Drive with 10 KHz 10kV SiC Mosfet for 2.3 kv Motor Drives	No	No		Dr	Krishna		Mainali		NC State University			Research - Postdoc Curriculum - Postdoc
Power America: Medium Voltage Gate Drive with 10 KHz 10kV SiC Mosfet for 2.3 kv Motor Drives	No	No			Sachin		Madhusoodhanan		NC State University			Research - Doctoral Student

Power America: Medium Voltage Gate Drive with 10 KHz 10kv SiC Mosfet for 2.3 kv Motor Drives	Yes	Yes	Dr.	Subhashish		Bhattacharya		NC State University	Dr.	Electrical and Computer Engineering	Research - Senior Faculty
Power America: Medium Voltage Gate Drive with 10 KHz 10kv SiC Mosfet for 2.3 kv Motor Drives	No	No		Awneesh		Tripathi		NC State University			Research - Doctoral Student
Power America: SiC Inverter for Electric Vehicle Traction Drive	No	No		Yang		Xu		NC State University			Research - Doctoral Student
Power America: SiC Inverter for Electric Vehicle Traction Drive	No	No		Adam	J	Morgan		NC State University			Research - Doctoral Student
Power America: SiC Inverter for Electric Vehicle Traction Drive	No	Yes	Dr.	Douglas		Hopkins		NC State University			Research - Senior Faculty
Power America: SiC Inverter for Electric Vehicle Traction Drive	No	Yes	Dr.	Wensong		Su		NC State University	Dr.	Electrical and Computer Engineering	Research - Senior Faculty
Power America: SiC Inverter for Electric Vehicle Traction Drive	No	No		Dhrubo		Rahman		NC State University			Research - Doctoral Student
Power America: SiC Inverter for Electric Vehicle Traction Drive	Yes	Yes	Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Power America: SiC Inverter for Electric Vehicle Traction Drive	No	No		Li		Yang		NC State University			Research - Doctoral Student
Resilient Information Architecture Platform for the Smart Grid (RIAPS)	Yes	Yes	Dr.	Srdjan	M	Lukic		NC State University	Assistant Professor	Electrical and Computer Engineering	Research - Junior Faculty Leadership/Administration - Research Thrust Management and Strategic Planning
Resilient Information Architecture Platform for the Smart Grid (RIAPS)	No	No		Yuhua		Du		NC State University			Research - Doctoral Student
SiC power devices & DC power distribution system	No	No		Ruiyang		Yu		NC State University			Research - Postdoc
SiC power devices & DC power distribution system	Yes	Yes	Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
SiC power devices & DC power distribution system	No	No		Qi		Tian		NC State University			Research - Doctoral Student
SiC power devices & DC power distribution system	No	No		Kai		Tan		NC State University			Research - Doctoral Student
SiC power devices & DC power distribution system	No	No		Suxuan		Guo		NC State University			Research - Doctoral Student
SiC power devices & DC power distribution system	No	No		Liji		Zhang		NC State University			Research - Doctoral Student
SiC power devices & DC power distribution system	No	No		Pengkun		Liu		NC State University			Research - Master's Student
Solid State Circuit Breaker	Yes	Yes	Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
Solid State Circuit Breaker	No	No		Richard		Woodley		NC State University			Research - Master's Student
Solid State Transformer Development	No	No		Dong		Chen		NC State University			Research - Postdoc
Solid State Transformer Development	No	Yes		Rajapandian		Ayyanar		Arizona State University			Curriculum - Junior Faculty Research - Senior Faculty
Solid State Transformer Development	Yes	Yes	Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREEDM/ATEC	Research - Senior Faculty Leadership/Administration - Director
Solid State Transformer Development	No	No		Li		Wang		NC State University			Research - Doctoral Student
Solid State Transformer Development	No	Yes	Dr.	Wencong		Yu		NC State University	Associate Research Professor	Electrical and Computer Engineering	Research - Research Staff
Solid State Transformer Development	No	Yes	Dr.	Hui Helen		Li		Florida State University			Research - Senior Faculty
Solid State Transformer Development	No	No		Qiantai		Zhu		NC State University			Research - Doctoral Student
Switched Reluctance Machine and Controller Development for Electric Power Steering	No	No		Zhao		Wan		NC State University			Research - Doctoral Student
Switched Reluctance Machine and Controller Development for Electric Power Steering	No	No		Hellon		Dhirmaj		NC State University			Research - Master's Student
Switched Reluctance Machine and Controller Development for Electric Power Steering	Yes	Yes	Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
Switched Reluctance Machine and Controller Development for Electric Power Steering	No	No		Adeeb		Ahmed		NC State University			Research - Doctoral Student
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Yonghwan		Cho		NC State University			Research - Doctoral Student
System Demonstration: GEH - System Cost Benefit Analysis	No	Yes		Lisa		Chang		NC State University	Program Administrator	Management Innovations and Entrepreneurship	Curriculum - Staff
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Yue		Shi		NC State University			Research - Doctoral Student
System Demonstration: GEH - System Cost Benefit Analysis	No	Yes	Dr.	David		Lubkeman		NC State University	Research Professor	Electrical and Computer Engineering	Research - Research Staff
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Samir		Hazra		NC State University			Research - Doctoral Student
System Demonstration: GEH - System Cost Benefit Analysis	No	Yes	Dr.	Joseph		DeCarolis		NC State University			Research - Senior Faculty
System Demonstration: GEH - System Cost Benefit Analysis	Yes	Yes	Dr.	Mesut		Baran		NC State University	Professor	Electrical and Computer Engineering	Leadership/Administration - Thrust Leader Research - Senior Faculty
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Urvir		Singh		NC State University			Research - Doctoral Student
System Demonstration: GEH - System Cost Benefit Analysis	No	Yes	Dr.	Leonard		White		NC State University			Research - Research Staff
System Demonstration: GEH - System Cost Benefit Analysis	No	Yes	Dr.	Gerald	T	Heydt		Arizona State University	Regents' Professor	Electrical Computer and Energy Engineering	Research - Senior Faculty Leadership/Administration - Director
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Apurva		Raman		Arizona State University			Research - Master's Student
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Shashwat		Singh		NC State University			Curriculum - Master's Student
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Carl		Kerchmar		NC State University			Curriculum - Master's Student
System Demonstration: GEH - System Cost Benefit Analysis	No	No		Jeffrey		Thomas		NC State University			Research - Master's Student
System Theory Modeling and Controls	No	Yes	Dr.	Romeo		Ortega		Supélec			Curriculum - Senior Faculty
System Theory Modeling and Controls	No	No		Diandra		Pringleau		Florida State University			Research - Undergraduate Student
System Theory Modeling and Controls	No	No		Melanie		Gonzalez		Florida State University			Research - Undergraduate Student
System Theory Modeling and Controls	No	No		Touria		El Mezayni		Florida State University			Research - Postdoc
System Theory Modeling and Controls	No	Yes	Dr.	Alex		Stankovic		Tufts University	Doctor	Electrical	Research - Senior Faculty
System Theory Modeling and Controls	No	No		Zhai		Yu		Arizona State University			Research - Doctoral Student
System Theory Modeling and Controls	No	Yes		Rajapandian		Ayyanar		Arizona State University			Research - Senior Faculty
System Theory Modeling and Controls	No	No		Farzad		Ferdawzi		Florida State University			Research - Doctoral Student
System Theory Modeling and Controls	No	No		Sanaz		Piran		Florida State University			Research - Doctoral Student
System Theory Modeling and Controls	No	No		Yingying		Tang		Arizona State University			Research - Doctoral Student
System Theory Modeling and Controls	No	Yes	Dr.	Aranya		Chakraborty		NC State University	Associate Professor	Electrical and Computer Engineering	Research - Junior Faculty
System Theory Modeling and Controls	Yes	Yes	Dr.	Iqbal		Husain		NC State University	Distinguished Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
System Theory Modeling and Controls	No	Yes	Dr.	Chris		Edrington		Florida State University	Associate Professor	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director

System Theory Modeling and Controls	No	No			Md Tanvir	A	Khan		NC State University			Research - Doctoral Student
Testing Characterization and Design of High Voltage SiGate Turn-off (GTO) Thyristors	Yes	Yes		Dr.	Alex	Q	Huang		NC State University	Progress Energy Distinguished Professor Director of FREEDM and ATEC	Electrical and Computer Engineering/FREED M/ATEC	Research - Senior Faculty Leadership/Administration - Director
Testing Characterization and Design of High Voltage SiGate Turn-off (GTO) Thyristors	No	No			Qingyun		Huang		NC State University			Research - Doctoral Student
Testing Characterization and Design of High Voltage SiGate Turn-off (GTO) Thyristors	No	No			In-Hwan		Ji		NC State University			Research - Postdoc
The MidAmerica Regional Microgrid Education and Training (MARMET) Consortium	No	No			Mahammad		Narimani		Missouri University of Science and Technology			Curriculum - Doctoral Student Research - Doctoral Student
The MidAmerica Regional Microgrid Education and Training (MARMET) Consortium	Yes	Yes		Dr.	Mariesa		Crow		Missouri University of Science and Technology	F. Finley Distinguish Professor of Electrical Engineering	Electrical and Computer Engineering	Research - Senior Faculty Leadership/Administration - Director
The MidAmerica Regional Microgrid Education and Training (MARMET) Consortium	No	Yes		Dr.	Jonathan	W	Kimball		Missouri University of Science and Technology			Research - Senior Faculty
The Solar Endowment	Yes	Yes		Dr.	Jonathan	W	Kimball		Missouri University of Science and Technology			Research - Senior Faculty
Total	No	No			Gonzague		Henri		NC State University			Research - Doctoral Student
Total	No	No			Catie		McEntee		NC State University			Research - Master's Student
Total	No	No			Jian		Lu		NC State University			Curriculum - Master's Student
Total	Yes	Yes		Dr. Ning	Ning		Lu		NC State University			Research - Senior Faculty
Total	No	No			Jiahong		Yan		NC State University			Research - Doctoral Student
Total	No	No			Xiangqi		Zhu		NC State University			Research - Doctoral Student
US Ignite: Track 1: Collaborative Research: DISTINCT: A Distributed Multi-Loop Networked System for Wide-Area Control of Large Power Grids	Yes	Yes		Dr.	Aranya		Chakraborty		NC State University	Associate Professor	Electrical and Computer Engineering	Research - Junior Faculty
US Ignite: Track 1: Collaborative Research: DISTINCT: A Distributed Multi-Loop Networked System for Wide-Area Control of Large Power Grids	No	No			Yao		Meng		NC State University			Curriculum - Doctoral Student Research - Doctoral Student