FREEDM SYSTEMS CENTER

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

Director: Dr. Iqbal Husain

Associate Director: Dr. Ewan Pritchard

NC State University (NC State) Raleigh, NC

Arizona State University (ASU) Temple, AZ

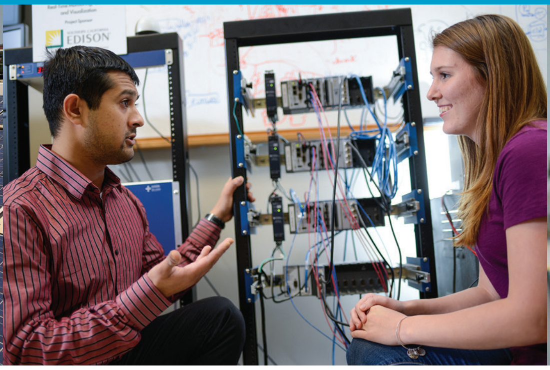
Florida State University (FSU) Tallahassee, FL

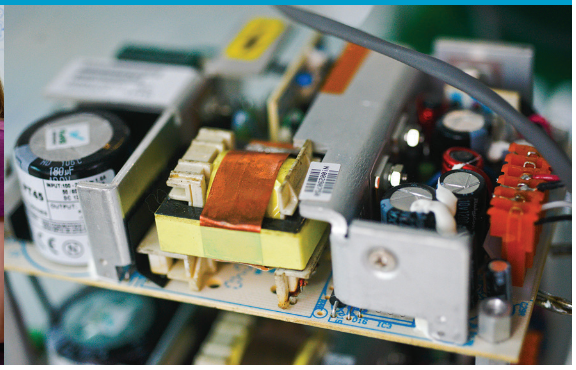
Florida A&M University (FAMU) Tallahassee, FL

Missouri University of Science and Technology (Missouri S&T) Rolla, MO

RWTH Aachen University (RWTH) Aachen, Germany

Swiss Federal Institute of Technology (ETH) Zurich, Switzerland





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Executive Summary

A: Achievements in the Reporting Year

This year, the FREEDM Systems Center again made important advances towards its transformative vision of developing and validating an *Energy Internet*. Center achievements for Year 8 are highlighted below.

1. System Demonstration Testbeds

GEH Testbed - Demonstrations of FREEDM System's salient attributes, grouped in IFM, IPM, IEM and PnP continue, one being an IEM demonstration focused on frequency based real time pricing and energy dispatch by SST. A new concept, the Solid State Synchronous Machine (SSSM) is being developed to support 100% penetration of DERs. A 10 hp wind turbine emulator and associated algorithms are now available to the testbed. This year the MS&T team has integrated the MQTT (Message Queue Telemetry Transport) component within the DGI module to improve communications between the energy cell devices (DESD, DRER, HEMS), SST DGI nodes, and PI Servers. The smart house, equipped with an *Ecobee* system for temperature and humidity control, was developed as a test chamber for testing heating and cooling loads. LV-SSTs have been differentiated as either 'black-start' or 'load' to enable seamless black-start operation; separate operations of black-start SST and the load SST have been verified experimentally.

A series of tasks were created to perform an overall cost/benefit analysis of various parts of the FREEDM System with the results being that present full deployment results in a negative net present value and an IRR below the average DISCO WACC; however, partial deployment is an attractive investment for early adopters.

A list of relevant codes and standards, generated by consensus, was evaluated; in general, the documents do not pose significant challenges to the deployment of FREEDM Systems as compliance can be obtained with reasonable to moderate engineering efforts. There is one noteworthy exception in the *National Electrical Code* related to voltage levels which could potentially preclude the use of a residential SST distributing 380VDC.

HIL Testbed - The evaluation framework has been developed which allows a systematic method for comprehensive system performance evaluation of FREEDM functions. 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. In other work, encryption through an open-source tool was implemented on the transport layer for the communications between the DGIs through the OPNET simulated network.

The gradient based scheme for Volt/VAR control, developed last year, was finalized and tested on a PSCAD based platform. The CoDES algorithm can now solve the optimization problem in a distributed way as long as the communications network formed by the agents is connected; long-term battery wearing can be quantified to each kWh that it is charged and discharged.

LSSS Testbed – The level of PV penetration achievable with traditional means *vs.* that achievable within the FREEDM System has been compared; the model, built in PSCAD, can simulate most types of PV arrays on the market. Frequency control was integrated into the LSSS for islanding applications; SST controls were upgraded to permit simulation of bi-directional power flows.

2. Enabling Technology

Distributed Grid Intelligence/Reliable and Secure Communication - Work was accomplished in the replacement of DGI's PnP with Message Queueing Telemetry Transport (MQTT). The use of invariants was expanded to make various improvements and to investigate the effect of uncertainty on all derived invariants. Work continues with the development of a resilient neighborhood-watch algorithm to secure the Cooperative distributed Energy Scheduling (CoDES) algorithm. Work has been done to detect and isolate faulty sensors, and mitigate system effects due to faults.

FREEDM Architecture Working Group - The FAWG provides a system level dialog amongst all of the key center researchers. The result is a sustainable system architecture reference process that spans a diversity of domains and intellectual backgrounds; a major accomplishment is the present development of the shared Web Portal (Wiki) for FAWG Documentation and the development of simulation-based validation of FREEDM Use Cases. This Wiki provides a central point for all of the 200+ center researchers to find the expected architecture, timing and messaging expected between components. The FAWG has grounding in Systems Engineering and is the result of the Systems Engineering process of years 4-6.

Solid State Transformer – The work to improve the ruggedness, efficiency, and power density of the single phase 7.2 kV, 20 kVA, Gen-III SST continues using the TI advanced fiber optical HV sensor; test results are very promising in that the output signal follows the original very well with sensing delays of only 70 μs.

The desired input, 7.2 kV, has not yet been achieved, partly due to immature prototype SiC device technology at the MV level; an improved reliability, 2-stage cascade structure will be used in the interim. Switching losses have been lowered. The proposed predictive control is projected to achieve soft startup, overcurrent limiting, short-circuit fault protection, and automatic fault recovery without complex control strategies. The HIL testbed now uses several modeled SST nodes having both average models and detailed switching models.

Fault Isolation Device - Development of the GEN-III FID based on a Piezoelectric Actuated Fast Mechanical Disconnect Switch (PA-FMS) continues; mechanical testing was conducted to compare the static force *vs.* deflection of the modeled equipment with experimental results. A preliminary open-air test was performed to visualize and measure the physical distance between the contactors. A tiny vacuum leak in the test chamber was located and repaired; a good overall vacuum inside the chamber has been achieved. Voltage breakdown tests indicate a steady state breakdown voltage of ~15 kV with a maximum breakdown voltage of ~22 kV. Work on the electronics portion of the hybrid FID continues; a new fundamental theory has been developed which will guide the selection of devices. An approach for Basic Impulse Level (BIL) compliance for a solid state transformer and at the same time mitigating the switching frequency components of current injected into the distribution system primary.

DESD - The development of plug-and-play distributed resources for the AC and DC grid interface, specifically high-power, high-energy devices at the 380 VDC level continues. The full utilization of GaN devices into the Gen-III DESD has further improved efficiency. A Battery Management System has been integrated into the Gen-III DESD. A higher power level DESD development effort was initiated; expected power delivery is in 10 kW range. Lithium Titanate Oxide (LTO) batteries have been selected as the energy storage cells in the DESD system that will be integrated within the GEH testbed. Comparison testing indicates that the Lithium Iron Phosphate battery is *relatively* safe when penetrated or crushed compared with Lithium Cobalt Oxide (LCO) batteries, which in Center performed destructive testing, proved to be unsafe.

Fundamental Science

Post Silicon Devices - A novel SiC Merged-PiN-Schottky (MPS) rectifier is proposed to improve the trade-off between on-state and turn-off switching losses, improving SST efficiency. High temperature characterization of previously fabricated MPS devices is presently ongoing. The work demonstrates for the first time that the MPS rectifier is an ideal choice for diodes operating at elevated junction temperatures. The work to fabricate and to demonstrate normally-off Metal-Oxide-Semiconductor (MOS) GaN/AlGaN High Electron Mobility Transistors (HEMTs) power devices at the 50 A, 600 V level with an on-resistance of 1-2 mΩ-cm^2 continues. A lateral GaN P-N junction diode was successfully fabricated on AlGaN/GaN-on-Silicon substrate. The device demonstrates breakdown voltage of 135V (I_{off} = 1 μA) and forward current density 191 mA/cm^2 at 50 V when characterized at 200°C. Regarding packaging, a power module test package suitable for 200˚C testing of 10 kV SiC Diodes was developed and tested.

Systems Theory, Modeling and Control - A comprehensive state-variable model of the FREEDM System has been developed to allow for feasibility, stability and dynamic performance analysis of the physical construction. The SST's front-end rectifier output voltage reference has been found to be the deciding factor in extending the feasibility bounds of the system. The feasibility bounds have been utilized to determine the operational ranges based on the different loading conditions; methods are proposed to expand the operational range. When multiple SST systems are connected in a tree configuration, power sharing algorithms are proposed to maintain the feasibility of the total system. 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. A detailed and accurate analytical model has been developed based on the actual Gen-II SST hardware and DSP controls; the model has been validated through simulation. Models for dynamic studies in OpenDSS have been implemented.

The predictive control method was applied to the IEM layer of the FREEDM System in order to dynamically optimize the power references and operational cost. A visualization of the system's dynamical behavior utilizing Lyapunov exponents has been developed.

Education and Workforce Development: University Education - The undergraduate research and summer REU programs have continued to attract and engage exemplary students. In Year 8, over 8 industry member company visits were conducted at the Center headquarters with live broadcast webinar to partnering universities. Course sharing has continued among partnering universities. Center sponsorship of UG senior design project teams continued were expanded to students at NC State and ASU in Year 8. [See Volume I Section 3.1] Outreach continues to community colleges and other institutions with engineering programs.

Education and Workforce Development: Pre-College Education - Teachers participating in the RET program continue to have broader impact. The majority of RETs have reported that they transferred knowledge gained at FREEDM into their classroom course materials and student projects. Their summer experiences in the Center have enhanced their abilities to excite their students about engineering in their classrooms.

Education and Workforce Development: General Outreach - The Center has broadened K-12 participation by increasing its outreach efforts to state-wide school systems and by having an open invitation for middle and high school field trips. During Year 7, outreach events exceed expectations by engaging over 1,650 K-12 teachers and students. Students visiting the Center get the benefit of observing a working engineering lab and also interacting with professionals at all levels.

Education and Workforce Development: Diversity Advances in the Center – At the end of Year 7, Dr. Roy Charles was hired as the Center's first Diversity Director. This marked a significant change in the efforts of the Center's efforts to identify and attract diverse students to the undergraduate and graduate academic and research opportunities offered. Dr. Charles provides year-round attention to such efforts, and was instrumental in rewriting the Center Diversity Strategic Plan. Since the completion of the plan and its approval by the Site Visit team at the end of Year 7, Dr. Charles and the rest of the Center leadership have worked closely to put the plan into action. This year, the Center has reached a wider audience of prospective students through recruitment trips and targeted outreach, and continued efforts have strengthened the Center's position as a destination for advancing one's academic and research training. In year 8 there was a significant increase in undergraduate involvement in Center activities across nearly all diversity target populations. Additionally, the Center experienced a gain in the representation of Hispanic / Latino students that reversed the absence of students last year; and finally, after taking a second trip to the University of Puerto Rico at Mayaguez in the 2015 fall semester, the Center is seeing the rewards of its efforts with the enrollment of students in its EPSE program. The Center is pleased with these accomplishments and sees the opportunity for an even greater involvement of diverse students across all metrics that will result from a sustained recruiting effort.

Technology Transfer and Commercialization - The Center reported seven new inventions, fifteen patent filings and two awarded patents in Year 8. Startup companies include GridBridge, Bing Energy, General Capacitor and Harrison Analytic Technologies. FSU Licensee Oscilla Power became a finalist in the Wave Energy Prize sponsored by DOE. Breakthrough technologies developed under the Post Silicon Device Thrust and the SST Thrust moved closer to industry production with continued development.

International Partnerships/Collaborations - The Center continued official collaborative partnerships with ETH in Switzerland and RWTH-Aachen University in Germany. One student participated in foreign study at ETH in Fall 2015. Supelec in France also provided expertise for research in fundamental controls. The Center Associate Director also attended a two day smart grid consortium event in the United Kingdom to explore potential partnerships. The most substantial effort was to generate a Center to Centre research proposal with entities in Northern Ireland and the Republic of Ireland after a jointly hosted international energy research workshop held in Dublin, Ireland. Center students and staff also worked on international projects in the Dominican Republic and Colombia with partners Pos-En and Schneider. Lab tours were hosted for visitors from Japan, France, Thailand and China.

Center Infrastructure – Major infrastructure successes in year 8 include the continued support from the Dean's appointed research management advisor, Dr. Rajinder Khosla. Dr. Khosla brings a wealth of knowledge about managing large research profiles as well as having served as a former program manager for the NSF. The implementation of the Cluster Hire for Energy Economics, Energy Policy, Life Cycle Analysis, Energy Systems has served to provide critical gaps within the Center expertise and have already begun to provide strengths in the joint research proposal with Ireland call CREDENCE. This proposal is an example of the possibilities available as a result of this local expertise. The Center's Webinar program has reached new accolades within the past year with more webinars, more engaging speakers and more engaged audiences. The deepening of the relationship with PosEn for deployment of new DC Microgrids in select regions has enabled deeper relationships with other center partners, namely Schneider, ABB, and Toshiba as potential component suppliers. The practitioner model of having Pos-En employees within the facility much of the time has also served as a positive reinforcement of the relationship. The center has also been employing more distributed management to Center Directors and to Thrust Leaders, which has enabled a higher level of accountability at every level, provided a higher degree of engagement and also relieved center Directors to focus more on global strategy. Finally, center testbeds have achieved several significant upgrades, allowing them to become more critical to use by center members in the future and increasing the potential for higher membership numbers and levels.