Objective:

➢ To comprehensively demonstrate the stable operation of a radial, multi-bus, distribution system in islanded mode using droop control.
➢ To validate the operation of multiple SSTs operating in Islanded mode.
➢ This research poster focuses on the following technical aspects:
  • Development of control structure to ensure successful transition of SSTs from grid connected mode to Islanded mode.
  • Development of droop control for frequency control in Islanded LSSS
  • Successful demonstration of droop control in islanded LSSS

Technical Approach:

LSSS in Grid Connected Mode

LSSS in Islanded Mode

Building Block Module of SST in Grid connected mode

Building Block Module of SST in Islanded mode

Accomplishments:

Power Profile at 822 A and 858 A

Voltage Profile at 822 A and 858 A

State of Charge of DESD modules

Voltage Profile at 822 A

Next Steps:

➢ The primary LSSS objective of year 8 is to demonstrate successful plug and play with hierarchical and distributed droop control.
➢ Milestones met have been the successful operation of LSSS in islanded mode using droop control, and seamless transition of SSTs between grid connected mode and islanded mode.
➢ The following are the future goals of LSSS
  • Implementation of hierarchical control and distributed frequency control in LSSS.
  • Validate and integrate DRERs into LSSS and implementation of autonomous energy management control.

Potential Impact:

➢ This model forms a constructive and concrete platform for integrating frequency control into the LSSS for islanding applications.
➢ Additions to LSSS and distributed control will be delivered to the testbed level. This model helps in achieving the specified goals.
Objective:
- Verification of the protection system operation in ASU laboratory test bed.
- Verification of the protection system operation in the Hardware–in-the-Loop system in Florida including the effect of three phase fault caused voltage reduction.

Technical Approach:
Wireless directional differential protection detects fault and sends trip signals. The system is built with two commercially available SEL-351S relays and two SEL-3031 radio transceivers. The wireless communication link works with 9MHz mirrored bits connection, EIA-232 communication port connects the digital relay to the transceivers. The protection system was first tested in the ASU analogue test bed, the observed delay of the trip signal was less then 6ms. A more comprehensive tests were performed in Florida using the RTDS computers, which simulated the FREEDM Loop and initiated and controlled the tests. The test arrangement is shown in the enclosed figure. The measured trip time of FID for different faults are listed in the enclosed table. The average trip signal delay is less than 8ms. The communication worked well when the two SEL-3031 transceiver placed in two different buildings with a direct distance of around 75 meters.

Accomplishments:
Pilot wireless protection scheme performance of the HIL system have been validated. The typical delay of the digital relay detects the fault is 8ms. The voltage in the transmission line is close to zero when there is a symmetrical fault. The test proved that pilot directional differential protection can provide feasible and reliable protect for FREEDM loop.

Next Steps:
- The figure below shows the delay of the trip signal, voltage and the short circuit current. This delay can be further reduced.
- Development of backup protection for the FREEDM Loop.
- Developing a protection unit, which can be incorporated in the FID and eliminate the high cost of digital relays.

Potential Impact:
- Capabilities of the radio link wireless communication is reliable and effective over long distance
- The protection system can provide reliable interconnection with the DGI system
- Commercialization of the FREEDM system
Y8.HIL.1 Automated Analysis of Control Algorithms Using the HIL Testbed
Sindhuja Sundararajan, Mark Stanovich, Isaac Leonard, Harsha Ravindra, Mike Sloderbeck, Michael Steurer

Objective:
- Evaluate and characterize performance of control algorithms using real-time HIL techniques
- Develop a framework and guidelines for performance evaluation and characterization of control algorithms utilizing HIL Testbed
- Included in this framework is the creation of meaningful/relevant performance metrics

Technical Approach:
- Identify
  - Parameters that govern control performance
  - Response quantities to measure
  - Metrics for evaluating performance
- Establish range of parameters and intelligently choose meaningful and practical sample spaces (e.g., Latin Hypercube sampling)
- Extract generalized results (e.g., response surfaces)
- Automate testing procedures
- Exercise framework with FREEDM developed control algorithms

Accomplishments:

Next Steps:
- Explore effectiveness of other techniques to choose sample points
- Continue to improve usability of the HILTB
- Scale the cyber-physical capabilities of the HILTB to support simulation of hundreds of control nodes

Potential Impact:
- Unbiased, well-defined, and repeatable evaluation of control algorithms
- Tool for experimenting with and developing new control techniques
- Feedback for improving control algorithms and their implementation
- Expertise and capability from experts in HIL techniques is readily accessible to FREEDM Industry Partners via the HILTB thrust
Objective:

1) Implement the ECN feedback function in the simulated routers inside OPNET
2) Build a prototype realization for traffic rate regulation on mambas running DGI for the corresponding DGI function
3) Test the traffic regulation algorithm

Technical Approach:

1) The traffic monitoring module runs inside OPNET as a server, which compiles ECN messages when congestion occurs and send them to all mambas by multicasting
2) The traffic regulation module runs on mambas as clients. Traffic regulation is through interaction with the OS firewall through iptables rules
3) The rules increase or decrease the UDP packet delivery rate of the OS on the source terminals upon receiving the ECN notifications from OPNET
4) A closed loop control is thus formed to control the UDP packet delivery rate on the source terminals to adjust it for optimized network congestion adaptation
5) Program coding inside OPNET is C
6) Program coding on mambas is Python

Accomplishments:

1) The intended functions have been finished
2) The experiment results meet the goals set

Next Steps:

1) Tune the algorithm parameters in the traffic regulation module to find the optimal values for different network conditions
2) Integrate the OPNET module with the ECN function in DGI v3.0
3) Solve several OPNET compatibility problems for SITL UDP packet formats

Potential Impact:

1) No noticeable negative impacts have been observed on the mambas by the traffic regulation function on CPU load
2) The OPNET SITL module has some compatibility problems for real UDP traffic. Some packets cannot be well recognized to find the relevant information needed for the ECN messages. The problems will be solved as shown in the next step section.
Objective:

- To minimize power loss of FREEDM Systems
- To develop a decentralized Volt/Var Optimization (VVO) Method
- To implement the decentralized VVO on HIL testbed

Technical Approach:

- Problem Formulation
  \[
  \min f(V, \theta) = P_{loss} \\
  \text{s.t. } g(V, \theta, \mu) = 0, \quad V_{\text{min}} \leq V \leq V_{\text{max}}, \quad \text{voltage limits}
  \]

- Gradient Based Method
  \[
  \nabla f = \begin{bmatrix} \frac{\partial g}{\partial V_{\text{min}}} \\ \frac{\partial g}{\partial V_{\text{max}}} \\ \end{bmatrix} \lambda \\
  Q_{\text{SSST}}(k + 1) = Q_{\text{SSST}}(k) - \nabla f \cdot \beta
  \]

- A Master-Slave Based Control
  - Master
    - Calculates gradients and determine the optimal step-size
    - Sends the new updates to all slaves
  - Slaves – Group Control
    - Each VVC slave controls the nodes with similar sensitivity
    - After receiving gradients of the nodes under the same VVC slave, each VVC slave averages gradients and multiplied by step-size to get \( \Delta Q_{\text{SSST}} \) and then send the updated control command \( Q_{\text{SSST}} \) to the nodes

Test Results:

- The decentralized VVO is implemented on a 7 Node HIL system

Conclusions:

- The decentralized VVO is able to maintain acceptable system voltages
- The decentralized VVO is implemented successfully as part of the DGI systems
Objective:
To develop and demonstrate the Cooperative Distributed Energy Scheduling (CoDES) algorithm for FREEDM system (Fig. 1) with the following features:

• Consider various system operation constraints to optimize different application scenarios (e.g., next operation interval dispatch schedule, real-time re-dispatch)
• Fully distributed by utilizing peer-to-peer communication
• Increase robustness to single point of failure and communication link failures
• Improve system scalability
• Ensure the system participants’ privacy

Technical Approach:

• Formulate the system objective as a convex optimization problem
  \[
  \min_{u(t), t=1, \ldots, T} \sum_{t=1}^{T} C(x(t), u(t), w(t))
  \]
  o \(x(t)\): System states
  o \(u(t)\): Controllable Inputs
  o \(w(t)\): Uncontrollable Inputs

• Utilize the distributed optimization technique to solve the optimization problem
• Four-step algorithm evaluation
  o MATLAB simulation
  o DGI platform implementation and evaluation
  o HIL testbed integration and demonstration

Accomplishments:
• Developed the second version of CoDES algorithm that:
  o Calculates the charging/discharging schedule of the DESDs that minimizes the system total electricity bill for the next 24 hours
  o Considers DESD efficiencies and degradation cost
• Implemented the CoDES algorithm in the DGI 2.0 platform
  o Calculate the 24-hour schedule within 30 seconds on single Linux machine running 4 DGI instances
• Deployed the program into single board computers (Fig. 2)
  o Calculate the 24-hour schedule within 3 minutes for a 4-node system

Next Steps:
• Investigate the real-time re-dispatch based on the CoDES result and system real-time operations
• Integrate the CoDES algorithm into HIL testbed to evaluate performance

Potential Impact:
• Preliminary result showed a 35% operation cost (total electricity bill) reduction comparing coordinated and uncoordinated operation scenarios for FREEDM system (Fig. 3)
Objective:
- Operate the SST as an Energy Router by optimizing its power reference, $P_{grid}$, according to a hybrid day ahead and real-time energy market

Technical Approach:
- The Energy Cell is scheduled a day ahead and then updated in one minute real-time increments
- Frequency is filtered according to a moving average

Equations:
$$\text{Min} \sum_{t=0}^{1 \text{ day}} P_{grid}(t) \times \text{Price}(t), \quad \text{where}$$
$$P_{grid}(t) = P_{load}(t) - P_{PV}(t) + P_{charge}(t) - P_{discharge}(t)$$
$$\text{Price}(t) = C_{TOU}(t) + C_{frequency}(t)$$

Accomplishments:
Inputs and simulation results of the proposed strategy over 24 h:

- Load Cost: $5.2043$
- Load with PV: $4.1852$
- Final Price with DESD and ED: $2.1692$
- Algorithm Savings: $2.0160$

The real-time algorithm uses a rule-based method which considers the historical trends of the Energy Cell. Version 1 ready to implement

Next Steps:
- Consider battery lifetime and a transactive energy routing approach
- Extend the rule-based algorithm to apply to additional seasons, homes, and load patterns

Potential Impact:
- Real-time frequency based pricing allows Energy Cells to respond to frequency deviations, providing an ancillary service and increasing grid reliability
- An Energy Market for the Energy Internet: A competitive market, supporting bi-directional flow of power, benefitting both energy producers and consumers
**Objective:**
Control SST like a synchronous machine, and therefore achieving scalable, autonomous and distributed control of FREEDM System

**Technical Approach:**
- Volt-Var regulation mimics excitation system in SM
- Frequency regulation mimics rotor Swing Equation
- Novel dual droop control for any load, DER and DESD connected to SSSM

**Accomplishments:**
Finished the verification of SSSM’s functions and behaviors in a single SST/single Energy Cell testbed

**Next Steps:**
- Simulation and Experimental verification with multiple prototypes in Power System

**Potential Impact:**
- **Grand Challenge Solution:** Achieve scalability, stability and robustness for multiple SSTs/FREEDM systems
- **Grand Challenge Solution:** Achieve 100% penetration of renewable energy, dedicated design for Photovoltaic generation system with smoothed output and frequency support

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**Experimental results of low voltage testbed:**
- CH1: SST output power $P_{out}$ (1kW/div)
- CH2: SST frequency $f_{SSSM}$ (0.04Hz/div)
- CH3: DC bus voltage $v_{dc}$ (10V/div)
- CH4: DESD current $i_{DESD}$ (2A/div)
- X-axis: time $t$ (400ms/div)
Objective:
Develop a smart home energy management system with realistic and controllable load and distributed renewable energy resource. This system will serve as the lowest-level energy cell in the 1-MWh DC/AC hybrid microgrid test system (Green Energy Hub), as shown in Fig.1.

Technical Approach:
- Controllable and metered appliances
- Graphical User Interface
- Load Forecasting and Scheduling Algorithms
- Coordination with Energy Storage and Distributed Generation Resources

Accomplishments:
A fully functional smart house powered by AC/DC source
- Load emulator and appliances controlled by smart switches wirelessly by a ZigBee network
- Energy storage device operation cooperated with smart load through a MQTT client
- HEM algorithms implemented for peak shaving and minimizing energy bills under different rates (Fig.2 & 3)

Next Steps:
- Improve household load model and forecasting
- Coordination with other houses within the 1-SST microgrid and provide grid service
- Investigate impact of high penetration of DRER

Potential Impact:
- Provide a highly flexible and realistic test system for developing, testing, and validating the performance of theoretical control strategies, algorithms, and rate structures
- Give realistic estimation on costs and performance for cost benefit studies
**Objective:**

- Demonstration of three grid connected Low Voltage scaled SST (LV SST) with DESD (BESS) in GEH testbed
- Demonstrate islanding and black start functionality in GEH based microgrid platform
- Inter-SST Communication

**Technical Approach:**

- Black start SST control
  - Droop method is used for seamless black start
  - Capacitor voltage of LCL input filter is controlled
  - DESD and Dual Active Bridge (DAB) regulate high voltage side dc bus
- Load SST control
  - Conventional current controller is used to regulate power factor and high voltage side dc bus
  - DAB converter regulates low voltage side dc bus

**Accomplishments:**

- Design, implementation and experimental validation of three LV SST testbed
- Control strategy development and validation of multiple control modes of three LV SST
- Implemented MODBUS communication using Zigbee

**Next Steps:**

- Reconnecting Capability of Multiple SSTs
- DRER Integration

**Potential Impact:**

- Develops Controls for SST based system
- Broadens Ability to Share GEH Resources and Technology
Objectives:

This project is a cost to benefit analysis of the FREEDM distribution system. **Cost analysis of a FREEDM system:** versus a conventional system. **Benefit analysis:** determine the main benefits the FREEDM system offers and quantify these benefits over. **Tradeoff / sensitivity analysis:** tradeoff of performance versus cost, and sensitivity of the study is accomplished by an innovative probabilistic model.

Technical Approach:

- Identify the functions of the FREEDM system that will provide new and / or additional benefits to distribution systems.
- Develop a mapping between the functions to identify the benefits.
- Quantify the benefits and costs, and model the benefits and costs probabilistically (i.e., with a probability density function).
- Do a cost-benefit analysis over the lifetime of the FREEDM system. This entails a calculation of the payback period probabilistically (e.g., the probability density of a variable that is a function of several probabilistic variates).
- Evaluate the tradeoff of use of FREEDM components in the system – again in probabilistic terms.

Accomplishments:

- Mapping of functionalities to benefits, and cost evaluations of the SST, FID, and conductors.
- Evaluation of the value of reliability enhancements.
- Calculation of the break even point for investment in FREEDM assets.

Next Steps:

- Complete cost to benefit analysis including the tradeoff of inclusion of FIDs.
- Improve the probabilistic models.
- Document the project, including a technical paper on the innovative probabilistic method used.

Potential Impact:

- Justification of the cost of investment in the FREEDM system.
- Commercialization of the FREEDM system.
Objective:

FREEDM Deployment under different PV penetration scenarios.

Scenarios:
• Case I: Full FREEDM Deployment for high PV Penetration
• Case II: Partial FREEDM Deployment for high PV Penetration
• Case III: Partial FREEDM Deployment for Commercial Scale PV

Technical Approach:

• Conduct Impact Study
• Quantify the Benefits
• Monetize the Benefits

Accomplishments:

Impact Assessment:
• Case I: Full FREEDM system for 80% PV Penetration
  ➢ Voltage Violation—no issue in either systems.
  ➢ Voltage Variation – VVI improved by 21.75% with FREEDM.
  ➢ Voltage Unbalance – VUI improved by 11.58% with FREEDM.
  ➢ Energy Loss – 73.84MWh saving due to FREEDM.
  ➢ Peak Demand Reduction – 1.8% reduction in 15-min peak and 30.37% energy demand reduction.
• Case II: Partial FREEDM deployment for 90% PV Penetration
  ➢ Voltage Violations– 767 annual incidences of voltage violations of 15-min duration with Base System; FREEDM has none.
  ➢ Voltage Variation – VVI improved by 20.52% with FREEDM.
  ➢ Voltage Unbalance – VUI improved by 20.71% with FREEDM.
  ➢ Energy Loss – 86.06MWh saving due to FREEDM.
  ➢ Peak Demand Reduction – 2.13% reduction in 15-min peak and 33.98% energy demand reduction.
• Case III: Partial FREEDM deployment for a Commercial Scale PV
  ➢ Voltage Violations– 35,360 annual incidences of voltage violations of 15-min duration with Base System; FREEDM has none.
  ➢ Voltage Variation – VVI improved by 28.25% with FREEDM.
  ➢ Voltage Unbalance – VUI improved by 13.10% more with FREEDM
  ➢ Peak Demand Reduction – 2.48% reduction in 15-min peak and 38.44% energy demand reduction.

Monetizing the Benefits:
➢ Annual benefit in terms of enhanced reliability is $2045 for full deployment case.
➢ Annual benefit of $6900 due to peak demand reduction was observed.
➢ Total annual benefit due to customer participation is estimated to be $530.
➢ Annual savings of $3482 due to reduced energy loss from Volt/Var Control.

Next Steps:

• Quantify other Benefits such as system resiliency, plug and play etc.
• Monetize benefits on voltage violation, voltage variation, voltage unbalance etc.
• Different circuits with different load and PV profiles.

Potential Impact:

• Identify cases for the early deployment of FREEDM System.
• Provide guidelines for performing the impact studies for FREEDM system deployment.
Y8.GEH2.3 FREEDM Cost Benefit Analysis based on Detailed Utility Circuit Models
Lisha Sun, Daixi Li, David Lubkeman, Mesut Baran

Objective:
- Simulate a real circuit for cost benefit analysis of FREEDM application scenarios using OpenDSS
- Perform quasi-static time series analysis on real distribution circuit provided by utility
- Provide technical cost and benefit input into comprehensive cost/benefit spreadsheet developed in parallel project

Technical Approach:
1. Circuit Characteristic
   - 3 miles
   - 12.47kV
   - 6,900 kW peak
   - 97% efficiency
   - 299 Transformers
   - 1240 Customers
2. Quasi-static Time Series analysis for a year using OpenDSS

Accomplishments:
- Case I: Full FREEDM Deployment for High PV
  - 80% residential PV
  - 294 SSTs
  - Energy (Year) Peak kW Demand Volt Violation (duration-yr) Δ Energy Losses (MWh) Circuit XFMR Total
    -38% -2.3% 105 hrs → 0 -29 83 54
  - Voltage Violation: -38% -2.3% 105 hrs → 0
  - Δ Energy Losses (MWh): -29 83 54

- Case II: Partial FREEDM Deployment
  - (i) High PV Penetration
    - 43% residential PV cluster
    - 25 SSTs to fix overvoltage violation
  - Energy (Year) Peak kW Demand Volt Violation (duration-yr) Δ Energy Losses (MWh) Circuit XFMR Total
    -21% -1.8% 237 hrs → 0 -19 8 -11
  - Voltage Violation: -21% -1.8% 237 hrs → 0
  - Δ Energy Losses (MWh): -19 8 -11

Next Steps:
- Analysis on circuits at voltage levels other than 12.47 kV
Objective:
Conduct a case study on the use of utility scale storage in a FREEDM system and quantify cost and benefits.

Technical Approach:
I. Simulate the use of a storage at a substation to smooth the total demand under different PV penetration scenarios.
II. Quantify the potential benefits provided by utility scale storage:
   - Reduction on generation ramp rate
   - Reduction on peak demand
   - Reduce intermittency brought by DERs
III. Use cases considered:
   1) Smoothing to reduce ramp rates
   2) Energy arbitrage

Accomplishments:
- Quantified the 15 minute ramp rate reduction based on simulation;
- Provided storage size based on Case 1;
- Quantified the hourly ramp rate increment.

Next Steps:
- Define impact metrics based on simulation.
- Monetize the costs and benefits of all potential deployment scenarios.
- Optimize the size of the battery.

Potential Impact:
- Determine a use case for utility scale storage at distribution level.

Conclusions:
1) PV increases 15 minute maximum ramp rate from 15kW/min to 59kW/min.
2) Utility scale storage helps to reduce the ramp rate to 34kW/min. A 1800Ah battery is needed for smoothing purpose.

Conclusion: PV increases hourly ramp rate considerably.
**Objective:**
Perform a comprehensive cost-benefit analysis of the FREEDM system.

**Technical Approach:**
- Developed deployment scenarios:
  - Partial Deployment
  - Full Deployment
- Identified primary benefit categories:
  - Increased solar PV penetration
  - Improved conservation voltage reduction (CVR)
  - Reduced circuit losses through volt-var control (VVC)
  - Improved feeder reliability
- Used power flow simulations and literature to monetize benefits of the FREEDM system
- Created a decision support tool to examine tradeoffs
- Focused on cost and benefits from the utility perspective

**Accomplishments:**
- Costs and benefits for full and limited deployment
- Negative NPV for all scenarios due to high initial cost
- Identified parameters that have largest impact on NPV

**Next Steps:**
- Monetization of other benefit categories (resiliency, price signals, DC plug-n-play)
- Consideration of different electricity markets and regulatory schemes.

**Potential Impact:**
- Identify configurations most suitable to first adopters
- Set cost-performance targets for FREEDM design
- Use economics to inform commercialization and deployment of FREEDM components

**Key Results**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Full Deployment</th>
<th>Partial Deployment</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV</td>
<td>$ - 81,000</td>
<td>$ - 15,000</td>
</tr>
<tr>
<td>IRR</td>
<td>0.5%</td>
<td>6.7%</td>
</tr>
<tr>
<td>DPBP</td>
<td>22 years</td>
<td>9.7 years</td>
</tr>
</tbody>
</table>

Assumes 10% discount rate, 25-year component lifetime, constant annual benefits

**Sensitivity Analysis**

- Price of SST ($3,878)
- Discount Rate (10%)
- Price of 1Φ FID ($5,426)
- Value of Solar ($33/MWh)
- Electricity Price ($50/MWh)
- CVR (0.6%)
- VVC (1.4% E)
- Lifetime (25 years)
- Outage Cost (DISCO) ($14/cust-...)
- Capacity Price ($100/MW)
- Price Signals (30% Pd)
Objective:

Conduct further cost-benefit analysis and voice of the customer studies to identify trade-offs and value propositions of DE for America.

Technical Approach:

Collect data from utilities, smart grid and storage industries to assess business models. Find a balance between technical prowess and commercialization.

Accomplishments:

Stakeholders Interviewed
- Electric Utilities
- Smart Grid
- Government
- Renewable Energy Installers
- Univ. & Research Centers
- Commercial Developers

What issues keep you up at night?
- Storage
- Maintenance
- Business Models (PV)
- Resiliency & Reliability
- Peak load demand
- Customer participation
- Change management
- Smart grid development

Path to Energy Internet

Energy Internet

Next Steps:
- Commit to partners to launch pilot projects.
- Establish relations with utility commissions in NY, CA, HI.
- Commercialization – pricing, ownership, manufacturing.

Potential Impact:

Advance FREEDM system towards practical integration into America’s existing grid infrastructure.