2.5 Green Energy Hub

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2.5.1 Intellectual Merit and Impact

The objective of the Green Energy Hub (GEH) testbed is to develop a physical, fully operational, FREEDM System at a scale that is, (1) sufficient to demonstrate functionality of key components of the system, (2) validate the operational concept, and (3) confirm the soundness of the key underlying theories. The physical system also serves as a platform for the assessment of the communications and control functions and a testbed for future hardware and software systems that complement the FREEDM System.

The Center reorganized the overall testbed structure based on inputs from the Year 3 SVT and Center research team. Four major salient functions are identified for the FREEDM System: Plug-and-Play (PNP), Intelligent Energy Management (IEM), Intelligent Fault Management (IFM) and Intelligent Power Management (IPM). The FREEDM testbeds are organized to facilitate the development and demonstration of these features. The Green Energy Hub at NC State forms the third testbed with the objectives of (1) integrating Center-developed technologies into the Green Energy Hub (GEH) and demonstration of the FREEDM system functionality, (2) serving as a testbed for third-party technology integration and demonstration site, and (3) powering the ERC headquarters with green and sustainable energy.

2.5.2 Technical Approach

Before Year 7, the focus in the Green Energy Hub was on the testing and demonstration of the FREEDM component building blocks. This included demonstrations of the SST (Gen I, Gen II), FID (Gen I, Gen II), DESD (AC and DC), DRER (PV, Wind) and Residential Customer Load Emulator. Starting in Year 7, the focus was expanded to include multi-SST applications with an emphasis on energy management. Year 9 and 10 activities have continued with this theme, with projects involving a multi-SST testbed, single-SST residential demonstration, integration of IPM and IEM applications and a demonstration of multi-SST islanding and black start operation. These activities are discussed in more detail below.

2.5.3 Multi-SST Medium Voltage Testbed

The overall objective of this activity is to support an integrated GEH demonstration of the FREEDM System by developing a fully functional, efficient and reliable multi-SST medium voltage (MV) testbed. The main objectives include the development of three low-voltage 10kVA SSTs connected to 277V/12.47kV FREEDM transformer as a working test platform with scalable and configurable SiC power electronic building blocks for integrated GEH application demonstrations. For the 10kVA low-voltage SST, a SiC power module with three half-bridge, gate drives, thermal management, digital control and protection were holistically designed as a SiC-PEBB, as shown in Fig. 1. The AC-DC grid converter and DC-AC split-phase inverter shown in
Fig. 2 share the standardized hardware and control interfaces. The low-voltage SST is mounted in an IP54 enclosure for the outdoor installation. Fig. 3 shows the photos of the 10 kVA SiC SST prototype.

Fig. 1: SiC PEBB structure of 10 kVA SST.  
Fig. 2: SiC SST using PEBB with AC and DC interfaces.

Fig. 3: Photos of 10 kVA SiC SST prototype

The digital control platform, as shown in Fig. 4, uses commercially available DSP boards (TI 28377S) with isolated current sensors and isolated voltage sensors. The system-level communication structure is shown in Fig. 5 which features CAN communication between Battery Management System and DSP, MODBUS communication between DSP and DGI in the ARM board, and MQTT communication between DGI nodes.

Fig. 4: Photo of the digital control hardware.  
Fig. 5: Communication Structure.

Fig. 6 show how the SSTs are interconnected to form a three unit FREEDM system. The primary side of the SSTs interconnect into a single-phase 277 V supply which includes impedances to represent typically supply-side line impedances. The secondary of each SST is connected to a combination of AC and DC
devices, at either 380 V DC or 240/120 V AC. The devices include Distributed Energy Storage Devices (DESDs), power supplies to represent distributed generation sources or electronic load banks to represent residential load. Each SST has an associated Distributed Grid Intelligence (DGI) note for hosting FREEDM distributed applications.

![Distributed Grid Intelligence Node](image)

2.5.4 FREEDM Single-SST Residential Demonstration

The objective of this task is to develop a detailed residential test node for a 10kVA Solid State Transformer (SST) as envisioned in the FREEDM System. This test node provides the backbone and architecture to validate and test center developed DESD, Plug and Play DRER and DGI/RSC as well as developments from the SST team. Activity has focused in four areas: (1) Development of home energy management functionality, (2) Developing the wiring interface between the SST and household components, (3) Selection of a portable FREEDM demonstrator platform and (4) Integration of various software systems.

Previous Year 7 and 8 effort focused on building up a smart home demonstration with typical home appliance loads. This smart home can be powered by either conventional AC service or an SST. The house features an HEMS system with graphical interface that can monitor and control AC loads. The HEMS system interfaces with the SST, monitors PV system output, controls load and dispatches energy storage. Various energy algorithms such as time of use rate optimization and peak energy response have been implemented. The house has been augmented recently so it can serve as a thermal chamber for testing heating and cooling load applications as well. An ECOBEE smart thermostat facilitates the temperature and humidity control.
An overview of the various FREEDM devices and software systems being integrated together is shown in Fig. 7. A LabVIEW user interface monitors all data from FREEDM devices using data extraction from XML log files generated by MQTT clients running in SCADA. Each FREEDM device runs its own MQTT client that will publish or subscribe to any data it needs. The SCADA MQTT client only monitors the status of those data in this monitoring system.

2.5.5 Wind DRER

The wind turbine emulator DRER provides rotational renewable energy for the FREEDM system as a distributed renewable energy resource (DRER). A 10 Hp wind turbine emulation prototype has been built, as shown in Fig. 8a. The wind turbine emulator consists of an induction motor and programmable drive, and a permanent magnet synchronous machine (PMSM) used as generator. A back-to-back full power converter and its controls is based on DSP28335. The wind turbine prototype communication with FREEDM SCADA system through PC104 implemented with FPGA is also realized. Wind turbine mathematical modeling analysis has been completed and hardware implementation under various wind speed is tested. The emulator performance under various wind speed, static and dynamic response test results has been evaluated. The emulation control algorithm is implemented in Microcontroller dsPIC24F. The passivity-based PI control for the wind DRER system has also been developed [5].

This wind DRER provides a flexible platform to study wind renewable system inside the GEH laboratory. System level power management strategy has been performed with the SST, other DRER, and distributed energy storage devices (DESD). Fig. 8b shows the experimental results of wind DRER.
connected with the SST at the LV DC bus and supplying varying wind power generated with varying wind speeds while keeping the LV DC bus constant [6.7].

Fig. 8a: Wind DRER hardware prototype;  
Fig. 8b: Wind DRER operation with power injection into HV AC side under varying wind speeds and wind power generation

2.5.6 Multi-SST IPM and IEM Applications

The overall objective of this task is to demonstrate multi-SST IPM and IEM applications based on DGI in the Green Energy Hub. This effort is broken into two subtasks: (1) Decentralized Volt/Var Control and (2) Real-time Energy Dispatch.

Volt-Var control (VVC) is one of the main real-time control functions on a distribution system. Within the last three years the focus has been on development of decentralized control schemes for VVC. Decentralized schemes make use of the DGI to facilitate actual implementation, and thus achieve the main benefits of a decentralized control. This year’s efforts on VVC has focused on migrating the VVC to HIL and GEH testbeds and test the performance of the method. The VVC module has been implemented in DGI 2.0. For master-slave control scheme, communication between two DGI nodes has been established. Also, to receive data from the feeder, an interface between the DGI software and HIL system is needed. Fig. 9 shows how the VVC on DGI interact with the HIL system. Data exchanges shown in the figure are as follows: (i) Send/receive float number and/or string between a DGI node and HIL system; (ii) Array data exchange between DGI nodes so that Master can send data to Slaves and Slaves can receive the array sent by Master.
For the energy dispatch, an offline CoDES [3] algorithm has been developed in Y7 to calculate the 24-hours charging/discharging schedules of the DESDs, using day-ahead forecast profile. However, when the system approaches real-time operation, the actual device status might deviate from the forecast profiles. In order to handle this mismatch, the Load Balancing algorithm [4] previously developed by MS&T is utilized. The system framework of integration of CoDES and Load Balancing algorithms is shown in Fig. 10. The scheduling module uses the day-ahead forecast information to determine the optimal scheduling point for the coming 24 hours (1-hour resolution). When the GEH system approaches real-time operation, the DGI nodes collect real-time system status from the “Data Management Module”, and execute the load balancing algorithm to determine the next 5-minute operation status for the SST being controlled. The two different control time frameworks correspond to the day-ahead and real-time energy market, respectively.

Fig. 9: VVC for HIL system

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Fig. 10: CoDES algorithm with real-time operation

2.5.7 Multi-SST Islanding

The overall objective of the Low-Voltage Solid State Transformer (LV-SST) islanding test effort is validation of three LV-SSTs tied to MV FREEDM lab GEH testbed with DRER (PV) and DESD (BESS – Battery ESS). Functionalities of SST such as bidirectional power flow, islanding, and black start can be developed and verified with the LV-SST testbed. In Fig. 11, a circuit diagram of the low-voltage scaled multiple-SST testbed is shown. It consists of three LV-SSTs, two DESDs, one DRER, and a FID.
The islanding strategy is based on the well-known droop method that is used widely for the UPS or the Distributed Generation (DG) unit. Since the operation point of SST changes in a wide range, a modified droop method is developed by fully utilizing the communication capability of the FREEDM system. The FID collects data such as active power, residential load, and State Of Charge (SOC) of DESD and determines the reference of the active power of each islanding SST according to a proposed algorithm. Fig. 12a and Fig. 12b show the experimental results of the autonomous islanding operation of the multiple-SST system. The FID is opened at 0.2 sec and the PCC current becomes zero. The power flow of the islanding SSTs are changed at the instance and the load SST experiences no interruption.

FID

Fig. 11: Circuit diagram of the low-voltage scaled multi-SST testbed

Fig. 12a: PCC current waveform during islanding operation

Fig. 12b: Active power waveform during islanding operation

2.5.8 Distributed Grid Intelligence (DGI) Integration

FREEDM has developed a Distributed Grid Intelligence (DGI) software platform for hosting distribution management applications. These applications run in a distributed system that consists of multiple Solid-State Transformer (SST) and Fault Isolation Device (FID) nodes. A GEH goal is have integrated this platform into the GEH SSTs, enabling both power and energy management algorithms based on plug-and-play energy storage and distributed generation devices. The DGI Integration task involves implementing
the DGI communications scheme shown in Fig. 13. The MS&T team has 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 which are applications for IEM or IPM algorithm. An DGI application will get load information or other status from SST through SST’s own MQTT component and same way that application will send command to any FREEDM smart energy storage device using that device’s own MQTT component. Applications also might need the forecast or historical data, so an enterprise interface for DGI has been implemented. The main objective of this interface is to display and analyze the data in a SCADA system.

Fig. 13: GEH Data and Control Communications

2.5.9 Strategic Plan

Fig. 14 shows the strategic plan for the GEH that has been in place for the last three years. The first stage of GEH development focused on the integration of a single SST node. The second stage of GEH development involved integrating multiple SSTs (Gen I and II), FIDs (Gen I and Gen II) and FREEDM devices such as the DESD and DRER. Focus for the final stage has shifted to multi-SST and FID applications for energy management, fault management and system applications for power management that utilize DGI-based distributed algorithms.
2.5.10 Unique Approaches

The GEH test bed represents a small-scale setup of a working FREEDM System. This enables researchers to test and evaluate various aspects of how the hardware and software is integrated together to form a working system.

2.5.11 Best and Most Frequently Cited Papers:

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.


2.5.12 Key Graduate/Graduated Students

Dr. Navid Rahbari Asr, PhD 2015, First Employment: Ford Motor Company

Dr. Yonghwan Cho, PhD 2017, First Employment: Analog Devices

Jimit Doshi, MSEE 2015, First Employment: Tesla Motors

Dr. Rui Gao, PhD 2017, First Employment: Eaton Corporation (FREEDM Industry Member)

Dr. Sarah Hambridge, PhD 2017, First Employment: Grid Singularity

Dr. Kazi Mohammad ul Huq, PhD 2015, First Employment: Quanta Technology

Dr. Yue Shi, PhD 2018, First Employment: ABB (FREEDM Industry Member)

Jiahong Yan, PhD student

Dr. Yuan Zhang, PhD 2016, First Employment: Ford Motor Company