Y9.GEH1.1 Multi-SST Medium Voltage Testbed

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1. Project Goals

The overall objective of this project is to support an integrated GEH demonstration of the FREEDM System by developing fully functional, efficient and reliable multi-SST medium voltage (MV) testbed. The specific task objectives for this year include:

- Development of three preliminary 10kVA SSTs connected to the 277V/12.47kV FREEDM transformer as a working test platform with scalable and configurable SiC power electronic building blocks for the integrated GEH application;
- Design and verification of the local controller for each SST and communication interface to manage the setpoint of the local controller from global controls through DGI-enabled ARM board;
- Testing and validating the residential PV/storage system integration including 5kW distributed energy storage devices (DESD) and 5kW FREEDM distributed renewable energy resources (DRER);
- Demonstration of multi-SST power management (Volt/Var) and energy management (CODES) functionality in a reasonably realistic GEH environment with impedance variation;
- Replacement of preliminary SST with modular medium voltage SST using commercially available SiC semiconductors to improve system efficiency and power density by eliminating the low frequency bulky transformer for delivery in Q2 Y10.

2. Role in Support of Strategic Plan

As a key enabling technology for FREEDM System Center, the multi-SST MV testbed serves as a platform for fundamental science technologies, such as wide bandgap power devices for utility distribution system and smart grid applications. It also provides multiple DC and AC power interfaces and communication interfaces for center developed and/or commercially available DESDs, DRERs and smart loads. Based on the priorities identified by the FREEDM leadership team (LT) for Year 9 and the feedback from the Y8 site visit team, the role of the multi-SST MV testbed is to reliably demonstrate that it can be delivered and used as a practical testbed for the intelligent power management (IPM) and the intelligent energy management (IEM) functionality verification.

3. Fundamental Research, Technological Barriers and Methodologies

The fundamental research for the multi-SST MV testbed is to develop a reliable, high power density, efficient and cost-effective grid-side converter and split-phase inverter using SiC power devices.
The technological barriers need to be addressed:

- Modularized design with holistic integration of SiC power module, gate driver and thermal management;
- High efficiency topology for SST with DC and split-AC interfaces;
- To achieve highly reliable start-up and fault protection of the whole system;
- Multi-SST control structure coordinating the autonomous control and the distributed intelligence through communications.

The technical methodologies include:

- Generation of the detailed system specifications;
- System level simulation followed by multi-physics simulation analysis to meet design specifications and to identify critical component ratings;

- Optimization of the overall system performance by integrating the electrical, mechanical, thermal and control design;
- Fabricate and test the hardware and software of 10 kVA SST using SiC power electronic building block method.

4. Achievements

4.1 SiC Power Electronics Building Blocks (SiC PEBB) for SST Application

The Power Electronics Building Block (PEBB) concept is a platform-based approach where basic building blocks are consistent with one another, have a defined functionality & standardized hardware and control interfaces. Modular and hierarchical design principles are the corner stones of the PEBB concept. Adoption of building block(s) that can be used for multiple applications, results in high volume production, reduced cost, losses, weight, size, and engineering effort for the application and maintenance of power electronics systems. In this project, 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.

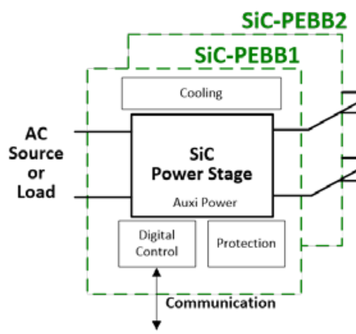

Fig. 1. SiC PEBB structure of 10 kVA SST.

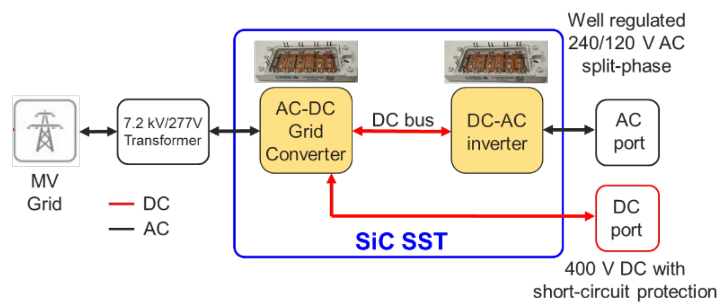

Fig. 2. SiC SST using PEBB with AC and DC interfaces.

4.2 Development of 10 kVA SiC SST hardware

The wall-mount IP54 enclosure is implemented for the outdoor installation. The system layout of the SiC SST is virtually assembled before the components are made using a 3D model. Fig.3. shows the photos of 10 kVA SiC SST prototype, which verified that hardware development of 10 kVA SiC SST with AC and DC interfaces was finished within 6 months because the adoption of a power electronics building block (PEBB) method effectively saves development time.

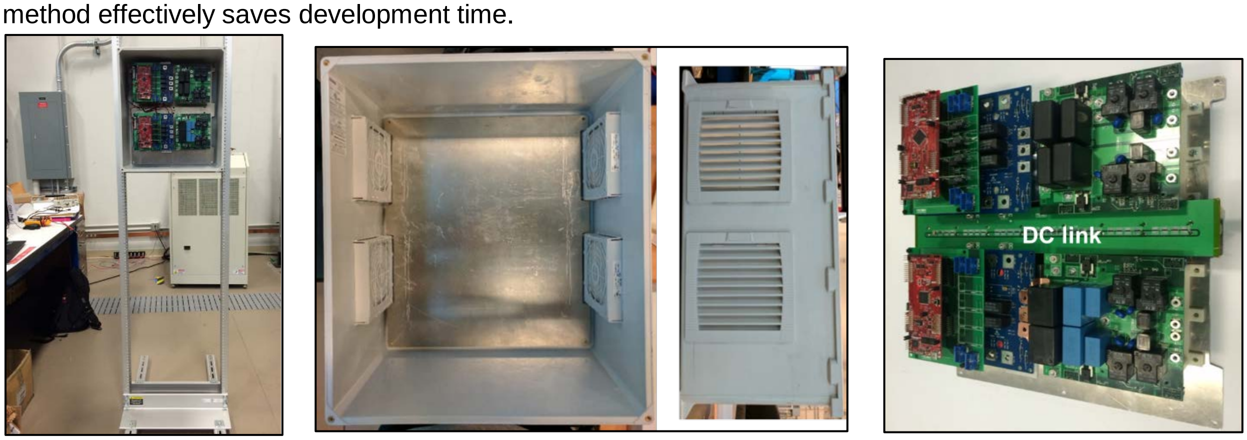

Fig. 3. Photos of 10 kVA SiC SST prototype

4.3 Digital control platform ready

The digital control platform using a commercially available DSP board (TI 28377S) with isolated current sensors and isolated voltage sensors was designed, fabricated and tested as shown in Fig. 4. One example of system-level communication structure is shown in Fig. 5. The CAN communication between Battery Management System and DSP, MODBUS communication between DSP and DGI in the ARM board, and MQTT communication between DGI and DGI are preliminarily tested.

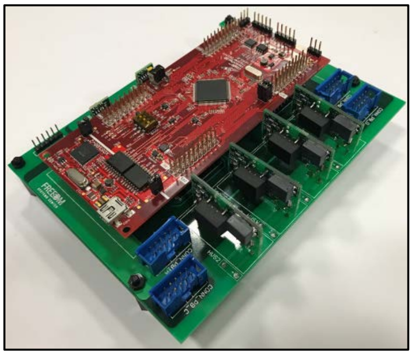

Fig. 4. Photo of the digital control hardware

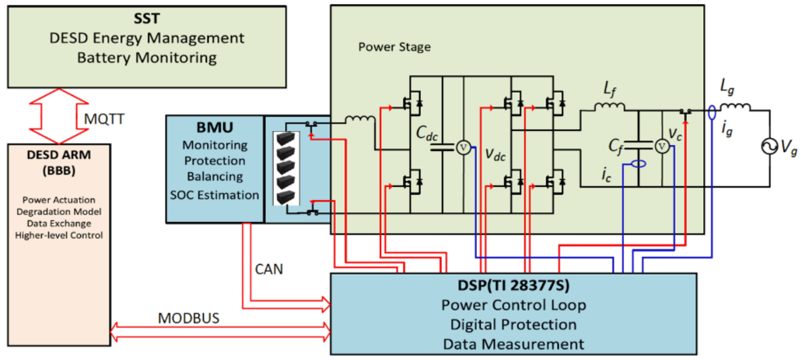

Fig. 5. Communication Structure

4.3 Passivity-based predictive current control for stabilizing multiple grid-tied converters

Interaction among multiple grid-tied converters (rectifiers or inverters) can be evaluated using frequency domain passivity theory. A predictive current control method is proposed to stabilize the interconnected multi-SST using distributed autonomous control under the conditions of the grid impedance variation. The two SST network achieves stability by using the proposed predictive controller, which is demonstrated via frequency domain analysis and system simulation with two voltage source converters (VSCs). Moreover, the passivity-based predictive current control is scalable to N number of SSTs. Fig. 6 describes that the controller utilizes the sampled value of v_c at every switching period to compensate for its effect in the power stage, thus eliminating the destabilizing effect of converter input admittance due to the grid impedance large-range variation.

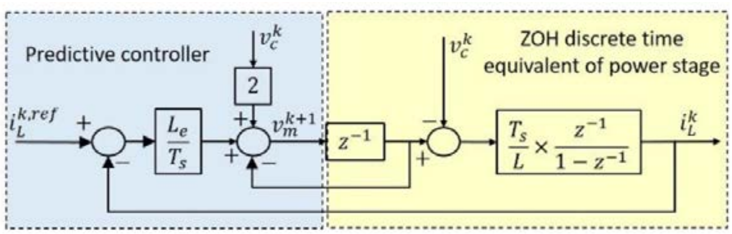

Fig. 6. Discrete model of power stage with predictive control

4.4 Three independent control loops of split-phase inverter

In this project, three independent feedback control loops of the split-phase inverter were designed while using the same hardware as the AC-DC grid converter. The neutral balancer control loop keeps the voltage difference of two DC capacitors to zero. Two half bridge inverter control loops keep spilt phase voltage identical under unbalanced load conditions. As a result, the proposed inverter can operate at the worst condition of the full-load at one phase and zero-load at the split-phase.

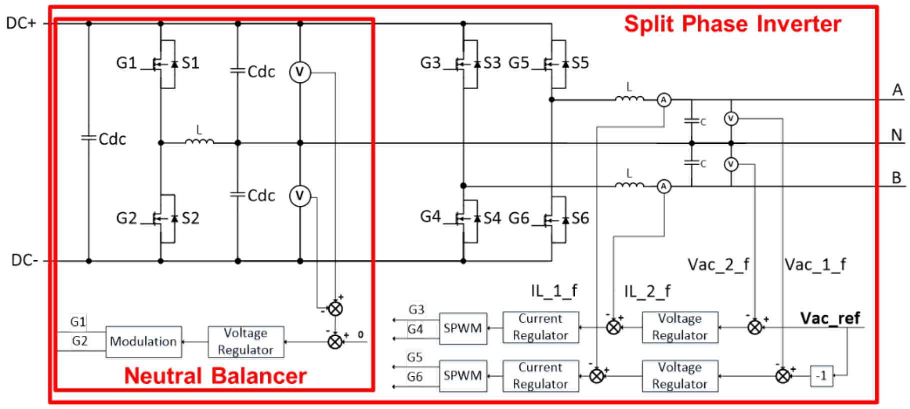

Fig. 7. Three independent control loops of split-phase inverter

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

Teamwork within GEH thrust:

- Working with Multi-SST Applications Task on integration of DGI with three SST system;
- Working with FREEDM Trailer Demonstrator on integration of Trailer Home Energy Management with a single SST residential node;

Team work among the ERC planes:

- Working with System Modeling and Control subthrust for multi-SST system global controller implementation;
- Working with DESD subthrust on integration of SST with DESD.

6. **Milestones and Deliverables**

Milestones

- Dec. Q4 2016 – Define multi-SST specifications; Enclosure and system layout design; Development of AC-DC and DC-AC converter power stage.
- Feb. Q1 2017 – Development of AC-DC and DC-AC local controller with reliable protections; Design of DGI interface with local DSP.
- Mar. Q1 2017 – Single SST local controller co-working with AC-DC and DC-AC power stages.
- Aug. Q2 2017 – Three working SSTs with controls integrated into GEH testbed.

Deliverables

Deliverable for SV (05/2017): Demonstration of three preliminary SSTs with basic multi-SST IPM and IEM functionalities, which are ready to operate in a reasonably realistic GEH environment.
Final Deliverable (08/2017): Three working preliminary SSTs with integrated DGI-based Volt/VAR and CODES functionality verified in a reasonably realistic GEH environment.

7. **Plans for Next Five Years**

- Hybrid low-frequency high-power transformer with partial power SiC SST to effectively improve the MV AC to LV AC converter efficiency (>99%) with full controllability, and to significantly reduce the system cost;
- EMI free MV SST circuit topologies, zero-voltage and/or current switching with minimum magnetics;
- Topologies and control methods that combine multiple functions (e.g. rectification and step-down) into one single topology to improve system efficiency and to reduce the system cost;
- Additional advanced control methods could be evaluated on the multi-SST MV testbed.

8. Member Company Benefits

The SiC building block method used in this project is a valuable and useful design reference for the member companies to develop PV-plus-storage system, SiC-based UPS, grid-tied PV inverter, and data center DC power system with high efficiency and reliability. Passivity-based predictive current control to stabilize multiple grid-tied converters is powerful tool to design the robust controller for smart inverter under condition of grid impedance wide-range variation. The split-phase inverter with three independent control loop enables the output voltage well regulated even with the unbalanced load, which effectively solve one of the key practical problems of the inverter applications.

9. References

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