Y9.GEH.1.4: Multi-SST Islanding, Black Start Functionality and Communications with DGI

Project Leader: Subhashish Bhattacharya

Students: Yonghwan Cho (PhD Student), Erin Fenton (UG REU and ECE student)

1. Project Goals

FREEDM system consists of SST, FID, DESD, DRER, and DGI. The SST-based microgrid system can have many functionalities using communication capability provided by DGI and other components such as DESD, DRER, and DESD. A new type of islanding and seamless reconnection strategies are developed to cope with the case when the utility grid is disconnected and to increase stability and reliability of the FREEDM system. The goal is to achieve the seamless operation mode transition between the grid-connected mode and the islanding mode.

Since the SST is connected to the grid, it is important to suppress the low-order current harmonics generated from the SST so that the grid is not polluted. The harmonic compensation schemes are investigated to regulate the harmonics effectively without degrading the stability of the control system. Moreover, nonlinear load which is connected to the grid can be distributed to the multiple SSTs which operate in parallel. Flexible harmonics control strategy is investigated to maximize the controllability of the Multi-SST system.

2. Role in Support of Strategic Plan

The success of this project will be to provide a SST enabled microgrid testbed to validate DGI enabled FREEDM architecture and also to provide a platform to quantify cost/benefit analysis for FREEDM system. This is not unique to FREEDM since specific companies can use this GEH microgrid testbed for their specific value-proposition and solutions and used cases. The control strategies of the multi-SST system developed in the project can improve the controllability and the stability of the FREEDM system.

3. Fundamental Research, Technological Barriers and Methodologies

With conventional method, the islanding operation of the SST is achieved by using its own DESD or DRER. However, if a SST does not have enough capacity of DESD or DRER, the SST cannot operate in islanding mode even when other SSTs have enough extra power.

A novel islanding strategy is developed to solve this problem. SSTs with abundant capacity of DESD or DRER can operate like the Uninterruptible Power Supply (UPS) and provide active power to other SSTs that do not have enough DESD or DRER in the microgrid system.

A seamless reconnection strategy is also needed to connect the microgrid to the utility grid without any interruption or delay once it is recovered from any system fault situation and ready to be used again. The challenge is to maintain the power sharing of the SSTs connected in parallel and to synchronize the microgrid to the utility grid at the same time.

The controller of each stage of SST requires fast and reliable dynamics to handle the sudden change of the power flow which is occurred during the transition period of the islanding and seamless reconnection. The controller design method is investigated in detail.

4. Achievements

4.1. Low-voltage scaled multiple-SST testbed Construction and Islanding operation

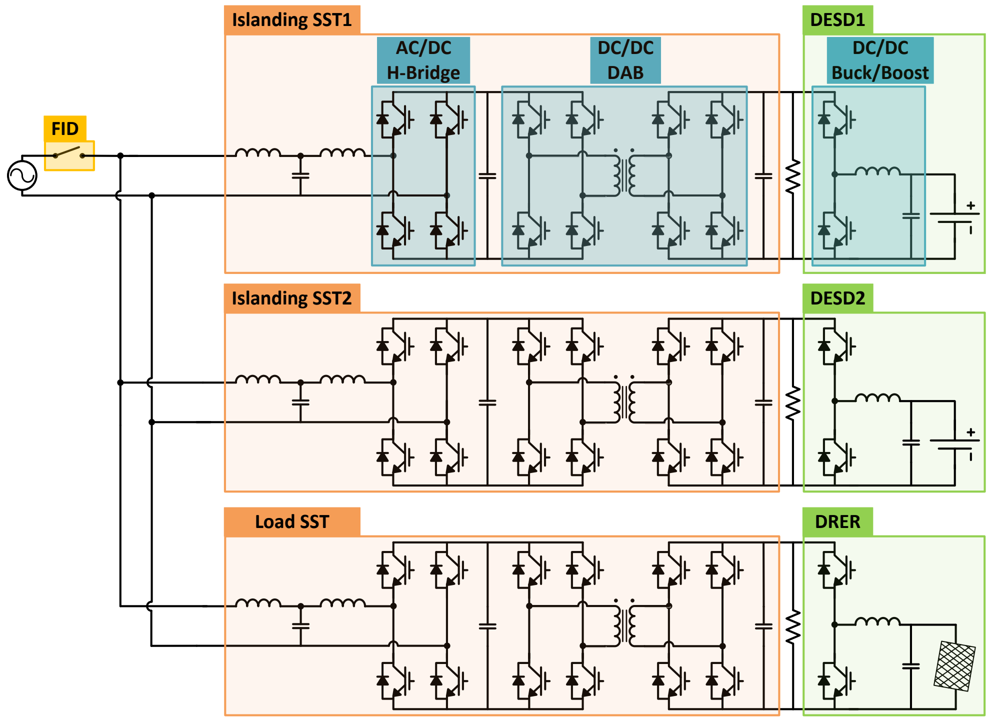

Figure 1: Circuit diagram of the low-voltage scaled multi-SST testbed.

In Figure 1, 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. Functionalities of SST such as bidirectional power flow, islanding, and seamless reconnection can be developed and verified with the multiple-SST testbed. In previous year, the testbed was built in FREEDM and a novel islanding strategy was developed and verified.

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.

Figure 2a and Figure 2b 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.

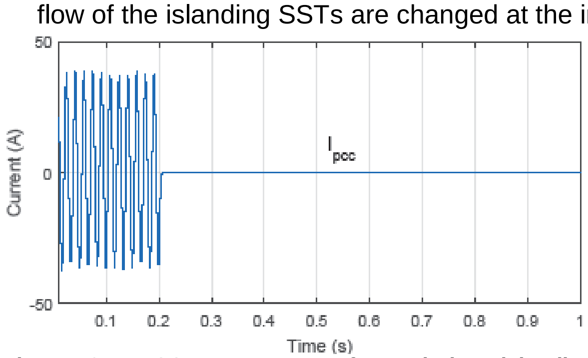

Figure 2a: PCC current waveform during islanding operation.

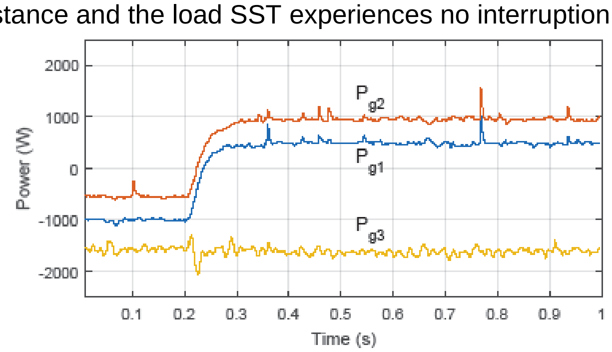

Figure 2b: Active power waveform during islanding operation.

4.2. Seamless reconnection of SST-based microgrid

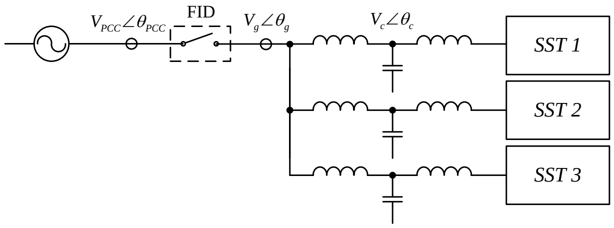

Figure 3: Circuit diagram of the multiple-SST testbed near the high voltage side PCC.

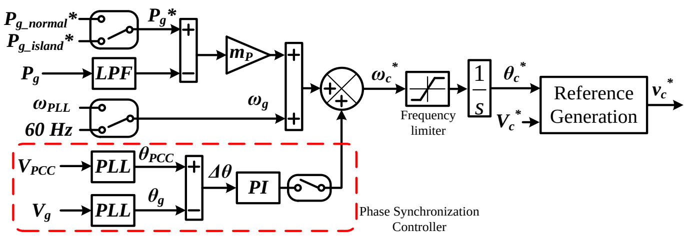

Figure 4a: Block diagram of the phase synchronization controller for islanding SST located closest to PCC.

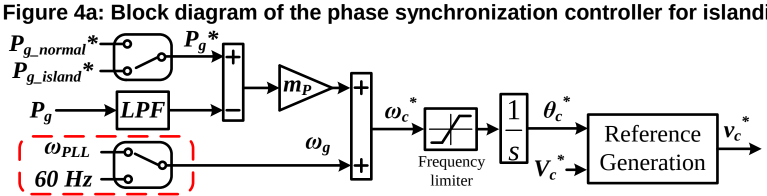

Figure 4b: Block diagram of the phase synchronization controller for islanding SST located far away from PCC.

Once the utility grid is ready to be used again, the SST-based microgrid system should be able to be reconnected to the utility grid without any interruption. Figure 3 shows the circuit diagram of the testbed near the high voltage side PCC. The microgrid voltage is synchronized to the utility grid by shifting the phase of the capacitor voltage of the input filter. The challenge is to maintain the power sharing of the system and to synchronize the phase at the same time. Thus, it is important to shift the phase of the capacitor voltages with the same rate.

Figure 4a shows the phase synchronization controller of the islanding SSTs which is located closest to PCC. The utility grid is measured to remove the phase difference between the microgrid and the utility grid. However, since the SSTs might be placed far away from PCC, the measuring of the PCC voltage could require long cables and make the system complicated. Thus, remotely located SSTs follow the change of the phase by using the PLL as shown in Figure 4b. Since the voltage magnitude is not synchronized, the FID should be closed at the zero crossing of the PCC voltage. Figure 5a and 5b show the experimental results of the seamless reconnection. It is shown that the microgrid is reconnected to the utility grid without any overcurrent or overvoltage issues.

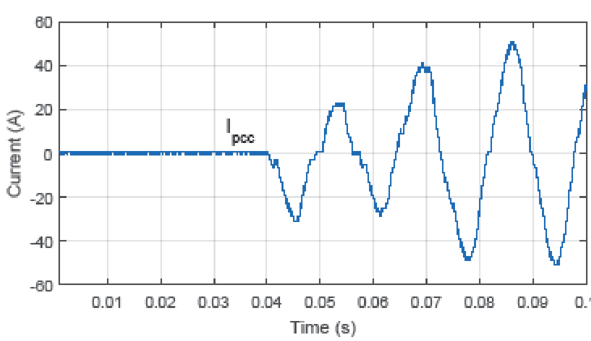

Figure 5a: PCC current waveform during the seamless reconnection.

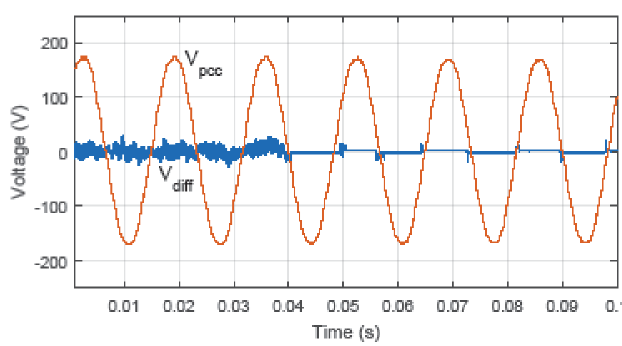

Figure 5b: PCC voltage and voltage across FID during the seamless reconnection.

4.3. Hybrid Harmonic Compensation scheme with multi-loop control structure

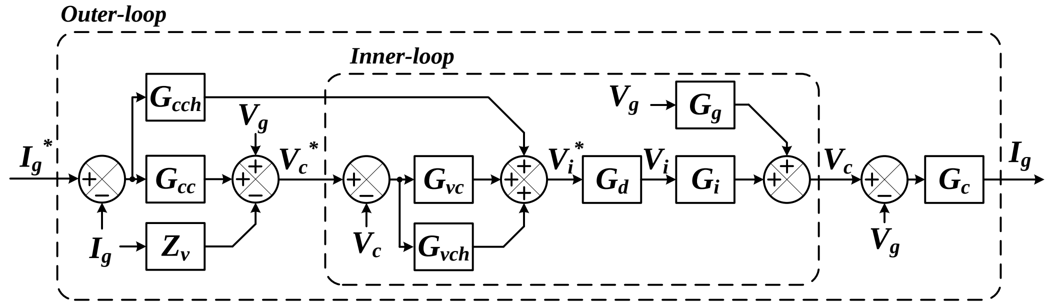

Figure 6: Block diagram of the hybrid harmonic compensation scheme in a multi-loop control structure for the load SST.

A multi-loop controller for high-voltage side AC/DC stage of the load SST is developed to both provide easy design criteria of the controller and implement hybrid harmonic compensation (HHC), which shown in Figure 6. The outer-loop controls the grid current and the inner-loop regulates the capacitor voltage of the LCL input filter. The outer current controller can be designed using the pole-zero cancellation method. The inner capacitor voltage controller can be designed based on the relationship between the capacitor voltage and the output PWM voltage of the H-bridge.

As shown in Figure 6, the current type harmonic compensation is used in the outer-loop and the voltage type harmonic compensation is implemented in the inner-loop, which is proposed as the hybrid harmonic compensation (HHC). Though the current type compensation is being typically used, it has not enough phase margin and is not appropriate for high frequency such as 11th, 13th, 15th, etc. Thus, it is applied only for low frequency such as 3rd, 5th, 7th. The voltage type compensation is used for high frequency due to its large enough phase margin. To implement the voltage type compensation, it is typically required to extract the harmonic components of the grid voltage. However, the extraction is not needed in the multi-loop structure and the grid voltage is directly used as a feedforward term since the fundamental component improves the dynamic performance of the system by compensating the nonlinear term of the plant.

Figure 7a and 7b compares the experimental results of the voltage type harmonic compensation and the hybrid harmonic compensation. Figure 7a shows that the total harmonic distortion (THD) of the grid current is 2.9% when only the voltage type compensation is used. However, the 3rd and 5th harmonics are not suppressed enough. On the other hand, THD is reduced to 1.7% when the proposed hybrid harmonics compensation is implemented as shown in Figure 7b since the 3rd and 5th harmonics are also well attenuated using the current type harmonic compensation.

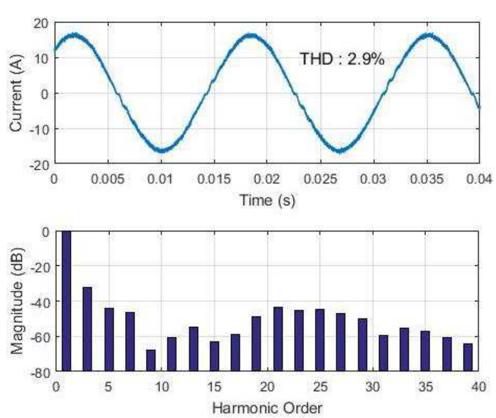

Figure 7a: grid current waveform and FFT analysis when only voltage type harmonic compensation is applied.

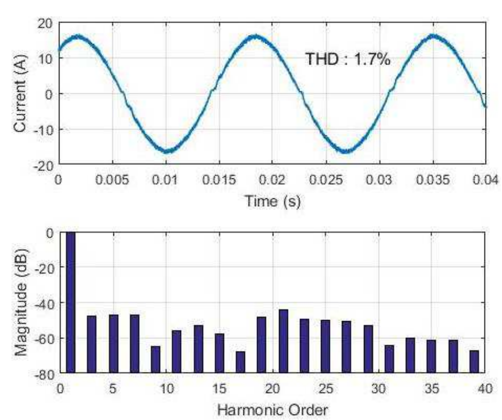

Figure 7b: grid current waveform and FFT analysis when hybrid harmonic compensation is applied.

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

This developed testbed will be delivered to GEH and can be valuable for both LSSS and HIL testbeds. The outcomes will be integrated in the GEH system demonstration. There are a lot of microgrid related research reported from academia as well as demonstration projects. However, none of these are related to multiple SST and their integration with DRER and DESDs, and do not have FIDs.

6. **Milestones and Deliverables**

Q3 (9/30/2016) - Controller design and experimental validation of islanding strategy in GEH testbed.

Q4 (12/31/2016) – Controller design and experimental validation of seamless reconnection strategy in GEH testbed.

Q1 (3/31/2017) – Controller design and verification of the sharing strategy of the grid current harmonics in GEH testbed.

Q2 (5/31/2017) - Experimental validation of the sharing strategy of the grid current harmonics.

Q2 (8/31/2017) - Improvement and documentation of the developed strategies.

Deliverable for SV (04/2017):

- Controller design and verification in GEH testbed.
- Experimental demonstration of the seamless reconnection strategy.
- Experimental demonstration of the sharing strategy of the grid current harmonics.

Final Deliverable (08/2017):

- Final report on the developed strategies.
- Experimental demonstration of multiple SST operation including islanding and seamless reconnection through DGI based communication and validation of IEM used cases in GEH testbed.
- Experimental demonstration of the sharing strategy of the grid current harmonics using multiple SST GEH testbed.

7. **Plans for Next Five Years**

The success of this project will be to provide a SST enabled microgrid testbed to validate DGI enabled FREEDM architecture and also to provide a platform to quantify cost/benefit analysis for FREEDM system. This is not unique to FREEDM since specific companies can use this GEH microgrid testbed for their specific value-proposition and solutions and used cases. GEH system integration and validation of three SST (LV prototypes) with DRER (PV) and DESD (BESS– Battery ESS) to demonstrate DGI based IEM and IPM functionalities, including islanding, and black-start in a microgrid platform. The various GEH used cases will be verified.

8. **Member Company Benefits**

- The multi-SST with DGI control will provide a testbed for industry to access **Energy Management** functions enabled by SST in different application scenarios – such as, industrial factory and manufacturing workplace; large warehouse energy management, large retail stores (such as Walmart and several others), etc.
- The demonstration of DGI based multi-SST control can accelerate and complement the HEMS project and interest industry to try out their devices and solutions for HEMS commercialization.
- The DGI based multi-SST platform can serve as a testbed for HIL implementation for development and validation of industry controllers for various **Energy Management solutions.**
- The multi-SST platform in GEH testbed can be used by industry to validate operation of "new' developed technologies such as SST's operation with legacy equipment and controllers on the feeder, such as VR (Voltage Regulators), recloser switches and "sectionalizer" switches. This testbed can enable protection coordination and validate protection settings of various equipment on the distribution feeder.

9. **References**

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