Y9.HIL.1: Hardware-in-the-Loop Testbed

Project Leader: Mischa Steurer (FSU)

Faculty: Raja Ayyanar (ASU), Mesut Baran (NCSU), Mo-Yuen Chow (NCSU), Chris Edrington (FSU), Jonathan Kimball (MST), Helen Li (FSU), Bruce McMillin (MST), K. Schoder (FSU), Ming Yu (FSU)

Students: Sourindu Chatterjee, Geoffrey Cline, Prakash Dunaka, Manish Jaisinghani, Uday Kanteti, Mark Myers, Jonathan Ng, Yue Shi, Tunji Thomas, Tong Yao, Qing Ye, Yuan Zhang, Bokang Zhou

Staff: Isaac Leonard, Harsha Ravindra, Mike Sloderbeck, Mark Stanovich, Tuyen Vu

1. Project Goals

The overall objective of the hardware-in-the-loop (HIL) testbed (HIL-TB) project is to provide a flexible platform that facilitates the design, analysis, and demonstration of FREEDM concepts using both physical and simulated devices. The specific goals for this year are:

- Scientific: Improve / continue development of systematic method for comprehensive system performance evaluation of FREEDM functions on the HIL-TB;
- Prepare the FSU Power Hardware-in-the-Loop (PHIL) facility for a 4kV class MVAC system demonstration in Year 10;
- Support DGI application testing on HIL-TB; demonstrate Volt/Var on HIL-TB for Y9 site visit;
- Support PHIL demonstration of the stability work being performed by Helen Li;
- Upgrade HIL-TB capabilities via Office of Naval Research (ONR) Defense University Research Instrumentation Program (DURIP) grant.

2. Role in Support of Strategic Plan

The HIL-TB is one of three primary testbeds along with the Green Energy Hub (GEH) and the Large Scale System Simulation (LSSS). The GEH is primarily composed of physical FREEDM components, while the LSSS consists solely of off-line (non real-time) simulated components. The HIL-TB fills the gap between the other two testbeds by providing a platform to study physical and simulated devices together. When compared to a testbed that features only physical devices, this mixture of real and simulated hardware allows researchers to analyze cyber-physical systems in a safer and more controlled environment. Since the HIL-TB is accessible remotely from all partner schools yet it requires several disciplines to operate (e.g. DGI, RSC, and the power network simulation all have to be functional for any given use case scenario) it naturally fosters collaborations between team members.

3. Fundamental Research, Technological Barriers and Methodologies

Compared to fundamental science layer projects, this project resides at the FREEDM test bed layer. As such, we do not primarily address fundamental research challenges. However, we foster an environment (the testbed) and manage a highly interdisciplinary team to bring together all the relevant pieces of a functional system in a real-time HIL simulation based demonstration. The challenges associated with such a project are primarily driven by the need to clearly define and establish the interfaces between all the sub-systems (SSTs, power distribution network, DGI nodes, protection algorithms, RSC network, etc.), such that a functional system of meaningful size can be established. Moreover, this project provides one of the key platforms for evaluating system designs. The central components to addressing these challenges are collaborative team work (i.e. bi-weekly phone calls, shared digital locations for files and work product, etc.) and allowing all team members access to the HIL testbed from their remote locations.

4. Achievements

This section outlines the progress made on the subtasks included in the Y9.HIL.1 project.

Performance Evaluation of FREEDM Functions Using the HIL-TB

The HIL-TB project team at FSU developed a systematic method for comprehensive system performance evaluation of FREEDM functions on the HIL-TB in Year 8. This work allows FREEDM researchers to systematically evaluate the performance of their control algorithms, components, and system concepts using a highly automated test environment. The HIL-TB is a diverse system of hardware and software components working together, principally the Real-Time Digital Simulator (RTDS), embedded controllers, and the OPNET network simulator. In order to coordinate these three systems for each experiment, an automated software framework was established to reduce user fatigue and bookkeeping error. This testing framework serves to assist in probing the experiment sample space, more easily compare control algorithms, and verify changes in a control application by observing its most relevant response quantities. The framework also supports experimental repetition, which can be used to determine the confidence interval of the obtained response quantities.

In Year 9, an optimization loop is being added to the HIL-TB evaluation framework. The parameter space to be probed in real time simulations often tends to be daunting, since in many cases the parameter space can be very large. For this reason, a practical approach which guarantees optimum parameter values would be ideal. As part of this research, the method of convex optimization has been introduced as a means of achieving optimum parameter values relative to the function that defines the applied algorithm. This optimization feature will be used in performance evaluation of several FREEDM applications including Volt/Var, CoDES, and MPC-based IEM.

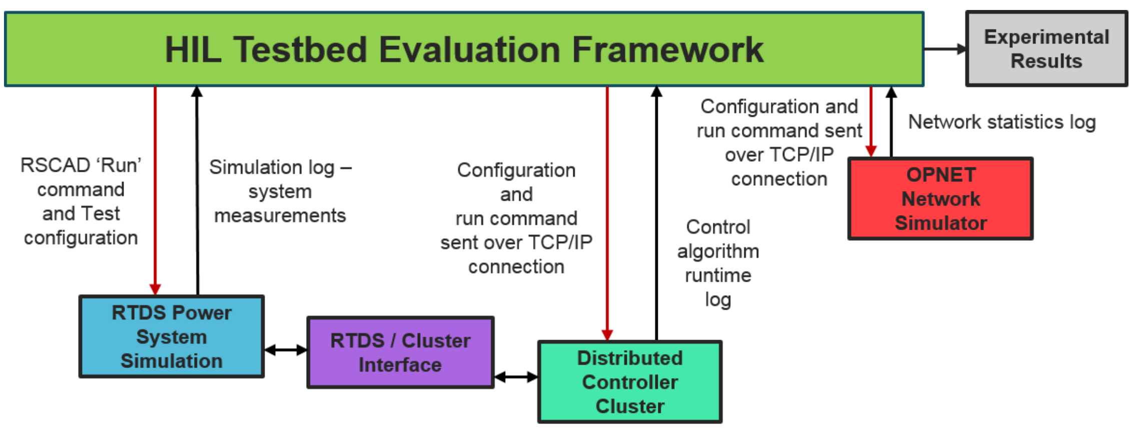

Figure 1 - HIL-TB Performance Evaluation Overview

Prepare FSU PHIL Facility for MV System Demonstration in Year 10

In preparation for a medium voltage system demonstration on the HIL Testbed in Year 10 (overview shown in Figure 2), the HIL Testbed team has performed several CHIL experiments to assess the capability of the FSU-CAPS MMCs to be operated in single-phase inverter mode. In this mode of operation, one or more MMCs could be used to emulate SSTs at the medium voltage level. CHIL experimental results shown in Figure 3 demonstrate the feasibility of this concept. A single phase line-to-line load was established by setting R_a=R_b=8Ω, and R_c=800 Ω. In this configuration, the expected

120 Hz ripple in the DC voltage and current waveforms is clearly visible in Figure 3. Preliminary results confirmed operation at approximately 3 kVac under full load. It is expected (and will be confirmed via further CHIL testing) that at slightly lower loading, operation at 4 kVac will be achievable for the purposes of the proposed Year 10 system demonstration.

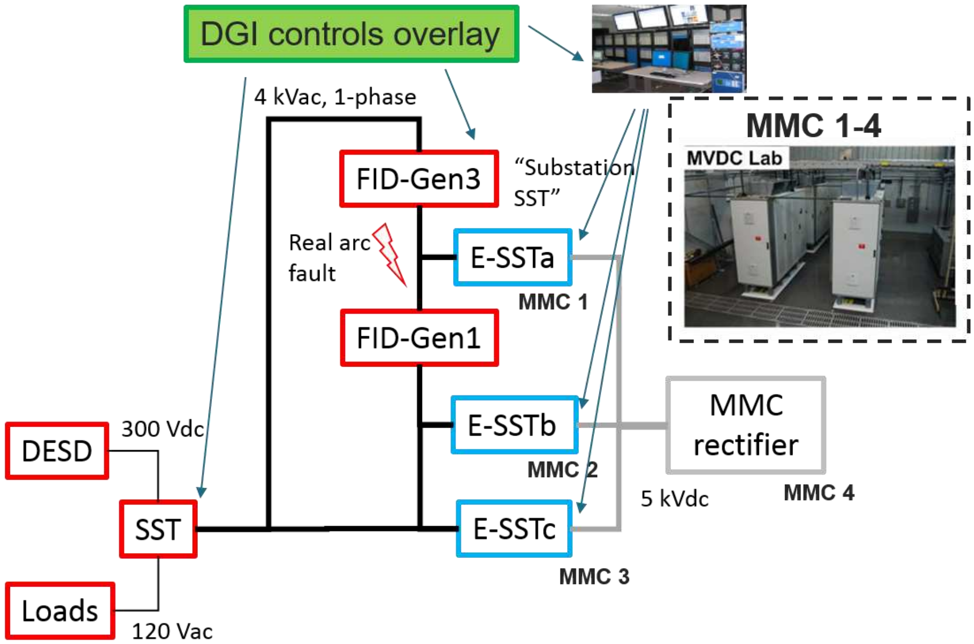

Figure 2 - Proposed Year 10 Medium Voltage System Demonstration at FSU-CAPS

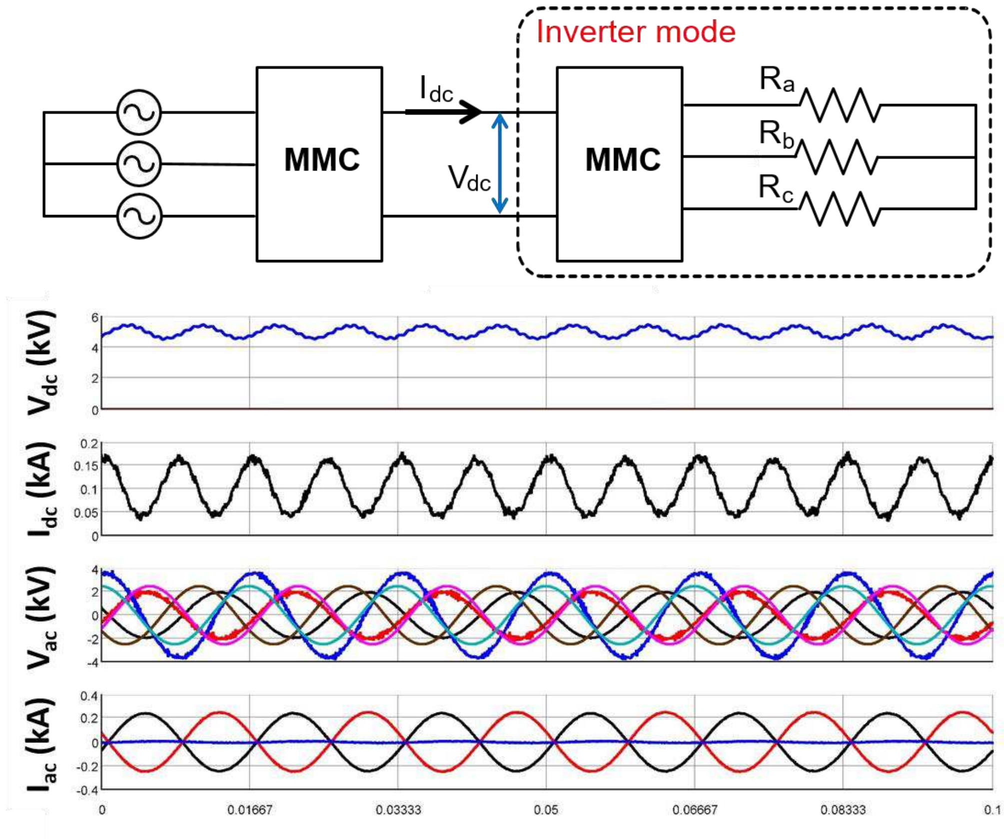

Figure 3 - MMC Single Phase Inverter Mode CHIL Experimental Results

<u>Support DGI Application Testing and Evaluation on HIL-TB</u>

The HIL-TB team supports DGI application testing and evaluation each project year as FREEDM research partners develop new algorithms and improve existing control software. During Year 9, the following tasks have been supported by the HIL-TB project team.

- Volt/Var Optimization and Implementation

  Within the FREEDM System, feeder voltage violation may occur due to changes in load or distributed generation. The Volt/Var application monitors voltage throughout the system and commands adjustments to SST reactive power output based on several objectives. During Year 8 the Volt/Var optimization module was developed for DGI 2.0, with preliminary testing occurring at the end of Year 8. Now in Year 9, the Volt/Var module has been verified on the HIL-TB as being able to adjust SST reactive power output to minimize system losses while keeping feeder voltage within specified limits. More comprehensive evaluation of this application will take place using the HIL-TB evaluation framework, and a demonstration will take place during the Year 9 site visit. Additionally, the results from performance evaluation on the HIL-TB will be used to de-risk Volt/Var implementation on the GEH.

- Community Distributed Energy Storage (CoDES) Development

  During Year 9 the existing CoDES implementation was expanded from a static scheduling solver (1-hour with pre-loaded profiles) with real-time operating logic to respond to real-time (1 minute) system feedback. The DESD dispatch schedule pre-calculated by CoDES will then be updated in real-time by sampling system status every minute and then executing the dispatch logic. Currently the software updates are being deployed in the DGI 2.0 environment, where they will be linked with the existing CoDES software before verification and evaluation on the HIL-TB.

- Robust SST and DESD Controller Evaluation
  This task involves the development and demonstration of robust SST controller concepts emphasized by the SVT. Using controller hardware-in-the-loop (CHIL) experimental methods on the HIL-TB, DSP/FPGA control boards developed by NCSU and programmed by researchers at ASU are accessed by collaborating partners, remotely, to verify advanced SST control features. During this project year, the robust controller design developed at ASU for Gen-III SSTs is being verified in CHIL on the HIL-TB. Figure 4 shows the transient performance of the SST controller during transition from grid-connected to grid-islanded mode.

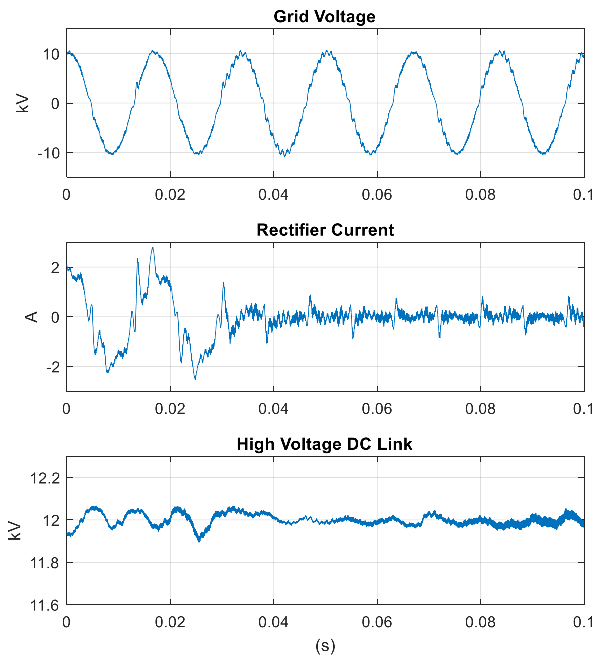

Figure 4 - 10kW Load SST Disconnecting from Feeder, Transient Behavior Verified Using HIL-TB CHIL

<u>Upgrade of HIL-TB Capabilities</u>
Significant enhancement of the hardware and software capabilities of the HIL-TB at FSU-CAPS has begun this project year via dual-use funding through a DURIP award from the Office of Naval Research. The award will enable full connectivity of the various systems at CAPS at the control network level for the purpose of testing and demonstrating advanced distributed control. Hardware upgrades to the network simulation capabilities of the HIL-TB are now in place in Year 9. More detailed information regarding this upgrade can be found in the Y9.HIL.4 Volume II report.

5. Other Relevant Work Being Conducted Outside of the ERC

HIL-based testing of systems is been pursued at several places outside the ERC, such as

- The National Renewable Energy Laboratory (NREL)
- Idaho NL
- MIT's Lincoln Labs
- RWE ERC at Aachen University, Germany

The FREEDM HIL-TB team follows those developments closely and interacts with researchers at those labs on a regular basis. While some of these labs certainly have greater computational capacities than the FREEDM HIL-TB, none of these projects are on a trajectory to achieve a similar level of integration between all relevant system aspects (controls, communication networks, and power hardware components via PHIL).

6. **Milestones and Deliverables**
   - Q3 (9.30.2016) – Provide the new LSSS team specifications for compatible platform development
   - Q4 (12.31.2016) – Demonstrate the inverter mode of the MMCs with existing CHIL setup
   - Q1 (3.31.2017) – Evaluation and demonstration of several DGI applications (Volt/Var, CoDES, MPC-based IEM)
   - Q2 (5.1.2017) – HIL-TB demonstration featuring Volt/Var control algorithm for FREEDM Y9 site visit
   - Q2 (6.30.2017) – PHIL system demonstration with MMCs emulating SSTs and/or FREEDM feeder sections

7. **Plans for Next Five Years**

   In Year 9, the HIL-TB became the major focus of the center to establish a final system level demonstration of the FREEDM approach for graduation in Year 10. Thereafter the HIL-TB will remain a vital asset to the Center for evaluating system level control and protection technologies, as well as active power components of future electric power distribution systems.

8. **Member Company Benefits**

   No member companies are related to this project.

9. **References**

   N/A