2.1 Hardware In the Loop Test Bed (HILTB)

Year 10 Projects and Participants			
Project Number	Project Title	Participants	Institution
Y10.HIL.1	System Demonstration on HILTV at MV level via PHIL	Steurer	FSU
Y10.HIL.2	Volt-VAR Control on FREEDM Systems	Baran	NCSU
Y10.HIL.3	Implementation and test of codes on HIL Testbed	Chow	NCSU
Y10.HIL.4	PHIL FREEDM System Demonstration with Gen-III FID and Gen-III SST	Huang	NCSU

2.1.1 Intellectual Merit and Impact

The FREEDM systems center and team has made several strides and achievements throughout the tenure of the project whether it be intellectual property in the form of advanced smart control strategies, advanced Distributed Grid Intelligence (DGI) control platform or building, testing and demonstration of smart electric equipment. The DGI platform in itself is an intelligent grid and network management system which can host multiple control strategies such as load balancing, fault management, advanced volt/var control, cooperative energy scheduling systems to control and manage power system components. All of these technologies along with several power system components have been integrated into a hardware-in-the-loop (HIL) testbed (HIL-TB) system at CAPS, FSU. This HIL-TB has supported design, analysis, testing and demonstration of FREEDM concepts using both physical and simulated devices. The testbed currently supports a highly interdisciplinary team to integrate various relevant pieces of a functional FREEDM system in a real-time HIL simulation based demonstration. The goal of HIL-TB is to enable fundamental science and technology concept to a system-integrated demonstration that could turn into a viable stakeholder venture.

2.1.2 Technical Approach

Over the past few years of the project, strides were made to achieve a full-fledged development and integration of control, communication network, and power system components into the HIL-TB. Fig. 1 depicts the progress and development of HIL testbed from year 1 through 10. This section provides information regarding the development of the HIL-TB at CAPS throughout the years through which current capabilities have been realized. In 2010, a digital real-time simulation setup and model of the envisioned Green Energy Hub was undertaken using real-time simulation platform RTDS [1]. In 2011, the integration of FREEDM's distributed grid intelligence was undertaken. The DGI hosts an operating system which supports 'plug and play' interface for advanced power and network control of smart devices, loads, renewable resources and storages. In 2012, successful integration of DGI software into HIL-TB was accomplished. The HIL-TB at this point consisted of real-time digital simulator running power system simulation, a set of general purpose computational platforms on which DGI software was hosted with capability of hosting 4 DGI/SST nodes. In 2013, the HIL-TB was successfully upgraded to a robust real-time cyber-physical capable electric power system testbed capable of exploring truly distributed control systems [2].

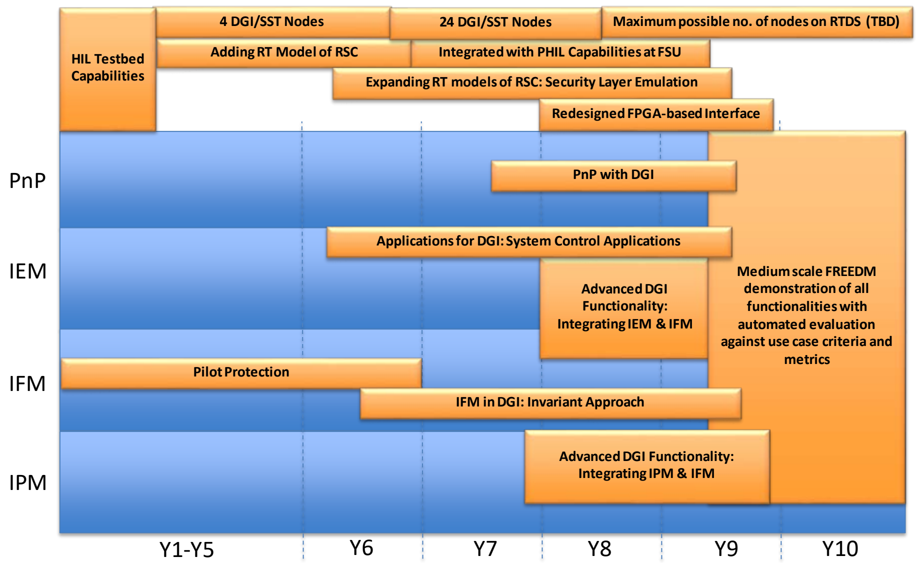

Fig. 1: FREEDM HIL testbed development road map

In year 6 of the project (2014), data communication layer and infrastructure was added to analyze the effects of different network characteristics on the DGI control software. The HIL-TB capabilities were further expanded by inclusion of additional newer, faster and more powerful computational platforms thereby increasing the number of supported DGI nodes from 4 to 24 while also supporting multiple DGI node capability on a single computational platform. A demonstration of HIL testbed with 5-DGI node system with each DGI controlling a separate simulated SST was achieved with DGI running the load balancing algorithm. In year 6, the testbed re-configurability management was updated by adding a VLAN-capable switch thereby eliminating the need for manual cabling changes with respect to network emulation studies involving DGI in the testbed. The network emulator tool, OPNET adopted in year 5 was also expanded to support 24 DGI nodes with several updated functionalities. In year 7 (2015), a full integration of the HIL testbed with the Controller and Power hardware-in-the-loop (CHIL and PHIL) capabilities were realized for 2 SSTs. The voltage invariance algorithm developed by collaborates from team at MS&T in DGI was verified in the testbed through the utilization of newly developed 7 node power system model in RTDS which utilized 7 DGI/SST instances. Remote accessibility feature of the HIL testbed was also improved thereby allowing multiple researchers utilize testbed at same instance. In year 8, (2016), a systematic method for comprehensive system performance evaluation of FREEDM functions on the HIL testbed was developed. A new RTDS-DGI communication interface was developed that increased the number of signals passed from real-time simulation of power system to DGI thereby enabling more complex and additional control scheme evaluations. This scheme allowed for use of 240 signals with a 200 Hz update rate. Updated were also made to the network emulation system by implementation of transport layer encryption for communication between DGIs. Explicit Congestion Notification (ECN) control was also implemented for communication network traffic flowing through OPNET.

In year 9, (2017), the experiments were conducted to further expand the testbed capability by use of MMCs at FSU-CAPS for single phase inverter mode operation. The feasibility of the concept was verified through CHIL MMC based experiments. Volt/Var management of power system through VVC algorithm in DGI within the testbed was successfully demonstrated in year 9. Significant enhancements and updates to the testbed were enabled through dual-use funding by DURIP award from the Office of Naval Research (ONR). This upgrade expands the DGI/SST emulation node count from 24 to more than 50. Fig. 2 shows the integrated HIL testbed facility and capability at CAPS at the end of year 9.

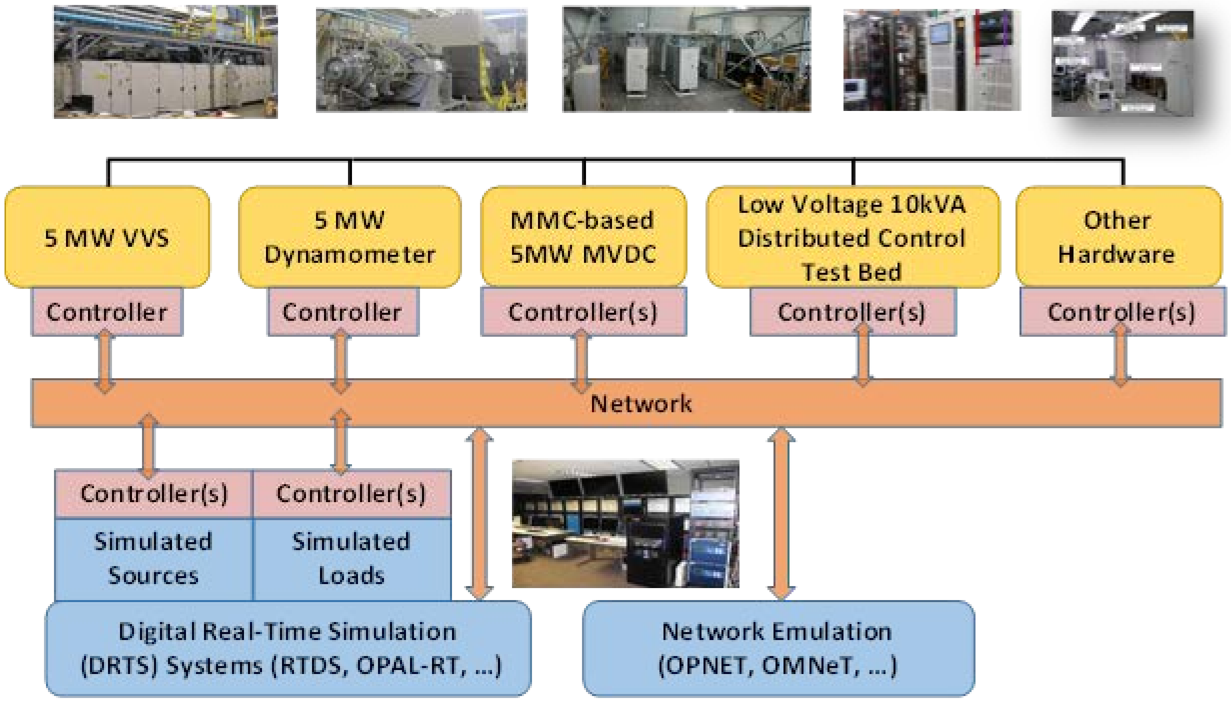

Fig. 2: Integrated PHIL, CHIL, Network Simulation Test Facility at CAPS, FSU

For year 10, the HIL testbed will support and demonstrate several experiments such as PHIL 4 kV class MVAC system which will be a subset of a large scale power system in simulation. The experiments not only demonstrate the power system but also showcase DGI functionality and interface of simulated and actual hardware as well as control schemes such as load balancing, VVC, CODES, fault management.

2.1.3 Unique Approaches:

Unlike other testbeds within FREEDM such as the LSSS which supports simulation only testbed and GEH that supports a small scale hardware setup, the HIL testbed not only builds upon real-time power system simulation platforms (RTDS, OPAL-RT) but also integrates the high power MVDC and MVAC testbeds along with a large number of computational platforms that enable and support DGI functionality with communication and cyber-physical security aspects. The testbed also supports a comprehensive and systematic evaluation of testbed functionality.

2.1.4 Technology Innovations:

In year 8, the HIL testbed team proposed and developed a systematic method for comprehensive performance evaluation of FREEDM function on the testbed platform. The evaluation framework will enable FREEDM testbed users to probe their algorithms for not only power system performance but also for performance under realistic and real-world network and communication constraints. In year 9, the testbed team demonstrated the use of hardware at CAPS to be utilize for FREEDM related applications by testing a single phase inverter mode operation of the 3 phase high power MVDC MMCs.

2.1.5 Validation of the Research:

Several publications that describe the testbed development through the years and its use have been produced [1], [2], [3], [4], [5]. The testbed has been utilized by several FREEDM team members to demonstrate and validate their research with respect to DGI functionality, advanced control algorithms, hardware testing.

- Pilot protection scheme was tested in years 5 and 6.
- Year 6 saw the development and testing of system control applications for DGI on HIL testbed. The testbed was used to demonstrate fault management algorithm in a CHIL environment developed to protect high voltage (HV) and low voltage (LV) electrical distribution circuits in FREEDM
- In year 7, a scalable intelligent energy management algorithm for optimal power dispatch of power system embedded in DGI was tested on the testbed platform. Other DGI embedded functionalities such as invariance based algorithm that aid in system stability were also tested on the testbed through CHIL environment.
- Year 8 saw significant use of testbed through development and improvement of various algorithms. The testbed was also utilized to demonstrate the operation of 15 kV ETO switch, and Gen-III FID at rated capability.
- In year 9, apart from utilization of testbed to improve DGI functionality, several CHIL based experiments were conducted to investigate inclusion of additional testbed capabilities such as testing og MMCs in single phase inverter mode operation.

2.1.6 Ref erences:

1. Mesut Baran, Mischa Steurer, "A Digital Testbed for FREEDM System Development," Power and Energy Society General Meeting, 2010 IEEE, 25-29 July 2010.
2. Mark J. Stanovich, Isaac Leonard, Sanjeev K. Srivastava, Mischa Steurer, Thomas P. Roth, Stephen Jackson, Bruce M. McMillin, "Development of a Smart-Grid Cyber-Physical Systems Testbed". ISGT, Washington, DC, February 2013.
3. Isaac Leonard, Harsha Ravindra, Thomas Roth, Mike Sloderbeck, Sindhuja Sundararajan, "FREEDM HIL Testbed: An Overview, Description, and Analysis of a Smart Grid Cyber-Physical System Testbed for Hardware-in-the-Loop Simulations", 2015.
4. Karl Schoder, Ziyuan Cai, Sindhuja Sundararajan, Ming Yu, Mike Sloderbeck, Issac Leonard, Michael Steurer, "Real-time Simulation of Communications and Power Systems for testing distributed embedded controls", E&T Energy and Power hub, July 2017.
5. Ziyan Cai, Ming Yu, Mischa Steurer, Jonathan Ng, "A New Grouping Protocol for Smart Grids", IEEE Transactions on Smart Grid, 2017.