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14. ABSTRACT To advance the development of tactical microgrid standards, stability and control studies rely heavily on extensive computer simulation, on experiments including when possible hardware-in-the-loop (HIL) testing, and on the development of suitable control systems to manage these tasks in real applications. To enable Controller-hardware-in-the-loop (CHIL) testing of microgrid controllers in development, The University of Texas at Austin Center for Electromechanics acquired a National Instruments field-programmable gate array (FPGA) cluster to work in conjunction with an existing real-time simulator. This allows the controls designer to achieve a faster and more
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## Report Title

Final Report: Assessing Military Microgrid Effectiveness through Real-Time/FPGA Hardware-In-the-Loop (HIL) Testing

### ABSTRACT

To advance the development of tactical microgrid standards, stability and control studies rely heavily on extensive computer simulation, on experiments including when possible hardware-in-the-loop (HIL) testing, and on the development of suitable control systems to manage these tasks in real applications. To enable Controller-hardware-in-the-loop (CHIL) testing of microgrid controllers in development, The University of Texas at Austin Center for Electromechanics acquired a National Instruments field-programmable gate array (FPGA) cluster to work in conjunction with an existing real-time simulator. This allows the controls designer to achieve a faster, and more cost effective, understanding of in-field controller behavior before progressing to full scale HIL testing.

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**(a) Papers published in peer-reviewed journals (N/A for none)**

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**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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Number of Manuscripts:

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**Books**

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**TOTAL:**

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Book Chapter

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**Graduate Students**

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**Names of Post Doctorates**

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**Names of Under Graduate students supported**

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### Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Elahe Doroudchi	0.30
<b>FTE Equivalent:</b>	<b>0.30</b>
<b>Total Number:</b>	<b>1</b>

### Sub Contractors (DD882)

### Inventions (DD882)

### Scientific Progress

Elahe Doroudchi, PhD candidate, completed a three month visiting researcher tenure at UT CEM from Aalto University in Finland. During this period, she was able to successfully utilize the Real-time Simulator and FPGA Cluster to test her DC Microgrid optimization algorithms. The results acquired during this period (January 2017 - March 2017) were submitted to the IEEE SmartGridComm Conference taking place in Dresden Germany in Oct 2017. We are still awaiting word on the acceptance of this paper.

### Technology Transfer

UT CEM has engaged with multiple DOD and Industry partners introducing them to the Real-Time Simulation and FPGA environment to enable CHIL and HIL testing of controllers. Many recognize the power of the environment and have expressed interest in leveraging this capability. To date multiple proposals have been written, but as of April 2017 no collaborative efforts have been funded. In addition, UT CEM has hosted multiple training sessions for UT engineering students on the technology.



**ASSESSING MILITARY MICROGRID EFFECTIVENESS THROUGH  
REAL-TIME/FPGA HARDWARE-IN-THE-LOOP (HIL) TESTING**

Contract Number: W911NF-16-1-0239

**Final Report**

Submitted to:

**ARMY RESEARCH OFFICE**

Submitted by:

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University of Texas at Austin

Center for Electromechanics

Center for Electromechanics  
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## **Foreword**

The Construction Engineering Research Laboratory (CERL) is in the process of developing a new tactical microgrid power system standard. Modern military operations are becoming ever more dependent on high quality reliable electrical power being available in a range of tactical environments. To meet this need a variety of diverse military power system equipment must be interconnected to form an ad hoc tactical microgrid. In the interest of minimizing the number of specialized support personnel that must be deployed, it is highly desirable that the assembly or reconfiguration of a tactical microgrid be able to be done by any warfighter. To make this goal feasible, the power grid equipment will need to be “plug and play”, which in turn requires that a new standard be developed to ensure all new equipment suppliers have guidance for achieving this capability. To advance this development, stability and control studies rely heavily on extensive computer simulation, on experiments including when possible hardware-in-the-loop (HIL) testing, and on the development of suitable control systems to manage these tasks in real applications. In conjunction with a real-time simulator, FPGA clusters, like the one acquired from NI through this DURIP award, can be used to provide Controller-hardware-in-the-loop testing capabilities. This allows the controls designer to achieve a faster, and more cost effective , understanding of how a controller will behave in the field before progressing to the stage of full scale HIL testing.

## **Problem Statement**

To support research in advanced power systems, The University of Texas at Austin Center for Electromechanics established a flexible MW-scale microgrid laboratory to enable evaluation of novel power system topologies and controls. In order for the UT-CEM microgrid laboratory to more effectively emulate shipboard and forward operating base power systems, UT-CEM proposed the purchase of a National Instruments PXIe Real-Time/FPGA Hardware-in-the-loop system (FPGA-HIL) under the Army Research Program DURIP Grant program. As proposed in September 2015, the total cost of the FPGA-HIL system for the UT-CEM Microgrid Laboratory was \$271,553.33.

The FPGA-HIL proposal was based on a quotation from National Instruments and consisted of FPGA Processor and PXI Chassis, eHS and FPGA IP Software Licensing,. After further review, very few vendors for a combined real-time simulation and FPGA environment are available on

the market, but National Instruments and Opal-RT have teamed to bring this capability to the power system design market.

### UT-CEM Microgrid Laboratory

UT-CEM has onsite a flexible, megawatt-scale microgrid that is available to assist in the validation of simulation models at relevant power levels and to conduct critical component and technology validation experiments. To reflect realistic installations, the various components of the microgrid are installed in two separate labs connected by an approximately 150 ft long primary distribution bus (Figure ).

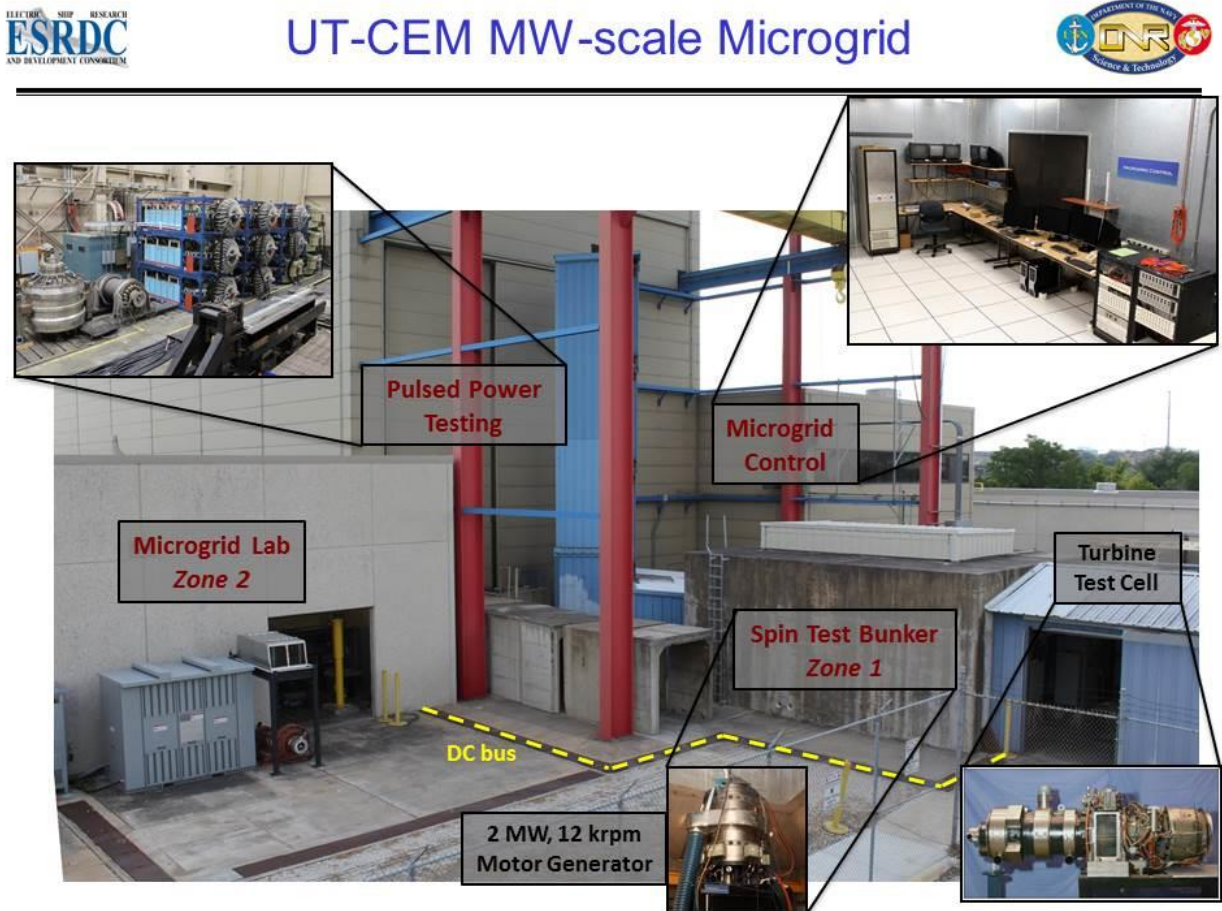


Figure 1: Distributed microgrid installation at UT-CEM.

The system is currently configured for dc distribution (Figure ), but the microgrid can also be configured for 60 Hz or higher frequency ac distribution as well. As of this writing, additional

power conversion stages are being installed onto the present microgrid. The acquisition of these additional power converters was also made possible thanks to a 2013 DURIP Grant from Office of Naval Research (ONR). These units, for a total of 7.5 MW of additional combined power, will add much more flexibility and reconfiguration options to the present architecture shown in Figure .

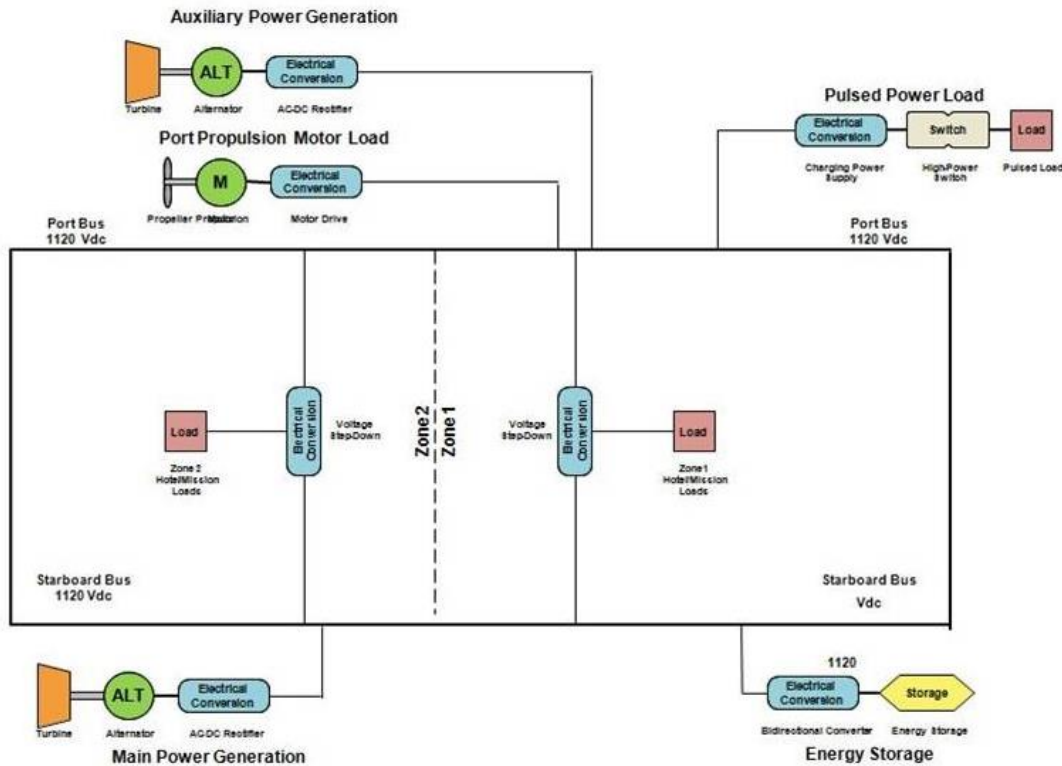


Figure 2: Schematic of present dc microgrid laboratory installation

The installation of these additional power converter units will enhance the UT-CEM microgrid capabilities as a flexible test-bed for HIL/PHIL testing of a variety of hardware at relevant power levels (see for example Figure ). The addition of an MRTS would extend the capabilities of the test bed and make it more adaptable as a HIL/PHIL or hybrid validation tool.

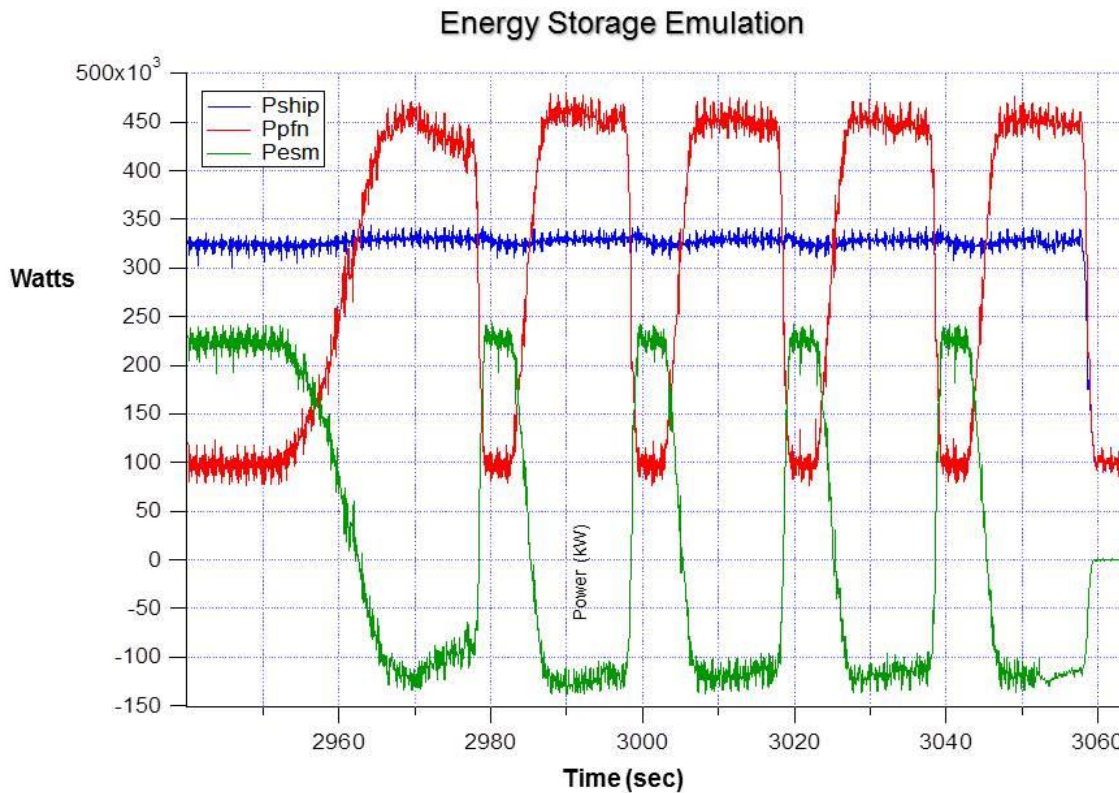
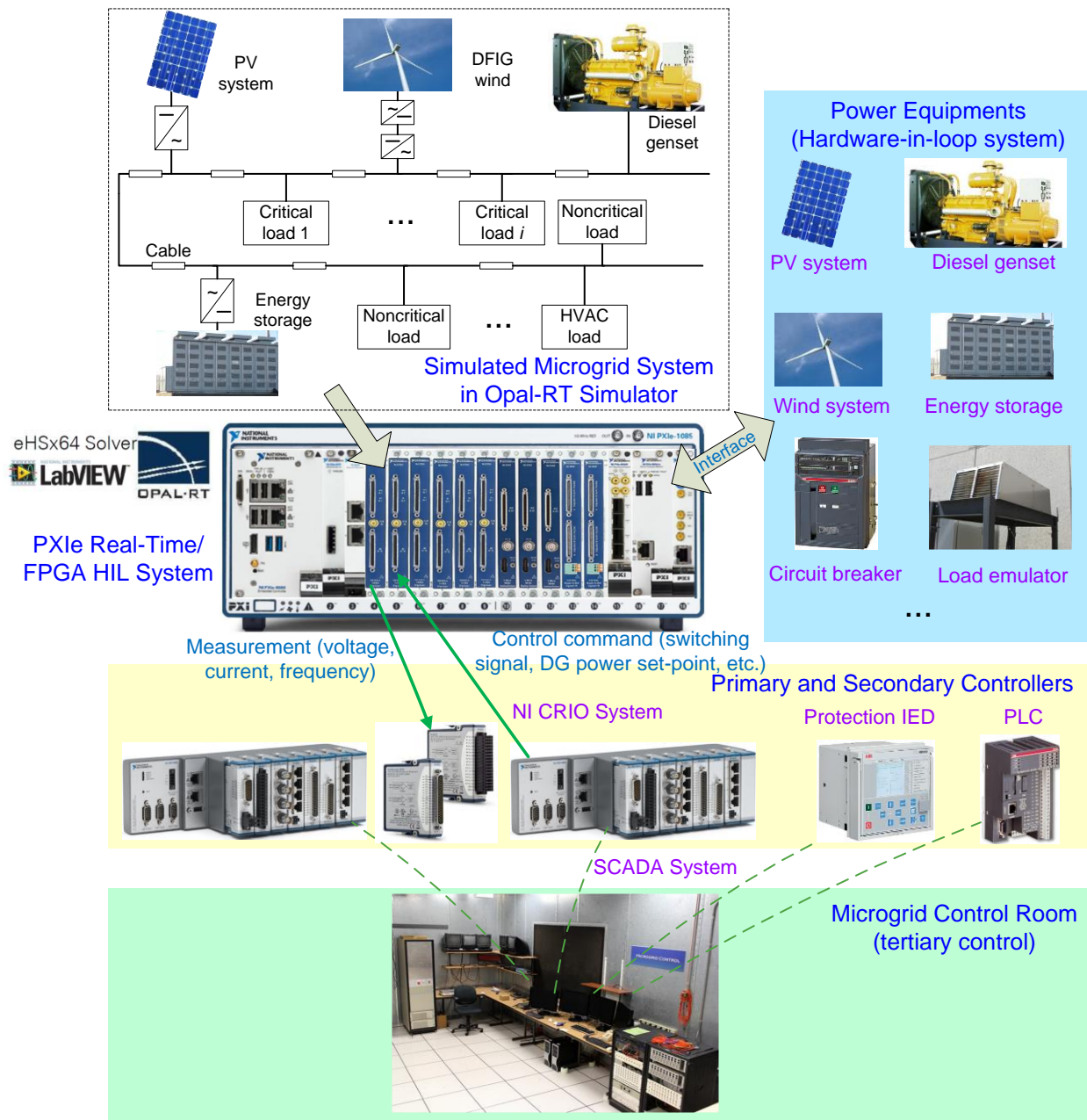


Figure 3: Example of HIL testing at UT-CEM: energy storage emulation on the microgrid

## FPGA-HIL System

UT-CEM currently leverages both its capabilities in MATLAB simulation and a real-time simulation environment to develop and evaluate the performance response of a microgrid to system level control algorithms. While the simulations that can be performed both on a PC and then within a real-time simulator are helpful in the development and validation of control algorithms, the time-scale of these simulations is limited to approx. 50 microseconds. Since most modern microgrids are designed to integrate and increasing number of both alternative power generation devices, energy storage, and intelligent devices which all depend on power electronics, it is necessary to evaluate the microgrid system performance relative to system level

control algorithms within an environment that can support response times  $< 1\text{ms}$ . This capability will be provided by the FPGA-HIL system. The diagram below shows how the FPGA-HIL system will be leveraged to simulate tactical microgrids at a timescale  $< 1\text{ms}$ . The results from this simulation can then be used to drive CEM's HIL environment powered by existing National Instruments CRio devices, allowing the microgrid simulation environment to be coupled microgrid hardware for complete validation of system control algorithms prior to field deployment:



The electrical power network (including diesel gensets, energy storages, renewable energy sources, loads, and electric network) is simulated in the FPGA-HIL system. In microgrid models, various power converters and switching control logics need to be simulated in real time with a microsecond-level time step. The NI FPGA HIL simulator's high-speed simulation capability is the main enabler for this challenging microgrid simulation. The FPGA-HIL simulation environment can be extended even further to integrate testing of physical hardware. Various primary and secondary control algorithms can be implemented on hardware controllers (such as NI cRIO system and other PLCs or IEDs). The hardware controllers have analog/digital I/Os which are used to exchange information with the FPGA-HIL simulator. The Opal-RT eHSx64 Solver is deployed on the simulator to enable high-speed real-time simulation. Hardware controllers can access the real-time measurements (i.e. voltage, current, frequency, etc.) from the I/O modules on the FPGA-HIL simulator. The control algorithm performs the real-time calculation to decide the switching signal for power electronics devices and set-point or on/off status for each controllable device. The control commands are sent back to the FPGA-HIL simulator to close the simulation loop.

Through this way, the primary and secondary control functions could be validated using the simulated network model in the HIL simulation. Actual load profile, solar irradiance data, and wind speed data could be fed in the HIL simulation to create realistic scenarios. The NI cRIO system is an ideal control platform to implement primary and secondary control functions for power equipments in microgrids. NI cRIO system can also easily perform data acquisition for various offline studies.

In addition, the proposed simulation platform can integrate a variety of power equipment (such as PV system, diesel genset, circuit breakers, etc.) in the HIL system. This equipment will be interfaced with the HIL system through amplifiers and I/Os. The FPGA-HIL simulator performs accurate power network simulation and exchanges signals with power equipment in real-time to enable the power-hardware-in-the-loop (PHIL) simulation. Through PHIL, power equipment provided from different vendors could be tested and validated in the HIL platform. In the PHIL, the NI cRIO system can interface either with the FPGA-HIL simulator or actual power equipment. The PHIL platform with NI cRIO system provides a flexible testing solution to

validate both hardware controllers and hardware power equipment in a realistic simulation environment. Validation of controllers on physical hardware in the lab is will save money long-term, as the controllers from the lab can be taken directly to the field for deployment testing.

### **Summary of Key Results**

The UT-CEM microgrid has already been used to perform experiments relevant to the CEED mission. A series of such experiments has been concerned with the sudden application or dropping off of a large load, and the sudden loss from or insertion into the system of a generating unit. The experimental study of the role of energy storage on the stabilization of the power bus has also begun.

Now that the FPGA-HIL system has been delivered and commissioned, it will be used to support existing Army funded activities for tactical microgrid research into optimal electric distribution and machine design. Interconnection of advanced power generation, distribution and conversion equipment is, however, envisioned for future power system installation. The FPGA-HIL will be a key piece of processing and test equipment for the demonstration microgrid at UT-CEM and will enable research into critical power architecture issues as well as land based power systems, both from the theoretical simulation perspective and from the standpoint of experimental hardware testing and generation/de-risking of control strategies.

It will make possible the acceleration of computer simulations modeling power systems and would support the ongoing and projected tests of actual hardware and control methodologies in a realistic environment under the CEED program. In this manner, the DURIP equipment can lead to improved program research.

The FPGA-HIL also supports applied research projects for both undergraduate and graduate students focused on power system controls. During Spring of 2017, an graduate student from Finland obtained a research grant to develop and test her optimization controller at UT-CEM to learn more about designing power system controls. She was able to fully test her controller initially in the real-time simulation environment, and plans to return to do additional Control Hardware-in-the-loop (CHIL) testing with the FPGA-HIL system to validate the control algorithms embedded on real hardware. Once a control scheme was developed and tested using MATLAB Simulink, the plant model is migrated to CEM's existing Multi-purpose Real-Time

Simulation (MRTS) system, while this time the optimization controller was hosted by a separate PC. This configuration was used each time to test and validate the control algorithm. The next stage of testing for these controls will be to embed the optimization controller on a control board and conduct CHIL testing. Once convinced it is a stable and robust controller, one can advance to Hardware-in-the-Loop (HIL) testing leveraging the power converters mentioned earlier in this report.

