REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
04-12-2017	Final Report	16-Aug-2016 - 15-Aug-2017

4. TITLE AND SUBTITLE
Final Report: Acquisition of Real-Time Simulator for Intelligent Power Networks in Operational Energy Applications

5a. CONTRACT NUMBER
W911NF-16-1-0515

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
106012

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Texas at San Antonio
One UTSA Circle

San Antonio, TX 78249 -1644

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
68926-RT-REP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Hariharan Krishnaswami
UU	UU	UU	UU		19b. TELEPHONE NUMBER 210-458-5086

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 05-Dec-2017

Agency Code:

Proposal Number: 68926RTREP **Agreement Number: W911NF-16-1-0515**

INVESTIGATOR(S):

Name: Ahmad F Taha
Email: ahmad.taha@utsa.edu
Phone Number: 2104585568
Principal: N

Name: Hariharan Krishnaswami
Email: hariharan.krishnaswami@utsa.edu
Phone Number: 2104585086
Principal: Y

Name: Nikolaos Gatsis
Email: nikolaos.gatsis@utsa.edu
Phone Number: 2104585519
Principal: N

Organization: **University of Texas at San Antonio**
Address: One UTSA Circle, San Antonio, TX 782491644
Country: USA

DUNS Number: 800189185 EIN: 741717115
Report Date: 15-Nov-2017 Date Received: 04-Dec-2017
Final Report for Period Beginning 16-Aug-2016 and Ending 15-Aug-2017

Title: Acquisition of Real-Time Simulator for Intelligent Power Networks in Operational Energy Applications

Begin Performance Period: 16-Aug-2016 **End Performance Period:** 15-Aug-2017
Report Term: 0-Other

Submitted By: Hariharan Krishnaswami Email: hariharan.krishnaswami@utsa.edu
Phone: (210) 458-5086

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: The project's objective is to acquire a real-time Hardware-In-the-Loop (HIL) simulator system that will enable research in intelligent, adaptive and reconfigurable power networks for mobile and fixed power installations to enhance DoD mission effectiveness. The long term goal of this effort is to create a strong research and education center at UTSA focused on innovative technologies and solutions for Energy-Systems Management At Real-Time (Energy-SMART). As mentioned in the DoD Operational Energy Strategy, "energy is a fundamental enabler of military capability." Operational Energy (OE) contributes to nearly 70% of DoD's fuel use by volume. There is a national need to develop technologies that will improve the use of energy by DoD. UTSA's research capability in modeling and simulating complex military unique platforms will be enhanced by the proposed real-time simulator system. The system will serve as a catalyst in creating and validating innovative Energy-SMART solutions to OE challenges.

Goal #1

UTSA will acquire a Real-time Simulator system manufactured by Opal-RT Technologies as mentioned in the original proposal. The main hardware unit in the simulator is the OP5600 V2 HIL Virtex6 FPGA-based Real-Time Simulator with high-performance Xeon E5 cores. The simulator is equipped with Analog I/O cards with 16 Channels each and Digital I/O cards with 32 channels each to accommodate various signals during HIL testing. The simulator has also several communication drivers as needed to model and emulate different energy sources and to communicate with different types of equipment and sensors used in a power network.

Goal #2

UTSA will acquire a 21KVA four-quadrant power amplifier for Power HIL (PHIL) testing is included as part of the equipment in a separate cabinet with appropriate communication and cables with drivers provided on the simulator for seamless PHIL testing.

Goal #3

UTSA will acquired appropriate software to run the simulator. The software platform includes (i) eMEGAsim - a

scalable real-time simulator that can achieve ultrafast, accurate and reliable real-time simulation of very large systems such as PV, wind, fuel cells, energy storage, power inverters and power grids; (ii) eFPGAsim with time steps reaching as low as 100ns for detailed study of power electronic converters; (iii) ePHASORsim for real-time transient stability simulations with time-step of >10ms capable of simulating 1000 bus power network.
Goal #4
As part of the contract, UTSA will have a total of 20 days of intensive and on-site/online training on software, hardware and integrated operation of the Real-Time Simulator and the Power Amplifier by the equipment manufacturer.
Goal #5
UTSA will initiate several research projects after the training, and the report will give samples of these research projects focused on Energy-SMART.

Accomplishments: A pdf file has been uploaded in the Upload Section summarizing the accomplishments for this project

Training Opportunities: Table 4 in the report uploaded summarizes the training provided to students during the reporting period on the equipment.

Results Dissemination: A summary of research projects initiated after the acquisition of the equipment is provided in the report.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Co PD/PI
Participant: Ahmad Taha
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Nikolaos Gatsis
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
as of 05-Dec-2017

Final Report

Project Title:	Acquisition of Real-Time Simulator for Intelligent Power Networks in Operational Energy Applications
Project Period:	08/16/16 – 08/15/17
Project Budget:	$280,410
Submission Date:	11/13/17
Recipient:	The University of Texas at San Antonio
Address:	One UTSA circle San Antonio, TX 78249
Award Number:	W911NF-16-1-0515
Project Lead:	University of Texas at San Antonio
Principal Investigator:	Hariharan Krishnaswami Associate Professor Phone: 210-458-5086 Fax: 210-458-5947 Email: hariharan.krishnaswami@utsa.edu
Co-Principal Investigators:	Nikolaos Gatsis, Assistant Professor Email: Nikolaos.Gatsis@utsa.edu Ahmad Taha, Assistant Professor Email: Ahmad.Taha@utsa.edu
Submitted by: **(if other than PI)**	Amy Ossola-Phillips Research Service Center Administrator Phone: 210-458-6472 Fax: 210-458-7973 Email: Amy.Ossola-Phillips@utsa.edu

Executive Summary

The project's objective is to acquire a real-time Hardware-In-the-Loop (HIL) simulator system that will enable research in intelligent, adaptive and reconfigurable power networks for mobile and fixed power installations to enhance DoD mission effectiveness. The long term goal of this effort is to create a strong research and education center at UTSA focused on innovative technologies and solutions for Energy-Systems Management At Real-Time (Energy-SMART). As mentioned in the DoD Operational Energy Strategy, "energy is a fundamental enabler of military capability." Operational Energy (OE) contributes to nearly 70% of DoD's fuel use by volume. There is a national need to develop technologies that will improve the use of energy by DoD. UTSA's research capability in modeling and simulating complex military unique platforms will be enhanced by the proposed real-time simulator system. The system will serve as a catalyst in creating and validating innovative Energy-SMART solutions to OE challenges.

UTSA has acquired a Real-time Simulator system manufactured by Opal-RT Technologies. The main hardware unit in the simulator is the OP5600 V2 HIL Virtex6 FPGA-based Real-Time Simulator with high-performance Xeon E5 cores. The simulator is equipped with Analog I/O cards with 16 Channels each and Digital I/O cards with 32 channels each to accommodate various signals during HIL testing. The simulator has also several communication drivers as needed to model and emulate different energy sources and to communicate with different types of equipment and sensors used in a power network. The simulator is placed in a closed cabinet with lockable doors and Ethernet switch board. A 21KVA four-quadrant power amplifier for Power HIL (PHIL) testing is included as part of the equipment in a separate cabinet with appropriate communication and cables with drivers provided on the simulator for seamless PHIL testing.

UTSA has also acquired appropriate software to run the simulator. The software platform includes (i) eMEGAsim - a scalable real-time simulator that can achieve ultrafast, accurate and reliable real-time simulation of very large systems such as PV, wind, fuel cells, energy storage, power inverters and power grids; (ii) eFPGAsim with time steps reaching as low as 100ns for detailed study of power electronic converters; (iii) ePHASORsim for real-time transient stability simulations with time-step of >10ms capable of simulating 1000 bus power network. As part of the contract, we have also had a total of 20 days of intensive and on-site/online training on software, hardware and integrated operation of the Real-Time Simulator and the Power Amplifier. As part of the contract, the supplier has also provided free five year annual maintenance with software upgrades.

We have initiated several research projects after the training, and the report gives samples of these research projects focused on Energy-SMART. The system will support UTSA research programs in power electronics, micro-grids, intelligent power networks, distributed generation, cyber-physical systems, fixed power installations, naval and ground vehicle platforms. The system will also be used to support both undergraduate and graduate level courses in power electronics, power systems, cyber-physical systems, optimization, senior design projects and graduate research for UTSA's engineering programs.

Table of Contents

Project Background

We have acquired a real-time simulator system which can perform controller hardware-in-the-loop (CHIL) and power hardware-in-the-loop (PHIL) simulations. This system will support the following long-term objectives of Energy-SMART research topics being explored at UTSA: 1) Creating novel power electronics and power systems architecture for military unique platforms, 2) Generating control algorithms for intelligent energy management of distributed energy generation and load, 3) Ensuring resiliency in cyber-physical systems architecture for energy security, and 4) Validating technologies in real-time on emulated models that accurately replicate an actual system. These objectives align well with the DoD Operational Energy (OE) Strategy Document [1] and the Power and Energy Focus area in the Naval S&T Strategy document [2]. An overview of the acquired system is shown in Figure 1. The OP5600 Real-Time Simulator and the 21kVA four-quadrant DC and AC Power Amplifier are highlighted in Figure 1 with actual pictures from the laboratory. UTSA already has the solar PV emulator, programmable loads, controller hardware and power inverters which will work easily with the acquired simulator.

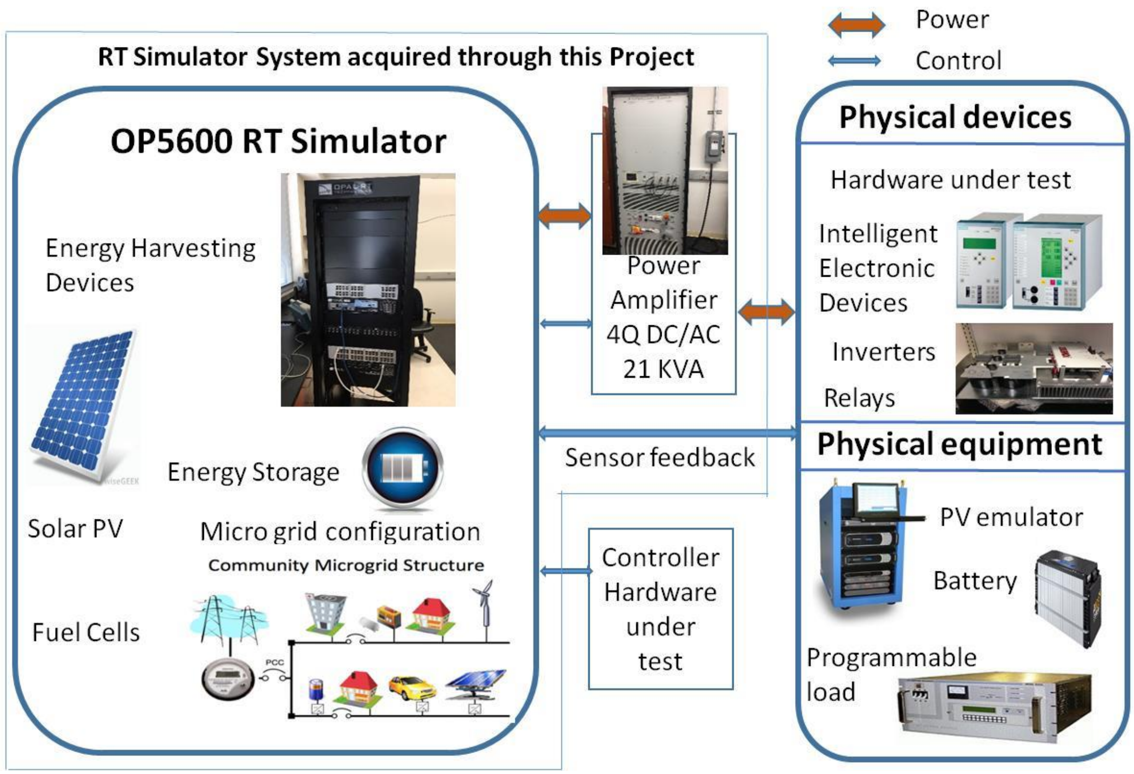

Figure 1 Overall Configuration of an HIL and PHIL setup showing the Simulator and Power Amplifier acquired through this grant

The innovation on the acquired HIL simulator system is in the comprehensive nature of the systems that it will emulate in real-time. First, this system allows 250ns simulation of power electronics, as bi-directional converters and inverters are the enabling technologies for intelligent power network management. Second, this simulator enables real-time emulation of solar panels, fuel cells, and all types of energy storage and energy harvesting devices. Third, this simulator allows real-time controller and transient simulation with time steps as low as 10μs for power networks.

Fourth, this simulator can have real controller and power hardware such as IEDs, protection systems, on/off switches, and a power amplifier in the loop. Finally, this simulator can easily import models from most simulation software such as Matlab/Simulink and power electronics simulation software. These five characteristics of the simulator span the Energy-SMART research areas in power electronics, micro-grids, intelligent power networks, distributed generation, cyber-physical systems, fixed power installations, naval, aircraft and ground vehicle platforms.

Details of Acquired Equipment

The following sections details the different parts of the equipment along with cost and any special circumstances associated with the equipment.

OP5600 Real-time Simulator

The OP5600 is the main simulator shown in Figure 2 along with other components in the rack. Table 1 lists in the items in the Simulator, cost and a brief description. OP8600 shown in Figure 2 is explained in the Power Amplifier section.

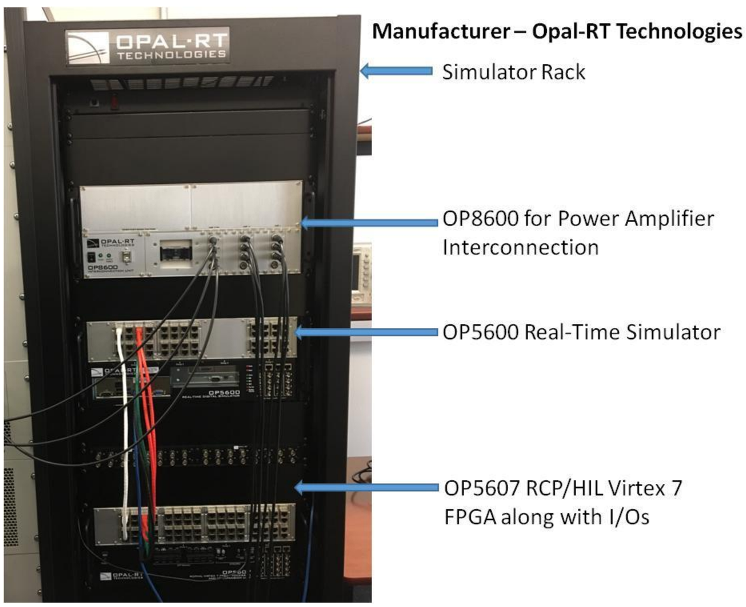

Figure 2 Purchased Real-time Simulator in Laboratory with different components named

Table 1 List of parts in the real-time simulator rack

Line	Part #	Description	Qty	Cost
1	OP5660-16	OP5600 V2 Simulator with Xeon E5 Cores	1	$17,030.00
2	OP5607-I/O	RCP/HIL Virtex 7 FPGA Processor and I/O expansion unit	1	$15,500.00
3		Red Hat Linux Compiler	1	$975.00
4	OP5330K1	Analog Output Card 16 channels 16 bits	1	$1,786.00
5	OP5340K1	Analog Input Card 16 channels 16 bits	1	$1,786.00
6	OP5360-2K2	Digital Output card 32 channels, can be 32 PWM	1	$4,456.02

7	OP5353K2	Digital Input card 32 channels, can be PWM input	1	$3,556.08
8	PCIeKit	IRIG/GPS Synchronization reference board	1	$781.00
9	SR1302268	Cabinet for the simulator 19” by 31.5” by 78”	1	$4,575.00
10	CDF1970VBK1	19 by 70 locable door for the cabinet	1	$500.00
11	RT-DRV-DNP3	Driver DNP3 slave communication for open, standards-based interoperability with IEDs in utility industry	1	$11,196.50
12	RT-DRV-61850G	Driver IEC61850 for protection relay interface	1	$7,350.00
13	RT-DRV-C137R	Driver for Phasor Measurement Units	1	$7,350.00
14		Additional 15% discount for items 12,13,14		-$3,884.48
		Sub-Total		**$75,429.12**

Software components

Table 2 lists the software purchased along with the equipment, cost and a brief description of the software and its capabilities.

Table 2 List of Software purchased along with Real-time Simulator

Line	Part #	Description	Qty	Cost
1	000-0130-0003	RT-Lab Host/workstation License – node-locked license specific to the simulator purchased	1	$7,044.10
2	000-0130-0011	eMEGAsim – Real-Time Target license, license needed for each core, obtained license for 2 cores	2	$31,103.80
3	000-0130-0050	ePHASORsim to simulate power systems network or any power network with a maximum of 1000 buses. Allows Python API	1	$8,400.00
4	S01-0039	eFPGAsim-eHS generic nodal solver for power electronic circuits simulation	1	$3,496.50
		Sub-Total		**$50,044.40**

Power Amplifier

The power amplifier along with the OP5600 simulator is shown in Figure 3 along with the interconnection box OP8600 installed in the simulator rack. Table 3 lists the power amplifier, interconnection box, cost and a brief description. The amplifier is rated at 21kVA and needs a three-phase 208V source. The installed three-phase source is also shown in Figure 1 (behind the amplifier). The installation cost of the three-phase power source has been included in the budget. The power amplifier weight was 800kG, and UTSA facilities coordinated an assessment of the 2nd floor lab to handle the power amplifier weight per square inch.

Table 3 List of parts needed for Power Amplifier and Simulator interface

Line	Part #	Description	Qty	Cost
1	PCU-3x7000-AB/400V/AG	Power Amplifier Four Quadrant 21KVA, 7kVA per phase	1	$101,510.00
2	OP8211-32	Interface Panel	1	$898.20

3		Rack Accessories	1	$343.00
4	TENGDAYINT	Integration service and factory acceptance test for power amplifier integration - includes manpower technical and engineering		$2,941.00
		Sub-Total		**$105,692.20**

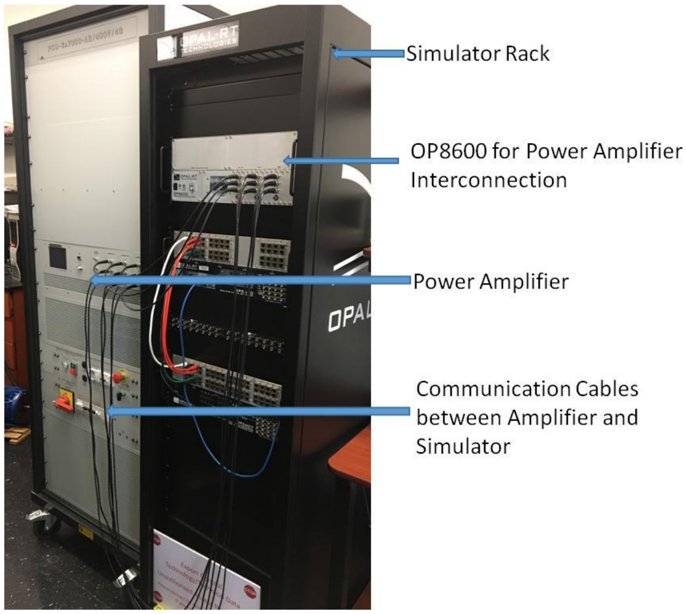

Figure 3 Power Amplifier and Simulator shown together with interconnecting cables

Training Summary

A total of 13 students, graduate and undergraduate, participated in full or in part the training conducted on the equipment and the software packages. Table 4 provides the dates of training and the content of training. The total number of days of training is 20. Table 4 also gives the cost of the training.

Table: 4 Dates of Training and the Content covered during the training

Training	Content Covered	Dates
	Training 1 by Amin Yamane PHIL	
Day 1	Introduction to ARTEMIS	03/20/2017
Day 2	Artemis solver compared to Simpower systems – hands on	03/21/2017
Day 3	Artemis decoupling elements-hands on	03/22/2017
Day 4	Introduction to PHIL applications	03/23/2017
Day 5	Hands on, challenges and possible solutions to the current projects	03/24/2017
	Training 2 by Vithuran Vilvarajah and Mathieu Mayer-Girouard Covering Artemis and RT-Lab	

Day 1	RT-Lab Training- Hands on	06/12/2017
Day 2	Hardware configuration and I/O management	06/13/2017
Day 3	Artemis and RT-Events training	06/14/2017
Day 4	API Python, Concept Recap	06/15/2017
Day 5	Power System/ Power Electronics simulations, using RT-Events	06/16/2017
	Training 3 by Marc-Andre Matieu and Derek Boychuk on Artemis	
Day 1	Introduction to ARTEMIS	03/20/2017
Day 2	Artemis solver compared to sim power systems – hands on	03/21/2017
Day 3	Artemis decoupling elements-hands on	03/22/2017
Day 4	Introduction to PHIL applications	03/23/2017
Day 5	Hands on, challenges and possible solutions to the current projects	03/24/2017
	Training 4 by Sergio Atayde on Power Amplifier Integration	
Day 1	Functional Verification tests for power amplifier	09/11/2017
Day 2	Amplifier Control in open loop	09/12/2017
Day 3	Voltage and current measurements in closed loop	09/13/2017
Day 4	Review of eFPGA sim and RT-Events, power amplifier –Hands on	09/14/2017
Day 5	Verification of the projects in online mode and ran an induction motor load through power amplifier	09/15/2017

Table 5 Equipment and software training and its associated costs

Line	Part #	Description	Qty	Cost
1		Onsite PHIL Software Simulation Studies	1	$7,440.00
2		Onsite PHIL Hardware Integration	1	$7,440.00
3		10 days customized training for eMEGAsim, ePHASORsim, eFPGAsim	1	$15,769.10
		Sub-Total		**$30,649.10**

Summary of Research Projects

Power Converters in Operational Microgrid Network and Naval Platforms

The proposed PHIL testing of Power Distribution Units (PDUs) is given Figure 4, as taken from the original proposal. In line with this research focus, several projects have been initiated using the Real-Time Simulator as the major equipment. The following sections provide a sample of three research projects that have been initiated along with preliminary research results. Further research will continue in this area of power converters in microgrid network and Naval research platforms.

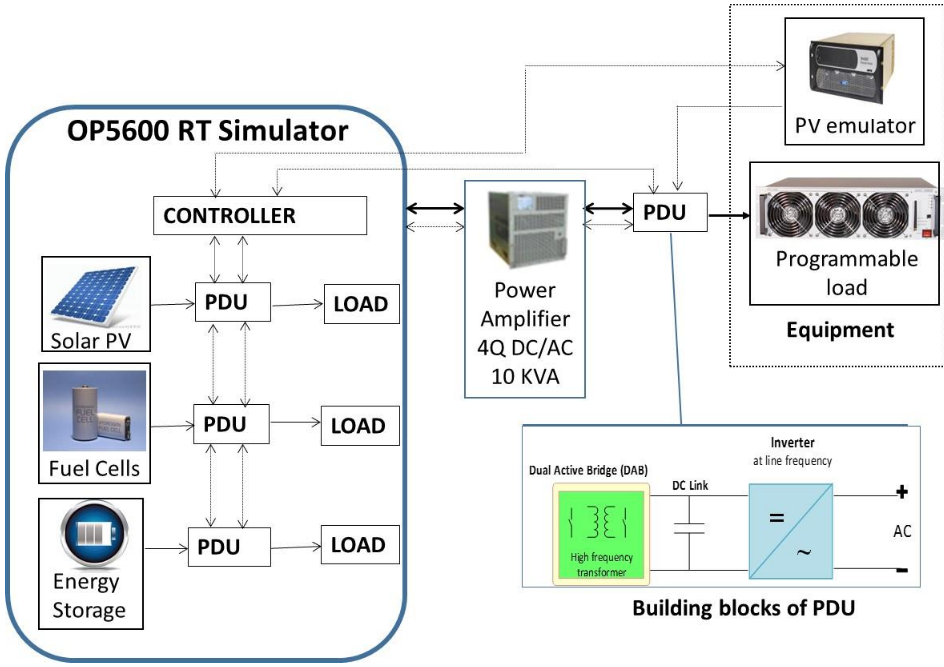

Figure 4: Proposed PHIL testing of PDUs in operational energy networks

<u>Modular Multi-level Converters as building blocks of PDUs</u>
Graduate Student: Turgay Duman; Advisor: Dr. Hariharan Krishnaswami (PI)

Modular Multilevel converters have many advantages over conventional voltage source converters. Some of those advantages are higher voltage levels, low THD, modularity, lower dv/dt per switch, and etc. However they usually contain more number of switches compare to conventional converters. Therefore simulation of MMC with higher number of switches can be complex and takes several hours to simulate offline for few seconds in real-time. Sim Power Systems (SPS) is the main toolbox of Simulink to simulate electric circuits. It is based on state-space equations of power systems. It uses precalculation of all possible state-space matrices for all switch possibilities. Therefore the simulation of circuits with higher number of switches will not be easy, nor will it be fast to simulate. OPAL-RT introduced ARTEMIS solver which enables to use State Space Nodal solver (SSN). SSN of ARTEMIS basically separates the electric circuit into small groups and finds the equation of each circuit. While Sim Power System is trying to solve a big complicated equation, SSN divides this complicated equation into small groups and solves each small group. Therefore complex power electronic circuits can be simulated without any switch count limitations. Figure 5 shows the block diagram of a three-port cascaded Multilevel Dual-Active-Bridge (DAB) based converter and Neutral-Point-Clamped (NPC) inverter.

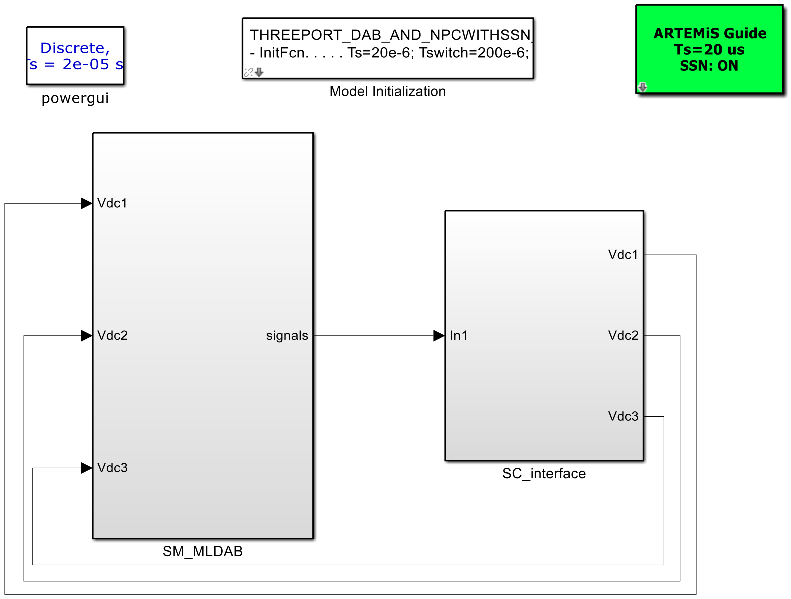

Figure 5 Block diagram of system as seen in RT-LAB using Artemis Solver

In this project three ports Multilevel DAB (ML-DAB) and NPC inverter are cascaded in series as shown in Figure 6. ML-DAB consists of one H bridge (4 semiconductor switches) and one NPC inverter (8 switches and 4 diodes). Neutral Point Clamped inverter has 8 switches and 4 diodes. Each port has 28 switches and 8 diodes. The system has 3 ports cascaded in series and has 84 switches and 24 diodes. As it can be seen in Figure 6, the system has been divided into 6 groups by using ARTEMIS SSN blocks.

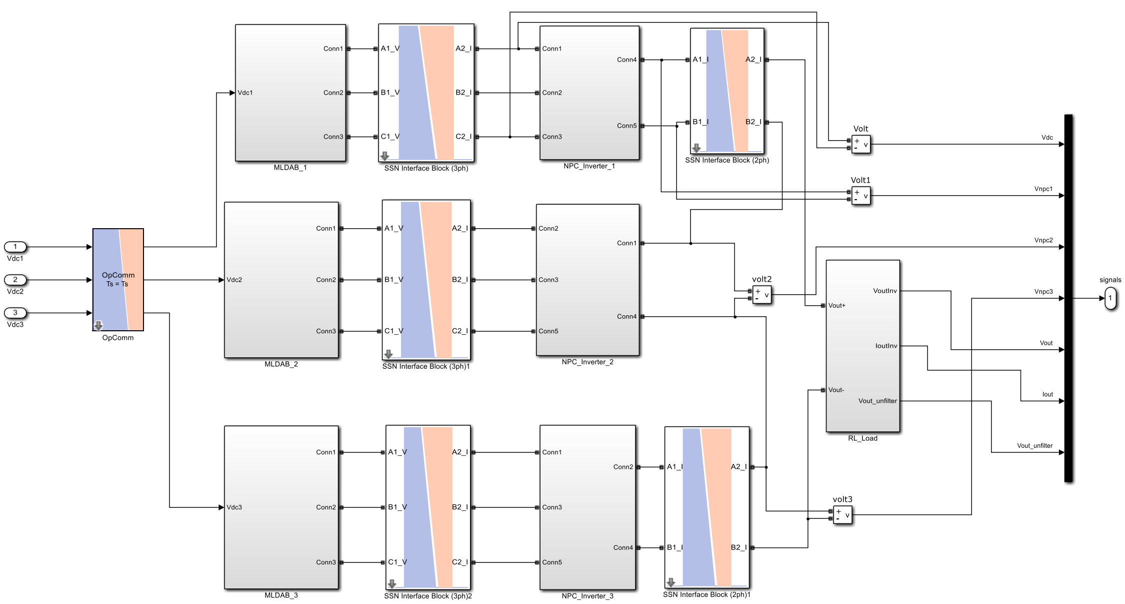

Figure 6 Three port cascaded MLDAB and NPC Inverter as modeled in RT-Lab using ARTEMIS solver

Preliminary results from the Real-time Simulator are shown in Figure 7 showing both the muli-level waveform and the averaged waveform for the sinusoidal output. These results show the capabilities of the real-time simulator to simulate large systems with multiple PDUs. Further research will continue in the area. Once the model is verified using ARTEMIS, the complete system can be realized using the Simulator which is the next step in the project.

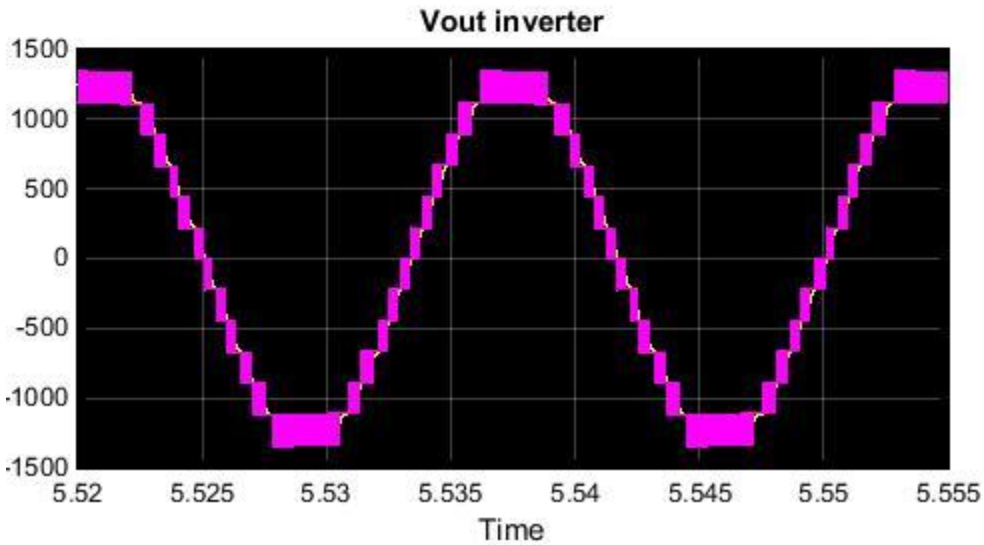

Figure 7 Multi-level waveform from the ARTEMIS solver

<u>Controller Hardware-In-the-Loop Testing using DAB converter interfaced with Solar Panel</u>

Graduate Student: Shilpa Marti; Advisor: Dr. Hariharan Krishnaswami (PI)

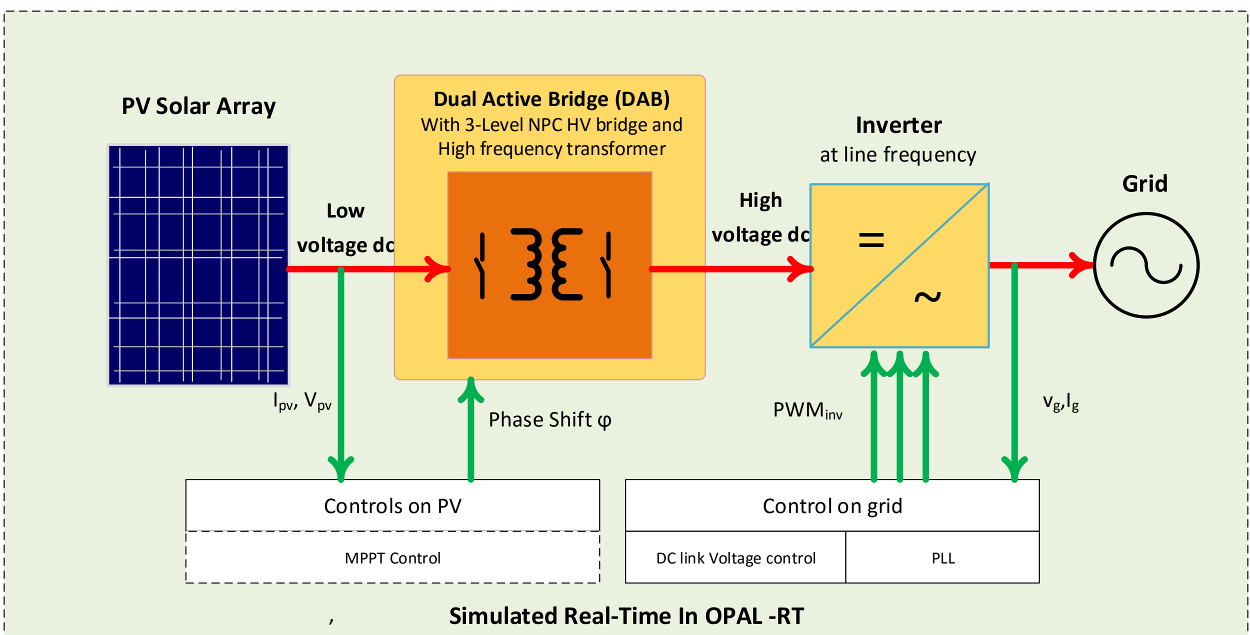

Figure 8 Block Diagram of the PV system connected to grid simulated in Real-Time.

In a two-stage grid connected photovoltaic (PV) systems, maximization of the input and the output power of the DC-DC converter depends on the variation of the converter efficiency, which in turn depends on the operating point of the converter. In some cases such as a Dual Active Bridge dc-dc converter interfaced with PV, as shown in Figure 8, the increase in PV input power leads to operating conditions with lower efficiency. Hence determining the operating point for different atmospheric changes of the converter is determined under real-time environment by simulating in OPAL-RT Simulator. Incremental Conductance MPPT algorithm for a two-stage, single-phase, grid-connected PV system with (ML-DAB) DC-DC converter and an H-bridge inverter is implemented in OP5600 Real-Time Simulator hardware to validate the theoretically determined operating region.

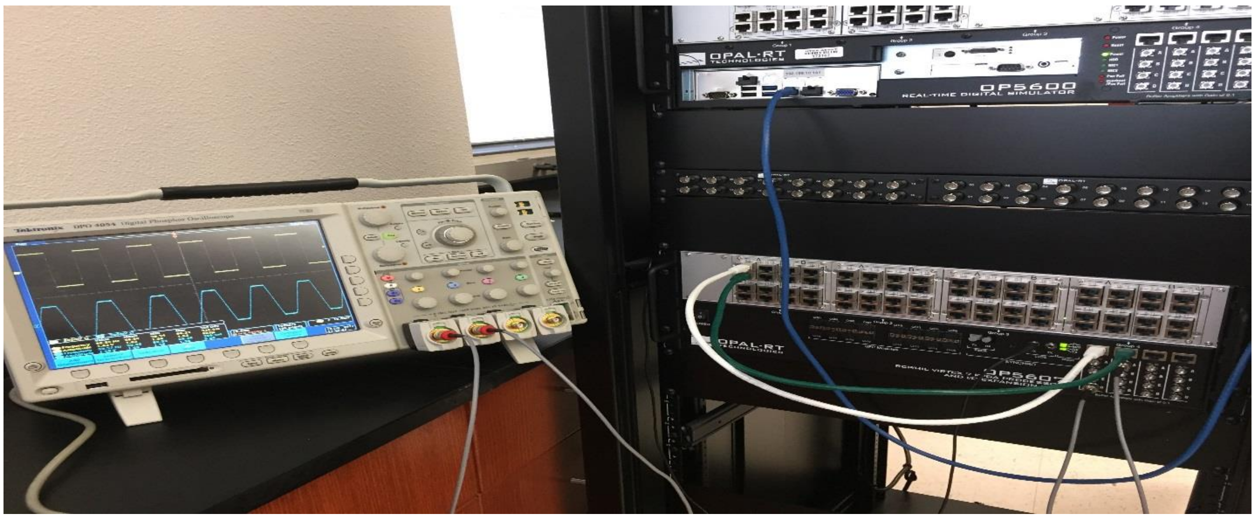

Figure 9 Real-Time implementation of MPPT algorithm on the Simulator

Rather than determining operating point experimentally, evaluation of operating range of the converter, for PV interfaced systems will help in developing efficient converter with wider operating points. Operating range of PV connected ML-DAB DC-DC converter is theoretically calculated and experimentally verified in Real-Time with the aid of OPAL-RT real time simulator. With the simulator we can scale up the system and evaluate the operating range to design more efficient ML-DAB converter. Robust, fast, distributed and cost-effective MPPT controller algorithms for the PV systems interfaced with modular PDUs can be developed and tested in Real-Time.

DC Microgrid Real-Time Simulation

Graduate Student: Felipe Salas; Advisor: Dr. Hariharan Krishnaswami (PI)

From Naval ship power systems to Forward Deployable Operating Bases, microgrid power systems benefit military applications for homeland defenses. Contributions in this area are very important and real time simulations are a huge factor when taking into account successful implementations. Forward Operating Bases have been in operation for years and making them deployable will allow preparation and readiness for any unforeseen circumstances. Efficient Energy systems in Forward Deployable Operating Bases (FDOB) are an area of research that looks to improve cost, reaction time, and overall performance. Using Distributed Energy Resources (DERs) within DC Microgrids in FDOBs give the ability to model efficient systems. Multiple sources of energy supply various loads within the FDOB. At times, depending on mission essential need, some loads may consume more power than others. This can lead to an energy system deficiency if energy sources are not allocated correctly based on availability. A combination of Fuel Cells, Solar, Wind, and Hybrid Electrical Energy Storage (HEES) are used to power these microgrids. Controlling how each source allocates its energy is essential. Transportation of fossil fuels to these remote FDOBs may also cause challenges in cost and availability. This potential logistics problem can effect overall cost and degrade the cost saving potential of a microgrid. Effectively pursuing optimization and designing microgrids efficiently will counter this potential harm. The Proton Exchange Membrane Fuel Cell (PEMFC) is a viable DC source to implement in a DC Microgrid. Many systems take advantage of this electrochemical technology that will be described in the Model implemented on a Real-time simulator.

The Simulink 'Fuel Cell Stack' model results in a constant 45VDC, 133.33A, and approximately 6000W output. Many detailed parameters can be set in using the PEMFC model from fuel ratios to atmospheric pressure adjustments. In the described system a simplified version at nominal temperature and pressure is used to display the use of this robust energy source in the Opal-RT Simulink environment. The proposed fuel cell stack system will supply a constant 200VDC to a bus which will suffice loads such as DC lighting, communication equipment, battery charging etc. The initial design approach is to incorporate a DC-DC Boost Converter with the Fuel Cell Stack to achieve a voltage bus rating of 200VDC. The efficiency of the converter must approximately maintain the 6000W output of the Fuel Cell model. Figure 10 below shows how the model is configured in Opal RT/Simulink using subsystems to allocate computational systems to the Opal RT CPU core and the GUI for the system scopes.

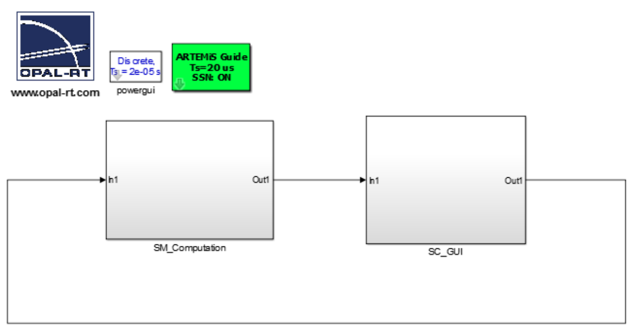

Figure 10 Opal RT Subsystems of Fuel Cell DC-DC Boost Network

This Opal RT configuration is necessary in order to compile systems in the real time simulator. The highest level in the simulation environment must consist of subsystems in which directly communicate to the Opal RTs CPU cores. The subsystem on the left labeled, 'SM_Computation', will consist of the Fuel cell and DC/DC Boost converter. The subsystem to the right labeled, 'SC_GUI', will consist of the graphical user interfaces in which this computation stays local to the host PC. The 'SC_GUI' requires the host PC to operate as the signals visual output waveforms. Further research is being pursued in this area of modeling Fuel Cells in Real-time Simulator Environment. This project when combined with the PDUs for solar photovoltaic systems will enable complete modeling of a forward operating base with renewable energy sources.

Ultra-small DC link Capacitor, GaN-Based AC Motor Drive for Fan and Pump Applications

Graduate Student: Reynaldo Gonzalez; Advisor: Dr. Sara Ahmed (ECE Department Assistant Professor in power and energy systems, joined ECE department after this project was awarded and has been actively using the Real-time Simulator)

One of the research objectives explained in the original proposal include modeling and simulating Wide Band Gap (WBG) based power electronics and this project presents preliminary research results in this area. In some applications such as a fan and pump, high performance is, in general, not required and regeneration is not needed. In addition, these application areas are somewhat sensitive to the price. In many cases, reduction of weight and volume is beneficial. The size and cost of passive components have become one of main concerns in terms of cost, volume, and weight. In the past, researchers tried to reduce the number of semi-conductors switches since the cost of semi-conductor switches was more significant than that of passive components. However, reducing passive components such as inductors, transformers, and electrolytic capacitors is much more significant than to reduce active elements in terms of size and cost effectiveness. In addition, the lifespan of electrolytic capacitors is typically shorter than the other components in the drive systems. Reducing the dc bus capacitance offers the improved input current THD, resulting in reduced input filter requirements. Combining the benefits of reducing the passive components with introducing a wide-band-gap semiconductor (gallium nitride - GaN) based drive will further enhance the performance. The functionalities and frequency capabilities of the GaN transistors will allow much higher switching frequencies which will result in reduced switching losses, and further compact filters and passives while still having pure sine wave power output.

In this project, the research team is building a GaN based AC motor drive with reduced passives. The DC choke is removed and the DC link capacitance is reduced while pushing the switching frequency of the inverter higher and the system performance is investigated. To reach this goal, the team have implemented a real-time simulation in Opal-RT for a 3 hp motor drive fed from a passive rectifier and feeding an induction motor (See Figure 11).

The simulation will allow the analysis of multiple scenarios (for example, capacitance value versus switching frequency used) for model performance optimization. Once the hardware inverter is ready, the team will analyze the system performance using Power Hardware-in-the-Loop testing. The Power Hardware-in-the-Loop setup will include the three phase source and input rectifier (diode rectifier) simulated in Opal-RT, the output of the rectifier will be amplified using the acquired 4-Q 21kVA power amplifier and will feed the hardware GaN inverter module hat is loaded with a 3hp induction motor currently available in our lab (see Figure 12).

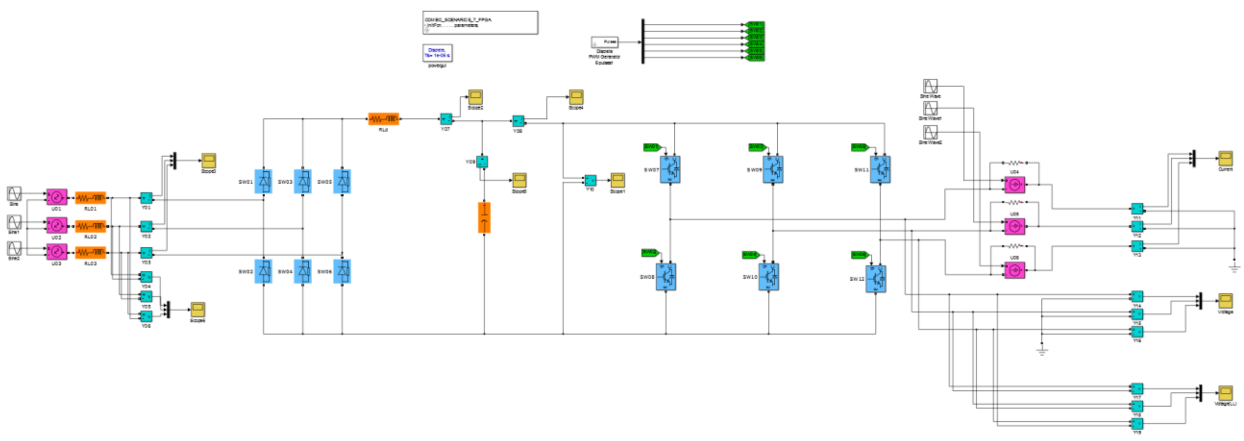

Figure 11 - Motor Drive Schematic as implemented in Matlab SimPowerSystems toolbox

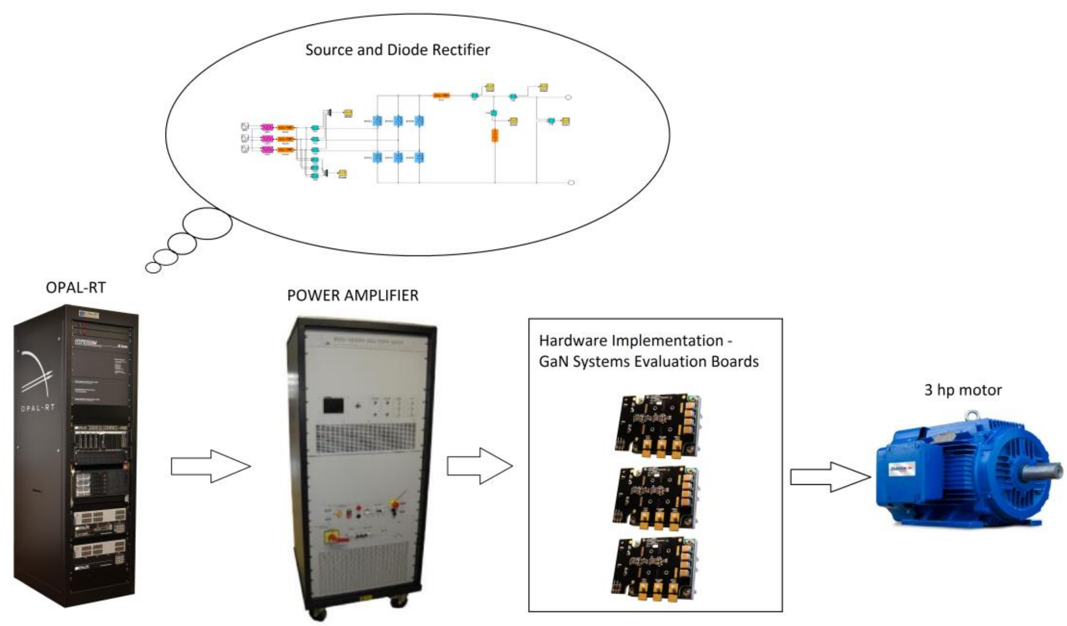

Figure 12 - Power Hardware in the Loop setup for this project

Adaptive Energy Management in Operational Distribution Networks with Renewables

Graduate Students: M. Bazrafshan, K. S. Ayyagari; Advisor: Dr. Nikolaos Gatsis(Co-PI)

Operational energy distribution networks, which can be found in base camps or ships, for example, are characterized by an array of requirements. They are envisioned to be fixed or mobile, depending on mission needs, but must share the attribute of re-deployability. To ensure sustainability, operational networks must accommodate a variety of distributed energy resources, ranging from fuel-fired generation and renewable generation, such as solar power from photovoltaic units, to energy storage units of various densities and charge/discharge time constraints. Depending on the mission objective and commands, many other diverse and evolving requirements are also present, and the network must be able to supply these loads with the required power in an uninterrupted fashion.

Several challenges emerge when making an effort to design operational energy networks with the previously mentioned attributes. The chief challenge among them is the uncertainty present due to a variety of factors. Firstly, renewable energy is by nature intermittent and depends on local conditions. Forecasting the amount of available renewable energy over a certain time horizon is possible; but forecasts themselves have errors, and the number of errors present tends to increase with an increasing time horizon. Secondly, mission objectives may change during network operations, which implies that the priority of loads to be serviced must vary accordingly. Finally, nodes in the electrical network may fail randomly due to incidences such as an enemy operation, but the overall network must always maintain its resilience.

In order for a networked energy system to operate under uncertainty, a holistic framework for intelligent power management is needed. We have developed stochastic optimization methodologies for operational energy network management that feature *adaptability to uncertainty* [3, 4]. These methodologies will be tested on the network simulator; see Figure 13.

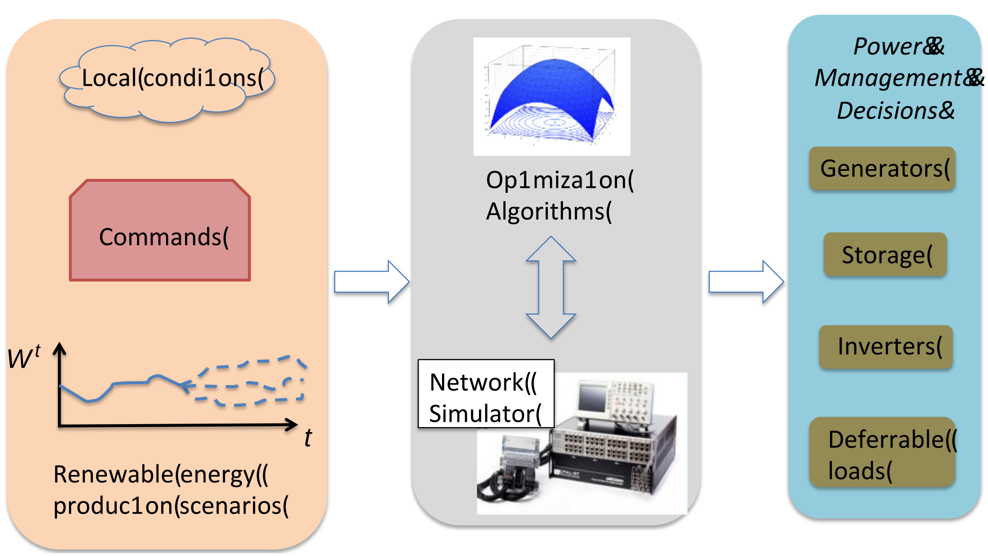

Figure 13 Adaptive Optimization Framework for Operational Energy Networks

Available resources in the operational distribution network comprise fuel-based energy sources, energy storage units, dispatchable inverters for voltage and reactive power support, and deferrable loads (i.e., loads that the intelligent power management algorithm can schedule for a later time according to the mission objectives). The intelligent power management algorithms we have developed can optimally allocate the aforementioned resources. Our next task is to run and test the previously mentioned algorithms for realistic operational distribution networks and microgrids on the acquired network simulator. Our goal is to test the algorithms on networks of different complexities and characteristics, such as base camp distribution networks or distribution networks on ships.

Real-Time Simulator Applications: Enabling CPS Advancements in Mobile and Fixed Power Installations

Investigator: Dr. Ahmad Taha (Co-PI)

Simulating the Coupling of the Operation and Transient Stability Timescales in Power Systems

Capacity expansion and generation planning, economic dispatch, and frequency regulation are decision making problems in power networks that are solved over different time horizons. These problems range from decades in planning to several seconds in transient control. For decades, these problems have traditionally been treated separately. With the integration of renewables, the time-scales separation shrinks as investigated in recent studies. Our work in this topic aims to integrate two crucial power network problems with different time-scales. The first problem is the steady-state optimal power flow (OPF), whose decisions are updated every few minutes. The second is the problem of load-following stability that spans the time-scale of several seconds to one minute. Specifically, the OPF problem is augmented to account for the costs associated with the load-following stability of a power network described by a set of nonlinear, uncertain differential algebraic equations (DAEs). The developed approach, scalable to networks with thousands of nodes, yields new OPF operating points that show much improved overall system costs and significant reductions in the frequency oscillations. We also consider integrating control of doubly-fed induction generators and utility-scale solar farms.

In this work, we plan to use the HIL simulator to test the integration of the operation and transient stability time-scales in power systems. Specifically, we plan to replicate large power networks with thousands of buses and hundreds of generators, solar and wind farms, and distributed energy resources in distribution networks, all in the simulator, while testing the developed algorithms of the time-scales integration. The nonlinear DAEs representing the transients and steady-state of power networks will also be simulated using the simulator.

Buildings-to-Grid Integration

By 2050, 70% of the world’s population is projected to live and work in cities, with buildings as major constituents. Buildings’ energy consumption contributes to more than 70% of electricity use. Future cities with innovative building operations have the potential to play a pivotal role in reducing energy consumption, curbing greenhouse gas emissions, while maintaining stable electric-grid operations. Buildings are physically connected to the electric power grid, thus it would be natural to understand the explicit coupling of decisions and operations of the two. Our recent work puts forth a mathematical framework for Buildings-to-Grid (BtG) integration in smart cities. The framework explicitly couples power grid and buildings' control actions and operational decisions. This work analytically establishes that the BtG integration yields a reduced total system cost in comparison with decoupled designs where grid and building operators determine their controls separately or via other demand response schedules. The objective of this study is to obtain localized control actions for power network generators and distributed energy resources, in addition to HVAC set-points for buildings in smart cities. The overall framework enables a more stable, grid-aware buildings operation and vice versa. The HIL simulator will be used with realistic models of thousands of buildings and generators to showcase building energy savings for the proposed BtG integration scheme in real-time, while potentially showing significant frequency and voltage regulation potential of buildings.

References

[1] US Department of Defense, "Operational Energy Strategy: Implementation Plan," March 2012. [Online.] Available: http://energy.defense.gov/Portals/25/Documents/Reports/20120306_OE_Strategy_Implementation_Plan.pdf

[2] Office of Naval Research, "Naval S&T Strategy," January 2015.

[3] M. Bazrafshan and N. Gatsis, "Decentralized stochastic optimal power plow in radial networks with distributed generation," *IEEE Trans. Smart Grid*, vol. 8, no. 2, Mar. 2017, pp. 787-801.

[4] K. S. Ayyagari, N. Gatsis, and A. F. Taha, "Chance Constrained Optimization of Distributed Energy Resources via Affine Policies," in *Proc. 5th Global Conf. Signal and Information Processing*, Montreal, Canada, Nov. 2017.