Hardware in the Loop Simulation of a Nano-Grid Transactive Energy Exchange

Mladen Kezunovic[1], Milad Soleimani[1], Haitham Abu-Rub[2], Sertac Bayhan[3], Mohamed Trabelsi[4]

[1] Electrical and Computer
Engineering Department,
Texas A&M University,
College Station, Texas, U.S.A,

[2] Electrical and Computer
Engineering Department,
Texas A&M University at
Qatar, Doha, Qatar,

[3] Qatar Environment and
Energy Research Institute,
Hamad Bin Khalifa University,
Doha, Qatar,

[4] Department of Electronic and
Communications Engineering,
Kuwait College of Science and
Technology, Kuwait,

***Abstract*—Nowadays, the electricity grid from the customer side is getting more complex. Number of customers with photovoltaic (PV) generation, plug-in electric vehicles (PEVs), and stationary battery energy storage system (BESS), referred here as Nano-Grid or n-Grid are increasing. With proper economic incentives and control mechanisms, the n-Grid may be used to ensure grid reliability and resilience if engaged in energy exchange with other n-Grids or the main grid. Such energy exchange framework is called transactive energy. The complexity and variety of the component integration and operation make n-Grid involvement in the transactive energy framework challenging. In this paper, a hardware-in-the-loop (HIL) simulation framework is introduced to provide solutions for some of the issues of power system and power electronics co-simulation that represent the backbone for the transactive energy exchange. Since grid decision making process has conspicuously different time constant in comparison with power inverters' switching frequency, including both in a simulation framework is challenging. A simulation framework in which PV generation and BESS are integrated to the n-Grid with power inverters is elaborated in this paper. Finally, a hardware-in-the-loop testbed implementation is discussed.**

Keywords—Photovoltaic, battery energy storage system, PV inverter, simulation, hardware-in-the-loop, nano-grid.

I. INTRODUCTION

A significant transformation is occurring in the power system due to the growth of distributed energy resources (DERs), and load growth through electrification of transportation. There is growing interest in building-to-grid integration at the edge of the grid. This trend influences the interaction of devices, people, and organizations to meet personal goals and to influence future grid operations, value creation and realization [1].

Transactive energy framework discussed in this paper is providing grid management and control solution that coordinates different elements of the nano-grid (n-Grid) system comprising photovoltaic (PV) panels, plug-in electric vehicles (PEVs) with mobile battery storage and stationary battery energy storage systems (BESS) [2]. High penetration of such elements on the customer side is expected to gradually appear in the upcoming years. This high penetration will change the residential and commercial load behavior. Therefore, it is essential to change the conventional view of these loads as being simple consumers.

Several solutions in the literature are addressing the transactive energy optimization framework in distribution grid such as multi-stage stochastic programming based on artificial bee colony [3], smart transactive energy in home-microgrids considering coalition [4], multiagent-based transactive energy operation [5] and new market opportunities introduced in [6]. Several groups are working on this topic such as "Reforming the Energy Vision" (REV) in New York state [7] and "The Gridwise Architecture Council" (GWAC) [8]. The implementation in field installations and extensive testing is needed to allow full characterization of the key transactive energy exchange aspects such as control, monitoring and protection.

While there are papers discussing hardware-in-the-loop (HIL) simulation of the transactive energy framework, practical implementations are lacking. In [9], a HIL testing of the framework in which synchronous generators and load banks are employed is discussed. References [10] and [11] introduce real-time simulation frameworks to test management approaches for air conditioners. To the best of authors' knowledge, there is no literature on testing an n-Grid comprising PV generation, BESS and PEV chargers.

The elements in an n-Grid are integrated using power inverters. The n-Grid controller makes the management decisions and translates them to switching signals for the inverters. Simulating this kind of controller is challenging since it is working with two considerably different time constants, which forces the simulation to run for the duration of the bigger time constant and with the resolution of the smaller time constant. For example, if the management system is updating transactive energy exchange decisions every 5 minutes and the switching frequency for the power inverters is 20kHz, large processing and random access memory units are needed to have a co-simulation including both of these systems. We have solved the problem at the simulation level, and demonstrated the feasibility in a hardware-in-the-loop (HIL) testbed, which are the main contributions of this paper.

The paper is organized as follows: Section II discusses the concept of n-Grid transactive energy exchange. In Section III, the power inverter designs are explained. Section IV presents the BESS and PEV charging/discharging scheduling program which is integrated with the power inverters. The inverter and battery transactive energy scheduling is explained in Section V. In Section VI, the integrated simulation model is implemented using a HIL simulator connected to a PV inverter. In Section VII, the main conclusions are achieved.

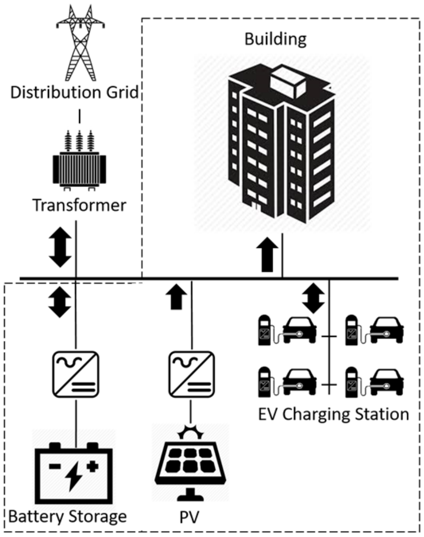


Figure 1. Schematic of the n-Grid.

II. BACKGROUND: N-GRID TRANSACTIVE ENERGY EXCHANGE

A schematic of an n-Grid is shown in Figure 1, confined with dashed line. The main elements of the n-Grid are load, stationary BESS, PV generation, and PEVs with mobile battery storage interfaced with a single bidirectional charger connected to the grid. It is possible to consider the n-Grid at a private residence with or without a PEV or a commercial building in which several PEVs can be charged and managed. It is assumed that both PEV battery and BESSs can work in both charging and discharging modes. The PV generation depends on the weather and solar irradiation, and the generated energy charges n-Grid batteries or is directly delivered to the main grid. To coordinate the operation of the n-Grid, an optimization and control algorithm is needed. The algorithm may be centralized for a cluster of n-Grids, and it coordinates with the individual n-Grid controllers.

Inside an n-Grid, there might be different scenarios of power flow as listed below.

1. When there is no PEV hosted, PV may be generating more than the load's need, and if the BESS is not full, the surplus energy flows to charge the local battery and there is no power exchange between n-Grid and the main grid
2. When there is no PEV hosted, PV is generating more than the load's need, and local battery is full, the surplus flows to the other n-Grids grid using the wires of the main grid.
3. When PEV is present in the n-Grid and its battery needs to be charged, and local battery is not full and electricity price is low, PV generation will be used to provide power for the local load, PEV and BESS and the shortage will be supplied by the main grid.
4. When PEVs are present in the n-Grid and need to be charged, and BESS SOC is more than the minimum limit, PV generation and BESS will be used to provide power for local load and PEVs and the shortage will be supplied by the main grid.

III. POWER ELECTRONIC INTERFACE

This section summarizes the power converter topologies used in this study to allow different transactive energy needs when interfacing the n–Grid to the main grid. A single-phase neutral-point-clamped quasi impedance source inverter (NPC-qZSI) is used in PV system while a bidirectional dc-dc converter is used to control battery charge and discharge cycles.

A. PV Inverter

Figure 2 (a) depicts the single-phase NPC-qZSI with LCL filter. It can be seen that the used power converter is a single-stage topology that allows the converter to boost dc voltage without any active components in the dc-side. Furthermore, the NPC inverter, which has considerable benefits such as lower dv/dt and lower total harmonic distortion (THD), is used to convert dc power into ac power. More details about this topology can be found in [1] and [13].

The modified level-shifted pulse-width-modulation (PWM) scheme is used to generate PWM signals for the single-phase NPC-qZSI as shown in Figure 2 (b) [13]. The modulation signals — $\sin(\omega t+0°)$ and $\sin(\omega t+180°)$ — are compared level-shifted carrier signals to generate the switching signals for S_{1a}-S_{2a} and S_{1b}-S_{2b}. On the other hand, to ensure shoot-through state, which allows the inverter to boost voltage, simple logic gates (OR gates) are used as depicted in Figure 2 (b). The rule of shoot-through state can be written as follows:

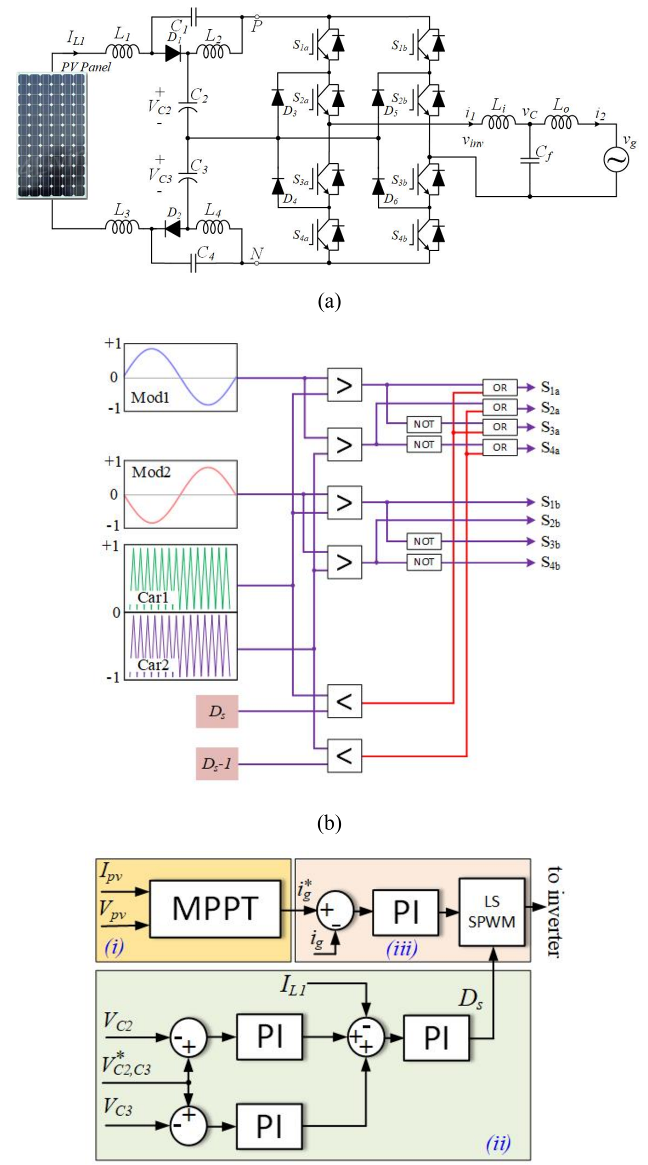
$$IF \quad \begin{array}{c} Car1 > Ds \\ OR \\ Car2 > Ds - 1 \end{array} \quad THEN\ turn\text{-}on\ S_{1a} - S_{4a} \tag{1}$$

The local controller of PV inverter is shown in Figure 2 (c). It can be divided into three parts:

i. The reference current generation based on MPPT: to ensure MPPT, Perturb and Observe (P&O) technique is employed.
ii. The dc-link voltage control (shoot-through generation): to ensure voltage balance on the dc-link capacitors (V_{C2}, V_{C3}) and to obtain shoot-through ratio (D_s), capacitor voltages are controlled by proportional-integral (PI) controller.
iii. The output current control: To control output current of the inverter, PI based control structure is used. The reference current signal is obtained through the reference current generation.

B. Bi-directional Battery Charger

To control battery charge and discharge cycles, the bi-directional dc-dc converter is used as shown in Figure 3 (a). This converter operates in boost or buck mode according to the level of battery state-of-charge. The local controller is given in Figure 3 (b). The controller, which is based on PI controller and simple logic gates, fulfills charging and discharging operation mode so as to regulate the battery voltage [14].



(a)

(b)

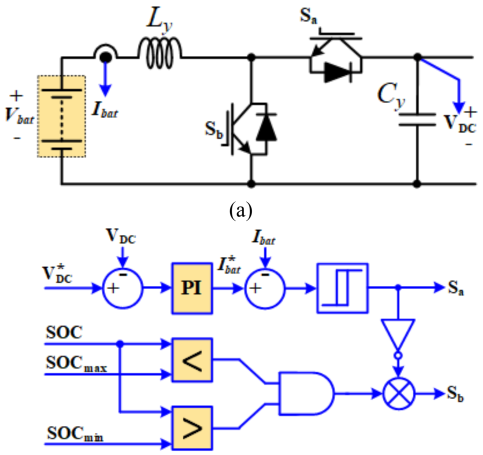
(c)

Figure 2. (a) Single-phase three-level NPC qZS inverter topology in PV generation system: (b) the level shifted modulation scheme [12]: (c) the local controller.

IV. BATTERY ENERGY EXCHANGE SCHEDULING

In the employed transactive energy framework, in order to be more accurate and take into account the occurrence of unexpected events, in addition to day ahead forecast, hour ahead forecast data is also employed [15].

As shown in Figure 4, a four stages control algorithm is utilized to manage the n-Grid energy exchange. In stage I, a chance constrained optimization is employed. The result of stages I and II are used to update the energy price based on the method introduced in [16]. In stage III, the goal is to supply the building energy by the integrated charging station and BESS considering uncertainties. In stage IV, to manage the difference between the predicted and real data, real time control is implemented.



(a)

(b)

Figure 3. Energy storage system with local controller.

A one-day scenario is generated. For PEV scheduling, a statistical analysis of PEVs consumption introduced in [17] is employed. The base load for the building is estimated using the data available in [18]. The cost of the energy not supplied is also calculated using reference [19].

In contrast with the deterministic optimization, the chance constrained optimization considers the uncertainties of the parameters using probability distributions. Chance constrained optimization is employed to deal with the uncertainty of PV generation, charging need of the charging station and energy need of the building load.

The main goal of the energy exchange scheduling is to minimize the operational cost of the n-Grid. In the proposed method, generated power by PV will be totally utilized. Battery storage power will be employed only when the grid's electricity price is high. Load loss is the least wanted situation. The optimal energy exchange scheduling is mainly done based on the electricity price in different moments of a day.

Different scenarios that can happen were explained in section II. However, the uncertainty related to the PEVs is so high and it is possible that the presence of PEVs in the charging station is not as expected. This uncertainty is considered in the control scheme.

V. INTEGRATION OF THE INVERTER AND BATTERY TRANSACTIVE ENERGY SCHEDULING

The battery energy exchange scheduling which is explained in section IV is implemented in MATLAB Simulink using S-Function block. The predicted output power of PV is based on California Irrigation Management Information System (CIMIS) [20]. The real-time predictions are shown in Figure 5. Operational cost of PV and BESS are calculated using [21] and [22]. The maximum output of the PV system employed in this paper is 153kW and the capacity of the stationary BESS is 113.4kWh. It is assumed that in the charging station, there are 18 available charging slots. The nominal charging rate of the chargers are assumed to be 7.2kw/h. The main grid in Figure 1

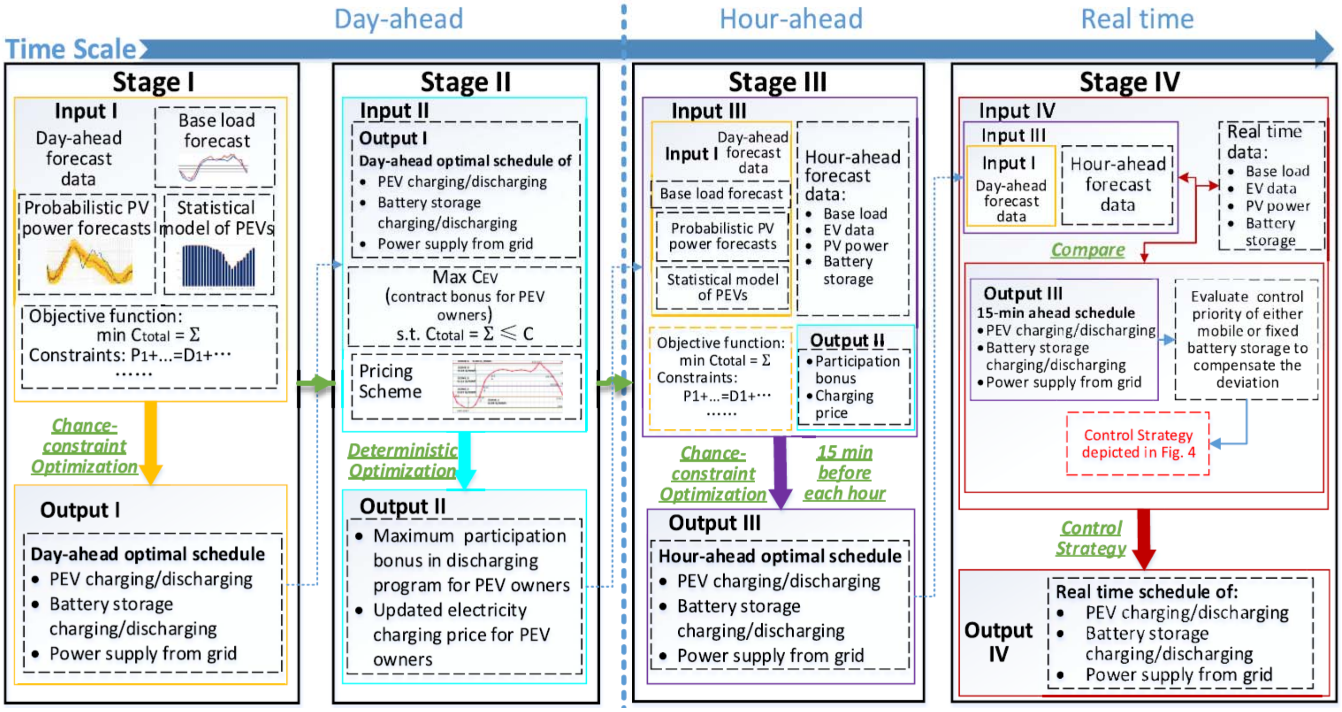


Figure 4. Optimization and Control Algorithm [15].

is assumed to be IEEE 33 bus test distribution system [23] and the n-Grid is connected to bus 18 of the system.

A schematic of the implemented simulation in MATLAB Simulink is shown in Figure 6. As shown in this figure, battery chargers and PV inverter, introduced in section III, are utilized in the same simulation with the transactive energy exchange scheduling program. The study needed to be done for this paper was having 24 hours of simulation. Using Dell Precision T3500 employed to run this simulation, the random access memory was enough for only around 600 seconds of the simulation and after that the simulation crashed. In order to solve this issue, the flowchart shown in Figure 7 was used to make the full 24 hours of simulation possible. In this approach, the state of the system was saved after each 5 minutes and the final state was utilized as the initial state of the next period.

The simulation is performed for 24 hours and the results are shown in Figure 8. It can be seen that although the results when instead of inverters, ideal power transfer between elements is assumed is close to the results of the simulation with power inverters included, there is a slight change which is the result of the voltage drops and losses of the inverters.

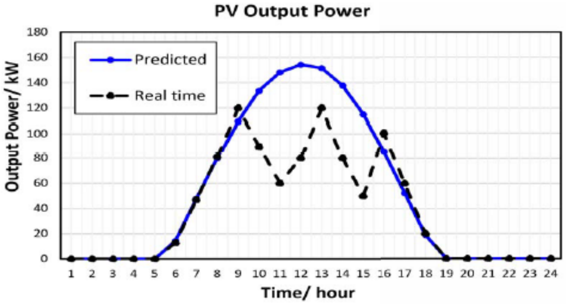


Figure 5. Predicted and real-time output power of PV.

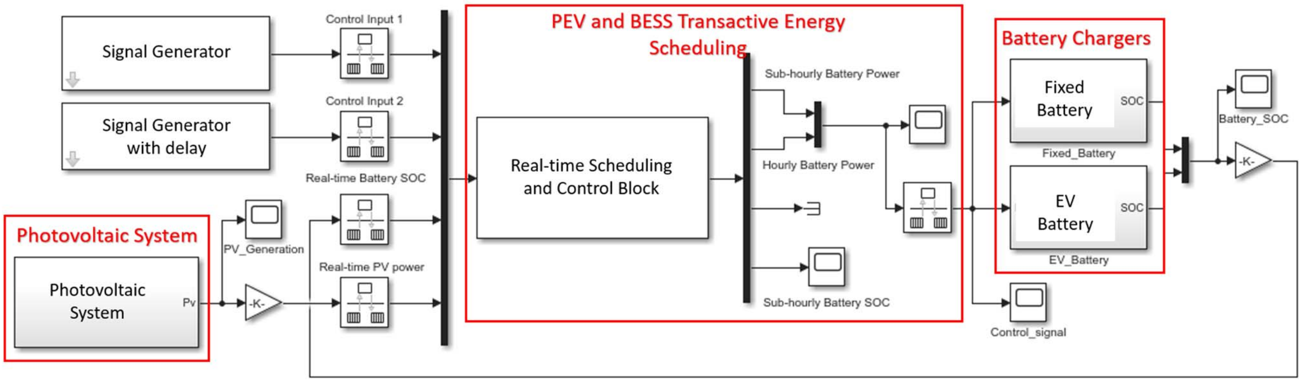


Figure 6. Implemented system in MATLAB Simulink.

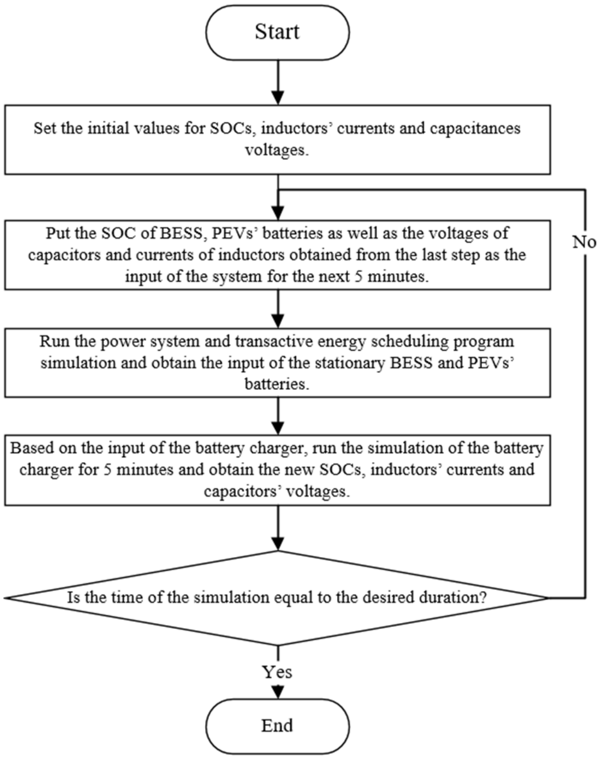


Figure 7. The algorithm of the integrated simulation based on sub-hourly updates.

VI. Hardware in the Loop Simulation

In section VI, a simulation framework is introduced in which power system and energy scheduling program are integrated with power inverters to provide a close to reality simulation environment. Although the simulation is completely done for 25 hours, since there are two systems with conspicuously different time constants, it took a considerably long time for the processing unit to provide the results which makes this framework unsuitable for this application. An alternative is utilizing real-time simulators. In this paper, Typhoon HIL is employed for this purpose. The same model used in section V is implemented in Typhoon HIL schematic editor. Instead of the PV inverter, only its control is modeled and its switching signals are sent to the NPC quasi Z-Source multilevel inverter using Typhoon HIL402 I/Os and the inverter's output power is sent back to the Typhoon device. The implemented switching control for the PV in Typhoon schematic editor is shown in Figure 9. A programmable DC power supply is connected to the PV inverter to feed it as the PV panel. The implemented testbed is shown in Figure 10. Since there was not a close loop control in the implemented HIL simulation, the results matches with what was already shown in Figure 8, however, the results were obtained in real-time.

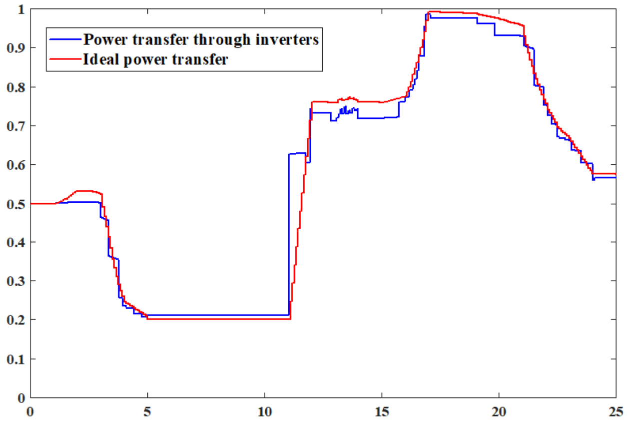


Figure 8. . Statement of the charge for ideal power transfer and power transfer through inverters.

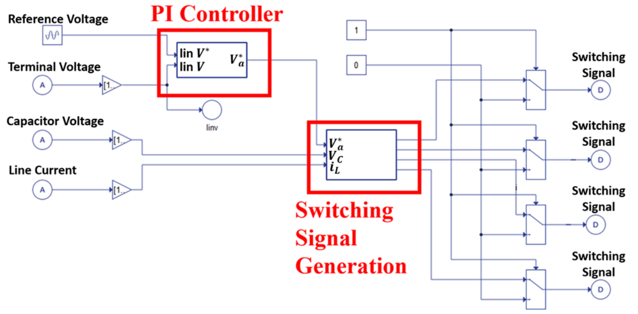


Figure 9. PV inverter controller.

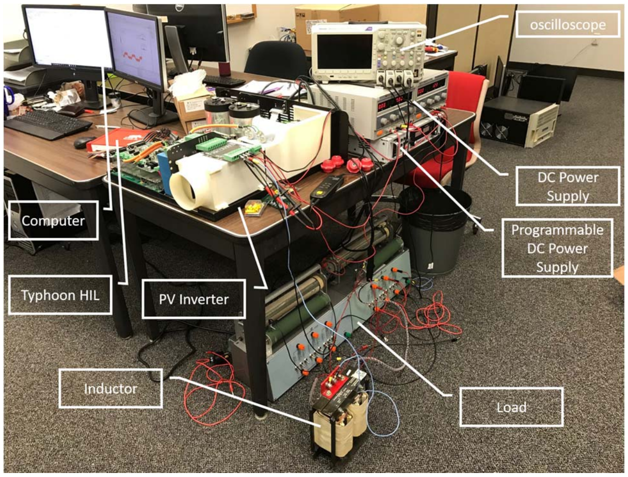


Figure 10. Implemented HIL testbed.

VII. Conclusion

In this paper, n-Grid is introduced and a four-stage optimization and control algorithm is employed to manage the transactive energy exchange between different elements in the n-Grid. The main control objective in the local n-Grid energy exchange is to maximize the profit for the n-Grid owner.

In the paper, MATLAB Simulink was used to include power inverters in the energy exchange scheduling simulation and to show their impact. Then, an HIL testbed was implemented to simulate the system in real-time. The following are some major findings:

- For different reasons including asset management, fault analysis, and power quality studies, it is essential to provide a close-to-reality simulation framework for transactive energy exchange studies.

- Using the proposed simulation approach, transactive energy exchange framework and power inverters are integrated into one simulation framework solving the problem of different simulation time constants.
- HIL simulator is employed to connect the integrated simulation framework to the physical PV inverter allowing for detailed study of the transactive energy exchange features.

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