Development of an Energy Management System for a Residential Microgrid in a Power Hardware-in-the-Loop Platform

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***Abstract*—A microgrid scenario composed by a PV generator, a battery system and residential loads in a power Hardware-in-the-Loop (HIL) platform is developed and tested. The electrical structure of the system, the component software modelling and hardware implementation are described. This paper proposes an EMS for microgrid power balance and execution of Demand Response (DR) Time of Use (TOU) and load shedding functions. Experimental results of each component of the scenario are shown.**

***Index Terms*—Hardware-in-the-Loop, Microgrid, Energy Management System, Demand Response, Smart Grid.**

I. INTRODUCTION

The change of energetic paradigm is marked by the integration of the traditional grid with distributed generators, renewable energy sources, and microgrids. Energy Management Systems (EMS) have become a significant component in Microgrids structures due to the importance of power balancing and management in systems that includes a variety of power sources [1].

EMS main functions includes monitoring, controlling, and to get an optimum performance of the system and operation in the Smart Grid infrastructure. The EMS runs with the data collected by the SCADA that supports the decision making for the optimization of the Grid [2]. The decision making in an EMS is also supported by load forecasting, weather and power prediction, and electricity markets information. It is also used to lead savings in the overall operating costs [3].

According to [4][5], HIL is a methodology increasingly recognized as an effective approach for simplifying the design and testing of hardware systems in a lot of research sectors. This is because traditional software-based simulations do not have the performance required to replicate real-time operational conditions.

This paper describes the development of a microgrid scenario in a HIL platform. The electrical system structure of the scenario was designed based on [2] and [6]. This scenario was implemented in a HIL Microgrid platform that has as a system core a modular system from dSPACE technologies and a set of Danfoss power converters to perform inverter based microgrid applications. The technical description of this platform is presented in [7][8].

II. SCENARIO DEVELOPMENT

The scenario for this work is a grid-connected microgrid composed by a photovoltaic (PV) generator, an energy storage system (ESS), and three residential houses as shown in Figure *1*. Taking for granted the functionality of the lower operational control levels of the microgrid that allow the power regulation, power generation, and power sharing in the microgrid, the experiment is focused in an Energy Manage System (EMS) that operates based in the power generation of the grid, the PV system generation, battery power, loads consumption, and state of charge (SOC) of the batteries.

The design of the scenario is focused in getting a high modular and flexible structure, with the capability to execute experiments with all the components modeled in software or scenarios with software and hardware component combinations. It allows to change or add any components without impacting the infrastructure, the operation, the functionality of other components or the complete system.

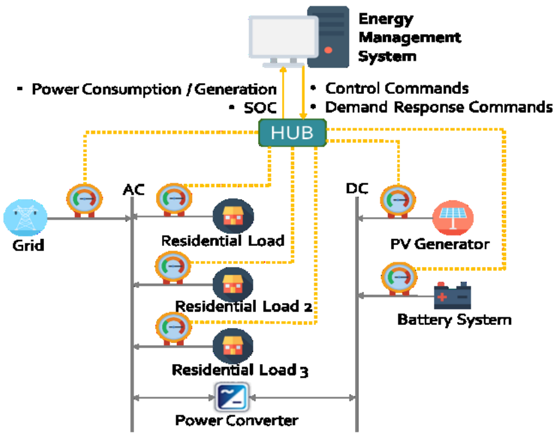


Figure 1. Scenario Functional Diagram

A. *SCADA*

This component was developed in the software dSPACE ControlDesk located in the setup workstation. The SCADA application includes the user graphic interface through the custom displays developed to show the main parameters, variable trends, and operation of each scenario component. The application also has the capability to save a record of the measured variables to a better data analysis of the simulations. The main scenario display is shown in Figure 2. It includes the whole vision of the microgrid, system components, main electrical parameters, and a tracking behavior of the variables.

B. *Solar Panel*

A 25 kW photovoltaic panel model was developed with the objective to simulate a real behavior of solar energy production. The mathematical model used in the experiment is proposed in [9], it is based on the Shockley diode equation. The behavior of the solar cell is modelled as a photo-current source, a single diode junction and a series resistance. This model evaluates the electrical DC output from solar irradiance and temperature parameters. To get the closest solar panel real behavior, all the constant parameters in the equation was replaced using the manufacturers ratings of a commercial photovoltaic panel. The selected panel to be used in the scenario is the Solarex MSX60 60W. The main typical electrical parameters of the photovoltaic module obtained in the product data sheet and in [9].

Solar irradiance real data behavior in Mayaguez, Puerto Rico was used with the objective to get a similar performance of PV generation compared to a real system. The data used was measured in Luis A. Stefani Engineering Building in the University of Puerto Rico at Mayaguez (18°12'34.9"N - 67°08'21.6"W).

C. *Power Converter*

The module used is a 2.2 kW Danfoss Drive reconfigured with a different control board to operate as a three phase DC-AC power converter. The converter has the enable and reset digital inputs, trip signal digital output, and PWM inputs for each phase. The PWM inputs allows to govern the IGBT gate driver depending of the control strategies implemented in the HIL device. Due to the photovoltaic generator modeled in this scenario have a power capability of 25 kW, the power reference of the real inverter was scaled to work up to 2.2 kW.

An LCL filter was connected to the inverter AC output to mitigate the harmonics generated by the switching in the inverter and leave only the fundamental frequency signal.

The voltage controller operates in cascaded control loop, i.e. an internal loop to control the current of the inductance and an external loop to control the voltage of the capacitor. The procedure to trade off the controller is presented in [10] that uses a Proportional-Resonant Control strategy. The main advantage of resonant control is its simplicity, although this is compromised when the design is performed to eliminate multiple harmonics.

To accomplish the connection between the inverter and the grid, a phase lock loop (PLL) was used to synchronize the signal generated by the inverter with the signal phase measured of the grid.

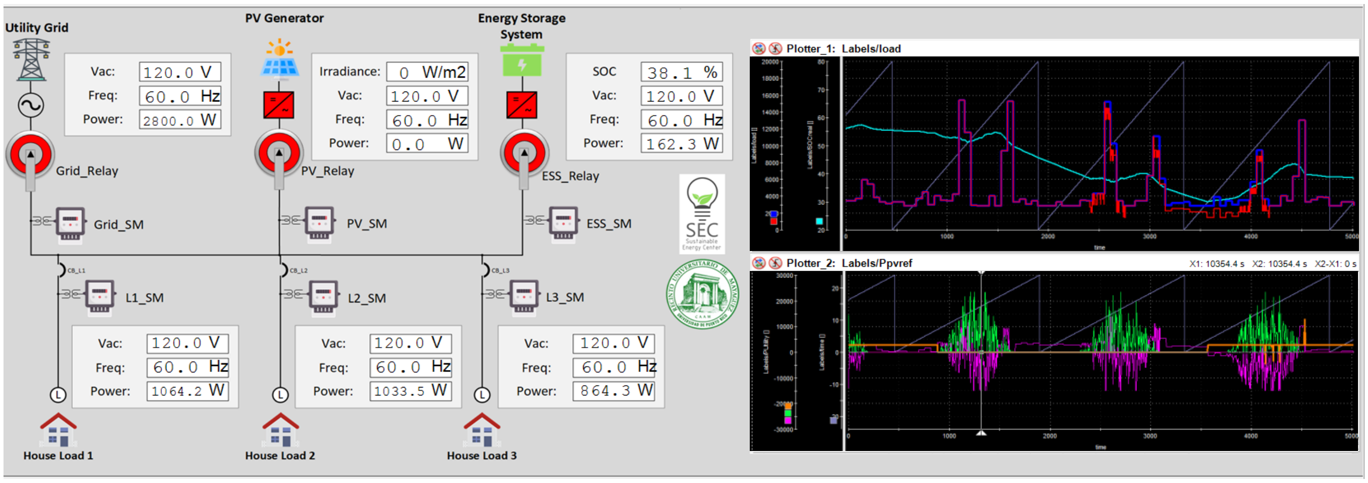
D. *Battery System*

This scenario uses a 15 kW electrical battery model based on a Thevenin circuit with two RC parallel branches, it is proposed in [11]. The model represents the behavior of a stack of 210 Ni-Cd cells and 22 Ah of capacity. The change of the internal attributes due to variations in the internal and external variables are considered. The model considers hysteresis effects during charging and discharging, including the transients between them. Parameters as state of health (SOH) and cell temperature are not considered in the battery model used.

E. *Smart Meter*

The implementation of the meter module was divided by the main functions of the smart meter. To accomplish the physical electrical measurements, a circuit board with voltage (LV25-P) and current (LA25-NP) sensors was constructed with the objective to acquire the signals with the analog dSPACE board. The processing module developed include the calculations of active power, phase to phase voltage, frequency, total harmonic distortion (THD), average voltage and average current.

Data communication between the smart meter and other scenario components is considered as ideal conditions, it means



Vac: 120.0 V
Freq: 60.0 Hz
Power: 2800.0 W

Irradiance: 0 W/m2
Vac: 120.0 V
Freq: 60.0 Hz
Power: 0.0 W

SOC 38.1 %
Vac: 120.0 V
Freq: 60.0 Hz
Power: 162.3 W

Vac: 120.0 V
Freq: 60.0 Hz
Power: 1064.2 W

Vac: 120.0 V
Freq: 60.0 Hz
Power: 1033.5 W

Vac: 120.0 V
Freq: 60.0 Hz
Power: 864.3 W

X1: 10354.4 s X2: 10354.4 s X2-X1: 0 s

Figure 2. Microgrid SCADA Main Display

that the regular Advance Metering Infrastructure (AMI) was not constructed, and the system communication delays are not considered.

F. *Residential Loads*

A small community of three 10.3 kW residential loads was modeled. Power consumption behavior of the residential loads was modeled following similar conduct patterns of obtained consumption data from families in Puerto Rico.

G. *EMS*

A fuzzy logic controller (FLC) is developed to accomplish the control objective of the experiment. The FLC is designed to maintain a constant flow from the electrical grid, preserving the stability of the grid keeping a flat power demand and to maximize the energy produced by the PV generator. EMS sets a power reference to the storage system depending of the power needed in the grid to supply the loads. Other important function of the control is to keep the SOC of the battery between 30% and 80%. The power balancing equation in the microgrid is presented below:

$$BattPower = PL1 + PL2 + PL3 - PV - PGrid$$

The FLC was developed in the Fuzzy Logic Designer MATLAB Toolbox. The system has two input variables: the SOC and the power current value of the battery (BattPower). SOC variable is defined with a value between 0 and 100. BattPower variable is defined with a value between -15,000 and 15,0000. The negative part of BattPower means that the battery is consuming power to increase the charge and the positive part means that the battery is delivering power to the microgrid. Figure 3 shows the definition and membership input function of each variable.

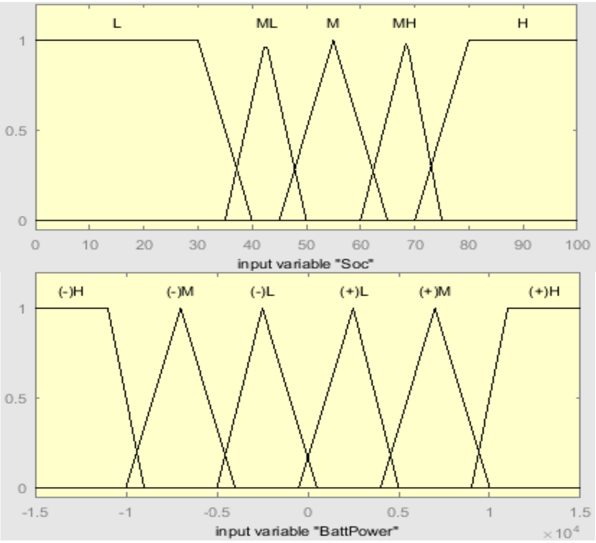


Figure 3. Membership Functions of the FLC

The outputs variables of the FLC are three levels of Demand Response digital commands. DR1 executes an incentive based Time of Use program that re schedule the used the washing and drying machine loads from the night to the middle day hours to take advantage of the peak PV generation at this hours. DR2 is a command that allows a low level of Demand Response through load shedding of some non-critical loads (external lights) and DR3 executes the shedding of all the non-critical residential loads (air conditioner).

H. *Complete Scenario*

Figure 4 represents the HIL diagram of the developed scenario.

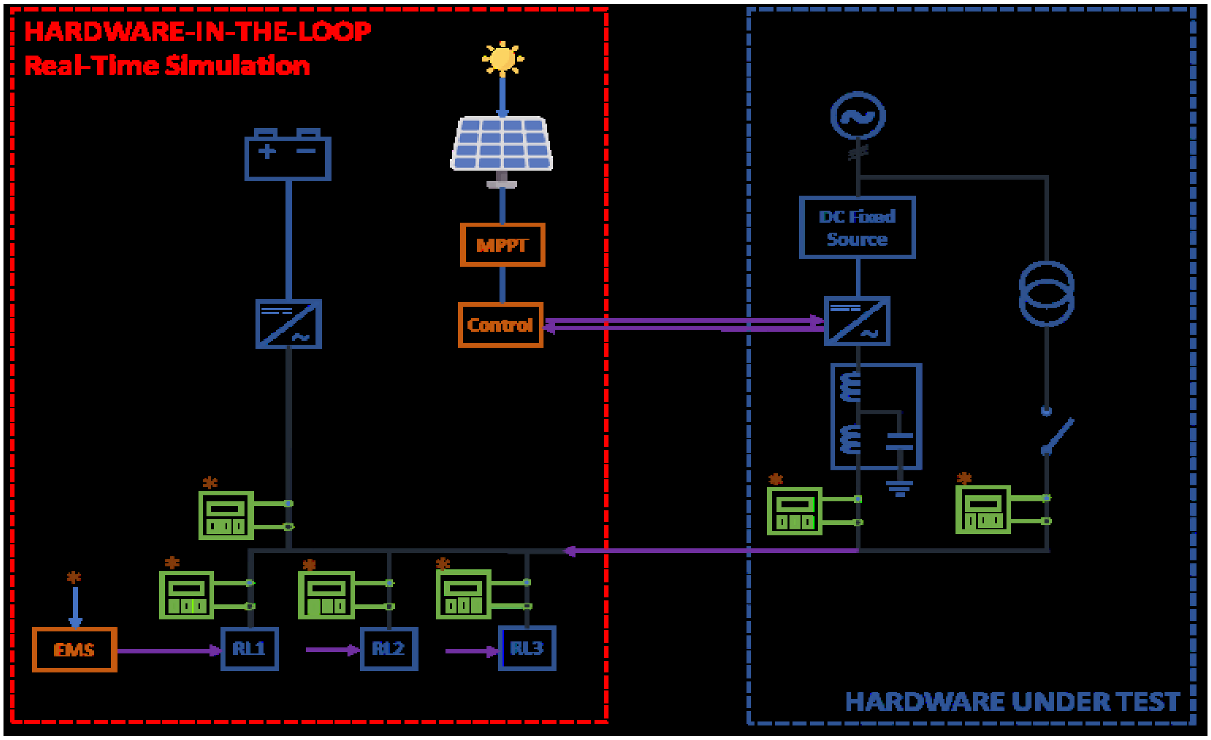


Figure 4. Hardware-in-the-Loop Scenario Diagram

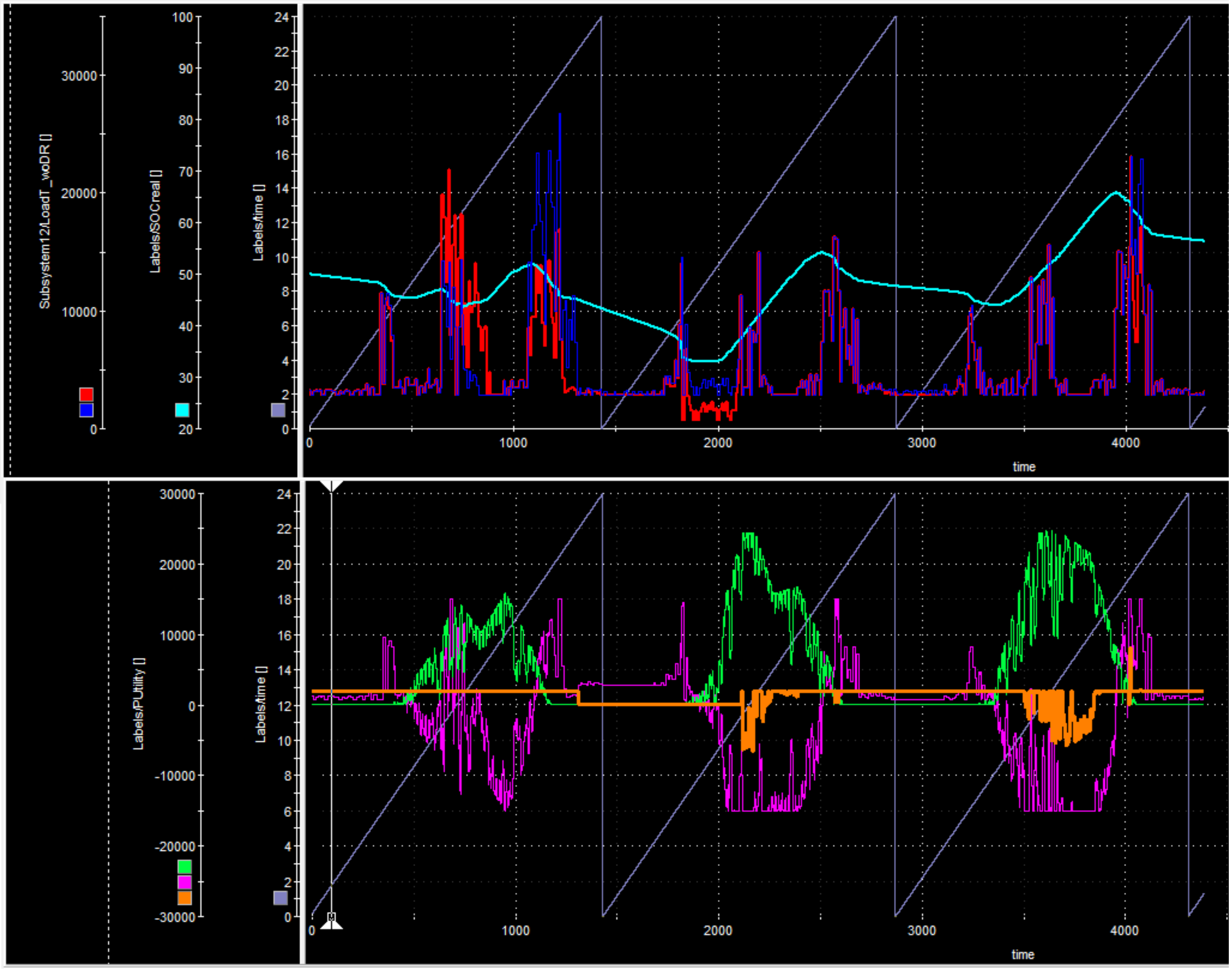


Figure 5. Complete Scenario Simulation Results

At the left of the diagram, the software modeled components are shown. As described previously, the simulated models and data behavior are the solar irradiance, solar panel, battery system, and residential loads. At the right of the diagram, the hardware configuration and electrical components are shown. The hardware implementation includes a fixed DC source, inverter, LCL filter, measurement boards, connection switch, and an isolation transformer.

As shown in the figure, the interaction between the solar panel and MPPT with the inverter is the power reference delivered through the control. The output interaction between the control and the inverter is made between the control commands as enable, reset, and PWM signals per phase. The inverter feedback includes the inverter trip signal, the internal filter current, capacitor voltage, and output filter current.

III. EXPERIMENTAL RESULTS AND ANALYSIS

The experiment results show the interaction between the PV generator, battery system, loads, and grid coordinated by the EMS. Figure 5 shows the graphical results of the complete scenario simulation. Top trend of the figure shows the load power consumption using DR programs (red line), load power consumption without using DR programs (blue line), and SOC of the battery (aqua line). Middle trend of the figure shows the PV power generation (green line), utility grid power (orange line), and battery power (fuchsia line).

The experiment was configured to execute three days. The first day as a cloudy day, second as partially sunny, and last day as mostly sunny day. The experiment begins with the battery SOC in 50%, then the medium SOC level causes the DR1 command activation since the beginning.

In this experiment, the objective grid power demand is 2 kW. EMS sets a power reference to the storage system depending of the power needed in the grid to supply the loads.

At the beginning the grid and the battery support the needed power to supply a load with a demand around 3 kW. When the sun rises the battery begins to charge, but near to minute 650 the battery had to contribute to supply the loads because of the several clouds in the day. These power peaks are caused because DR1 command reschedule the activation of the washing and drying machine from the night to the noon. It can be reflected in the different behaviors of the power load trends (with and without DR) during the day and night. The battery supplies the power peaks demanded during the first day in the morning and the night, generating a decrease of the SOC to a medium low level. It activates the DR2, then the external lights shedding during the night.

A blackout is simulated since minute 1310. It causes that the load power demand had to be supplied by the battery from here including the demand peak in the morning of the second day, having the effect of a fast decrease of SOC. This event takes the battery SOC to a low level, then the activation of DR3 in the minute 1820. This action helps the system to optimize the available energy and give time to improve the operation and a better energy generation. This energy optimization can be validated with the low decreasing behavior of the battery SOC and the DR command effects (comparing load trends with and without DR) between minute 1820 and 2115.

The grid recovers from the blackout at minute 2115. Due to the mostly sunny day, the PV generation levels are enough to charge the battery, supply the loads and inject power to the grid. Battery SOC recovers from the low level and reaches a medium level. Battery covers the power peaks of the second day night and the third day morning with the grid in 2 kW. This battery use causes the DR2 activation, then the external lights shedding during the night.

The third day had a high power PV production, reaching a medium high SOC level and injecting a lot of power to the grid. Due to the medium high SOC level, the DR1 was disabled, then the washing and drying machine was able to be used in the night of the third day, generating high power peaks around minute 4021. Around this event, the PV power generation and the battery maximum power were not enough to supply the load demand. The grid power is flat in 2kW almost all the experiment, but these high power consumption peaks causes that the grid had to supply this lack of power. The average grid power delivered in the experiment was 1.98 kW.

TABLE I. Complete Scenario Simulation Numerical Results

Energy [kWh]	***Day 1***	***Day 2***	***Day 3***
PV System	91.31	115.85	151.47
Battery Generation	51.89	64.00	51.14
Battery Consumption	(46.49)	(100.87)	(115.03)
Grid - Delivered	44.06	23.42	41.82
Grid – Net Metering	0.00	(4.27)	(9.63)
Residential Load	(140.78)	(98.40)	(119.41)
Residential Load w/o DR	(141.25)	(106.12)	(121.52)

The load consumption analysis shows that the day with the most energy savings generated by DR was the second day. This is because of the activation of the DR2 early in the morning and in the night, also because of the load shedding with DR3 due to the low SOC level.

IV. CONCLUSIONS

The design and implementation of the HIL system, focusing in energy management system (EMS) and advance metering components, are described. The described modular structure of the setup allows an important level of flexibility. The flexibility of the platform allows to develop HIL scenarios with software modeled components or using both type, simulated and hardware in test components.

Results show an EMS that that maximize the PV generation and effectively manage the Microgrid power flow. EMS also executes DR commands when the Microgrid needs energy savings and reduce power consumption with the objective to operate in the conditions descripted. A significant operation improvement in power consumption is achieved when DR take actions over the controlled loads avoiding an entire blackout in the Microgrid.

Experimental results demonstrate adequate response of the components on the scenario. The presented result in the work is a scenario with open research possibilities as advance power control, batteries modeling and characterization, photovoltaic panels modeling, components technology evaluation, and renewable system designs validation.

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V. REFERENCES

[1] P. Stluka, D. Godbole, and T. Samad, "Energy management for buildings and microgrids," *Proc. IEEE Conf. Decis. Control*, pp. 5150–5157, 2011.

[2] S. N. Kulkarni, "A review on Smart Grid Architecture and Implementation Challenges," pp. 3285–3290, 2016.

[3] P. B. Borase, "Energy Management System For Microgrid With Power Quality Improvement," in *2017 International conference on Microelectronic Devices, Circuits and Systems (ICMDCS)*, 2017, pp. 1–6.

[4] R. M. Kennel, T. Boller, and J. Holtz, "Replacement of Electrical (Load) Drives by a Hardware-in-the-Loop System," in *International Aegean Conference on Electrical Machines and Power Electronics and Electromotion, Joint Conference*, 2011, pp. 17–25.

[5] B. Lu, X. Wu, H. Figueroa, and A. Monti, "A Low-Cost Real-Time Hardware-in-the-Loop Testing Approach of Power Electronics Controls," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 919–931, 2007.

[6] M. Stanovich, M. Sloderbeck, K. Schoder, J. Langston, I. Leonard, and S. Chatterjee, "Microgrid Control Using Remote Controller Hardware-in-the-Loop Over the Internet," in *2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2018, pp. 1–5.

[7] J. F. Patarroyo-Montenegro, J. E. Salazar-Duque, S. I. Alzate-Drada, J. D. Vasquez-Plaza, and F. Andrade, "An AC Microgrid Testbed for Power Electronics Courses in the University of Puerto Rico at Mayagüez," in *IEEE Andean Conference ANDESCON 2018*, 2018.

[8] S. Alzate-Drada, K. Montano-Martinez, F. Andrade, and A. Irizarry-Rivera, "Advanced Metering Applications in Microgrids: A Hardware-in-the-Loop Electric Power Setup," in *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion MEDPOWER 2018*, 2018.

[9] G. Walker, "Evaluating MPPT converter topologies using a Matlab PV Model," *J. Electr. Electron. Eng. Aust.*, vol. 21, 2001.

[10] A. G. Yepes and F. D. Freijedo, "High-Performance Digital Resonant Controllers Implemented With Two Integrators," *IEEE Trans. Power Electron.*, vol. 26, no. 2, pp. 563–576, 2011.

[11] J. E. Carrasco and D. Serrano-jim, "A Ni-Cd battery model considering state of charge and hysteresis effects," *J. Power Sources*, vol. 275, pp. 595–604, 2015.