Internet-of-Things Hardware-in-the-Loop Simulation Testbed for Demand Response Ancillary Services

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ABSTRACT

Demand response (DR) has proven to show capabilities of providing ancillary services (AS) to grid operators. Advances in cloud computing and the availability of widespread and efficient network infrastructure bring tools that were otherwise inaccessible—financially or technologically—within reach. Building upon these advances, economically sound solutions to the established need for simulation testbeds for integration of distributed energy resources (DERs) systems into the power grid become available. This work presents methods of advanced power system modeling, integrated hardware design, and software development tools to develop a DR simulation testbed for grid stabilization in a power grid with a high presence of intermittent renewable generation. The result is a comprehensive package for internet of things hardware-in-the-loop simulation (iHILS) that was tested using DR aggregate control to provide stability to a grid with high integration of DERs.

Keywords: internet of things, demand response, distributed energy resources, simulation

1 INTRODUCTION

Spurred by aggressive renewable portfolio standards and the common desire for clean energy integration, today's electric grids have experienced an increase in the relative proportion of DERs. The intermittent nature of renewable energy resources—particularly photovoltaic (PV) and wind—has led grid operators to face increasing challenges with grid stabilization [1-3]. One of many solutions to addressing the new challenges is DR, which has been proven to be a viable solution for providing AS to the grid [4,5]. The majority of established DR programs are tailored to commercial and industrial customers and do not consider the residential market as a resource for providing AS due to cost inefficiencies [6-8]. Given that the residential market accounts for 40% of energy consumption on average, this leaves a large portion of controllable load untapped as a potential resource. Much research has been dedicated to the development of decentralized and networked solutions that can provide grid stabilization and raise overall grid efficiencies through the use of these residential resources [9-11]. In parallel, the number of connected devices in the IoT is growing exponentially and is expected to reach 28 billion by 2020 [8], thus bringing affordable wireless sensor and actuator networks within reach. Particularly, universal IoT governance with fault-tolerant, redundant, and secure infrastructures could empower innovative, scalable, and cost-efficient DR strategies.

The vast complexity involved in deploying a distributed network of connected sensors and controls to achive these goals makes implementation a daunting task. Through deployment and scaling of various strategies for implementation we can expect to face a panoply of challenges and unforseen problems. In an effort to preempt unforseen challenges, the creation of various testbeds which will be able to vet implementation strategies' effectiveness become valuable tools. This work presents a testbed system for network connected sensors and controls. We propose its application for use in testing devices designed for demand response systems and ancillary services, although, we can imagine any number of other applications for this tool. The iHILS system connects a limited number of real devices to a power grid simulation to gather performance data which include parameters such as communication latencies and response profiles. This data is then applied to creating additional simulated nodes and scaling the simulation without the need for additional hardware devices.

2 POWER SYSTEM MODELLING

PSIM software has been shown to be effective in modeling power and control systems for renewable energy [12]. The presented solution utilizes PSIM to simulate a power grid with high PV penetration. We incorporated new code into the original program package in order to enable it to communicate with network connected devices – prototype sensor and control devices – during simulation.

The features inherent to PSIM make system baseline measurements and event monitoring as simple as adding a virtual sensor to a simulated grid node. Adding devices to the simulation becomes a matter of specifying the number of active nodes making it an elegant solution to virtual scalability. Active IoT end devices installed in residential homes were integrated into the simulation. This allowed for the development of a comprehensive, highly secure, easy-to install, adapt and expand DR sandbox platform which incorporates hardware, software, analytics and cloud computing for controlled simulation.

2.1 System Model Overview

The PSIM sandboxed testing protocol can be visualized in Figure 1. The system module is comprised of the system being acted upon: in this case study, a power grid with high PV penetration. Accordingly, independent system variables are programmed depending on what type of event is being modeled; that is, for this particular simulation the solar insolation is modeled as the independent variable and is programmed to simulate the passing of a cloud.

Dependent system variables are affected by both independent variables and the effects from actuators from real devices connected in the external component module. The simulation presented in this work models a grid with high ratio of photovoltaic generation compared to conventional generation as a cloud passes over the city. Photovoltaic generation capacity is affected by fluctuations in available solar insolation. The grid frequency fluctuates as a function of changes in photovoltaic generation and load on the grid. When PV generation drops, so does grid frequency. If demand for power drops, frequency is recovered. These interactions can be exchanged with any number of variations or complexity. The result becomes a simulated system module with inputs and outputs connected to external devices through the chosen communications protocol. The external devices' actuators and sensors act according to signals sent from the control algorithm submodule described in 2.3.

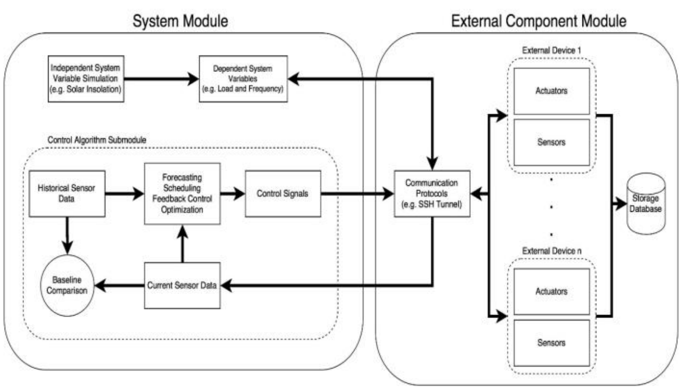

Figure 1: PSIM sandbox testing protocol

2.2 Power Grid Simulation

Modular system designs allow the simulation of a wide range of systems which can range widely in size and complexity. In alignment with the goals of increasing the penetration of DERs and empowering a smarter, more stable power grid, the case study shown in this paper simulates an islanded power grid with high PV penetration and cloud movement over a city. As the simulated cloud passes, solar insolation decreases and affects model response. In this case, fluctuations in load profiles and grid frequency. The various strategies for grid optimization presented in [13,14] are modelled as control systems in the simulation. The testbed gives a venue for testing the effects of the various strategies on grid stability and other system variables. PSIM gives a great measure of variability and control over modelling system response by giving access to base level code which can be included in programmable input/output blocks. We used this function extensively in building our simulation models and additional software features for external network connected devices and nodes.

With the simulated cloud passing over the simulated city, the solar insolation is varied over time and this in turn affects the array of solar panels and the ensuing cascade of power generation and feedback to the simulated power grid. System components, control points, and monitoring points can all be adjusted as necessary to model any given system of components. This portion of the simulation is representative of the independent variables acting upon the system in question. The overall system is affected by the influence from both the pre-programmed independent variables and the actions of the devices connected via the external component module. System load is also modelled as an input, though it is included through signal input from a file that contains historical load.

2.3 Aggregate Control Algorithm

As with any DR aggregate control algorithm, the purpose of this component is to optimize control signals to distributed sensor and control devices to compensate for changes in power grid parameters.

Closed feedback control loops for frequency control are modeled and tuned to incorporate sensor data and device response to prevent unwanted oscillations in process variables. Optimization goals for a simulation run are to obtain maximum system stability, and reduce the costs of power production.

The implementation of a device processing algorithm developed in MATLAB and C++ allowed the inclusion of optimization goals and historical load data as a baseline for initial determination of optimal control signals for distributed devices. The output would then be fed to the closed feedback control loops as well as stored in a control matrix that contains control signals for each (physical and virtual) node in the iHILS simulation network. In practice, we imagine that nodes will be polled for availability and placed in a hierarchical list based on time of last use. Nodes most recently used for a control decision output are placed at the bottom of the list to remain in normal operation until they make it back to the top of the list to be called upon again. The control algorithms are a submodule of the PSIM system module of the simulation handle the proportional-integral negative feedback control over DR signalling and maximum power point tracking for the solar generation portions of the simulation which were modelled closely after real photovoltaic panels. This was in an effort to accurately reflect the effect of reduced insolation on generation output. The plan is to input real insolation data into this model for future tests.

2.4 External IoT Integration

The external component module – IoT in the loop – receives control signals from the control submodule and reports sensor data to the control and system modules. The main function of this module is to communicate with the external devices that sense and report local loads and frequencies in a wireless sensor and actuator network (WSAN), then respond to control signals. In this simulation, the system acts to send control signals to the devices in response to the changes in grid frequency. The devices shed their connected controllable load and act to correct grid frequency back to required levels. Each connected device is able to monitor and report its own responsive activity and sensor data.

Figure 2: Network connected microgrid test station.

Each device is linked to the simulator in bi-directional communication by a functional block representing the device with input and output nodes. The PSIM simulation becomes a virtual grid which has real sensor and control devices attached to it. Figure 2 shows a microgrid test deployment station. It has a sensor suite with access to power data from battery, solar, and downstream loads. It also provides access to control over charge/discharge mechanisms for battery storage and several controllable load relay switches. The system is connected to the network via a single board computer with network access to MODBUS registers. The laboratory has developed several other connected sensor and control devices.

The simulated variables which are not controllable in practice, such as solar insolation are generated by the simulation. Some sensor data is necessarily artificial and generated as an output from the simulation and fed back to the devices' sensor inputs. Central control signal processing and output is handled by the simulation. In specific testing protocols, actual loads were connected to the controllable relays and monitored in real time, while load data was sent to a central database system which was read by the PSIM simulation. This method of telemetry and control is modelled after the actual architecture we imagine for dynamic load control with distributed sensors sending load data to a database over the internet. Figure 3 shows the PSIM portion of the external component module. All programming is handled within these device blocks. The block that is depicted with the wireless device icon handles all communications protocols between the external devices, control algorithms, and system variables.

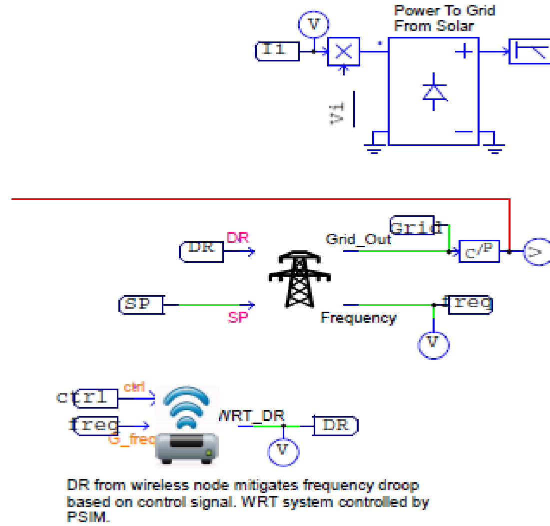

Figure 3: External component portion of PSIM simulation model enabling iHILS.

The control and sensor signals for power systems are sensitive data; unauthorized access or tampering could very well result in many serious problems. As such, the prototype IoT devices were designed with data security as a priority requirement. At the same time, system efficiency and convenience were considered. For the communication protocols our design incorporated SSH tunneling and encryption based on RSA key exchange over WiFi networks. RSA keys are able to be hard-wired into firmware before deployment for added security. In order to accomplish the task of having the simulator communicate directly with external components, a dynamic linked library (DLL) was created using C++ and Visual Studio to handle the bi-directional communication. In order to take advantage of standard file security protocols, a shared filesystem was created over SSH tunnel where PSIM and the external nodes communicate by writing and reading from assigned files associated with each respective node. The current method is used as a robust and simple means for implementation and proof-of-concept. It is easily converted to handle communication by direct socket communication over SSH tunnel.

3 RESULTS

Without DR control, all active end devices remain active throughout the simulation and are modelled to draw power continuously. Once DR control is integrated into the simulation, frequency droop is quickly mitigated . This is an oversimplified model of DR and future work is planned to include stochastic modelling of controllable node loads such as water heaters and non-stochastic controllable loads such as battery systems.

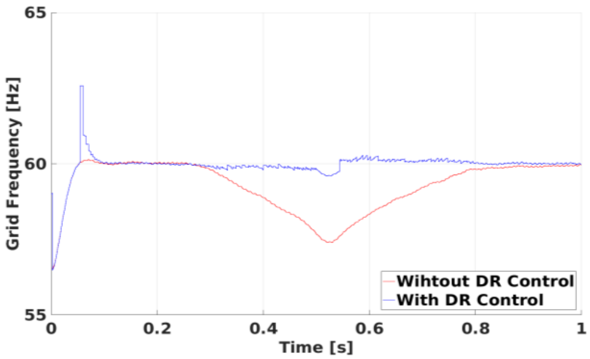

Figure 4: Grid frequency output results

The grid frequency, Figure 4, is affected by both the photovoltaic generation output as well as the amount of load shed by the devices. When we disable all real and simulated connected devices, we see the grid frequency droop as a result in loss of photovoltaic generation (i.e. a cloud passing over the city). When we run the simulation with real and simulated control nodes active we clearly see the response in grid frequency as the load is actively shifted. Frequency droop is mitigated as a result of active responsive load control.

4 CONCLUSION & FUTURE WORK

An iHILS testbed was presented in this paper and its efficacy for AS simulations tested using the case study of frequency regulation in response to a cloud moving over a city with a high penetration of PV generation. A modular power system model was constructed in PSIM to model a) the power grid system, b) the DR aggregate controller and c) a hardware integration module that communicates to external, off-site IoT hardware. Simulation results showed feasibility of iHILS simulation and iHILS's merits for testing the implementation of advanced DR control strategies and cyber security strategies in home area networks. It was able to demonstrate flexibility in modelling of both contingency events and normal operations while allowing for high resolution monitoring of simulated systems with a reduced investment in hardware and time.

The majority of effort in this work was in creating a testbed that had the ability to create the appropriate test scenarios. For future improvement, we will improve the grid model to be more realistic. For example, grid frequency was modelled to have a simple correlation with photovoltaic output and DR load. Future models will include a more realistic frequency response in time varying responsive load control scenarios. For dynamic load shifting, we assumed a fixed grid load profile from historical data. We plan to incorporate and apply artificial neural network predictive algorithms for load forcasting. This will include taking historical load data and current sensor data for prediction and actuation.

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