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Hardware-in-the-Loop (HIL) Simulations for Smart Grid Impact Studies

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Hardware-in-the-Loop (HIL) Simulations for Smart Grid Impact Studies

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***Abstract*— Hardware-in-the-loop (HIL) simulations are increasingly employed in power engineering as more inverter-based generation and smart appliances are connected to the electric grid. HIL techniques allow for the co-simulation of analytical models with actual devices whose complex behavior is computationally inefficient or difficult to model. They also allow for testing the behavior of these devices under adverse conditions that rarely occur in the field but are important to evaluate. This paper provides an overview of how HIL simulations have been used to date and proposes that HIL simulations should play an important role in evaluating new control strategies, especially at the distribution level, that are being proposed to allow for continued affordable and reliable operation of the electric grid. We present a new capability that was developed to evaluate the interactions between residential loads and the smart grid: smart home hardware-in-the-loop. The paper includes results from an HIL experiment that incorporates multiple technologies and controls.**

***Index Terms*-- Demand response, hardware-in-the-loop (HIL) simulation, home energy management system (HEMS), power system simulation, smart grids.**

I. Introduction

Hardware-in-the-loop (HIL) simulations have a long history, with applications extending to a number of disciplines. An HIL simulation is a method for including pieces of hardware in a real-time simulation to improve the fidelity of the simulation results. It is especially valuable when there are system components that are difficult to model. HIL simulations are also used to evaluate the performance of hardware, especially when it is important to test the physical devices against rare conditions or when it is impractical to reproduce the full physical system in a laboratory.

Early applications of HIL simulations were in the aerospace industry, when flight simulators were developed to train pilots on cockpit hardware without incurring any of the risks associated with flying [1]. The automotive industry has used HIL simulations extensively in the development of antilock braking systems, traction control, and electronic control units [2].

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Recently, HIL simulations have come into use in the field of power systems [3]. HIL simulations are commonly used to study renewable energy integration as inverter-driven generation and smart appliances have become more common [4]-[6]. The algorithms required to control these devices need to be developed and tested under realistic conditions but in a repeatable, controlled environment. HIL simulations enable algorithm development by simulating some components (such as solar insolation or grid conditions) while allowing the power hardware to respond and repeating the process to test the impact of changes in the controls. This method is also applicable to the development of controls for smart appliances [7]. Residential appliances can be controlled in a variety of ways to achieve cost savings, to consume more local renewable energy, or to mitigate congestion on the grid, and HIL simulations could allow these control strategies to be refined and their impact on the grid to be evaluated [8].

In this paper, we present different HIL configurations used in power systems research and a new application of HIL developed at NREL to investigate the interaction between residential loads and the smart grid. Section II describes the HIL configurations, section III details the experimental approach, section IV presents results, and section V covers conclusions and future work.

II. HIL Simulation Configurations

The basic concept for HIL simulations can be applied in different ways to study different systems. Some common applications of HIL simulations in power engineering are presented in this section, listed in order of increasing complexity, building to a new capability designed to evaluate interactions between residential loads and the smart grid: smart home hardware-in-the-loop (SHIL).

A. Controller Hardware-in-the-Loop

The simplest form of HIL is called controller hardware-in-the-loop (CHIL), and it allows a physical controller to be evaluated with simulated inputs, as shown in Figure 1a. Many types of controllers can be evaluated in this way, including embedded controllers for inverters, capacitor banks or electric vehicles, and stand-alone controllers such as smart thermostats. A power system simulation, running on a digital real-time simulator (DRTS), is configured using grid and weather conditions to provide realistic simulated input data to the controller hardware on a timescale from microseconds (for electromagnetic transient simulations) to milliseconds (for dynamic phasor simulations). The output signals from the controller hardware are fed back to the power system simulation in real time.

The simulation is updated based on feedback from the controller hardware, which in turn updates the signals sent back to the control hardware [6]. The input and output signals for the controller can be analog or digital. For a controller that outputs analog signals, an analog-to-digital converter (ADC) internal to the DRTS converts the analog signal to a digital input for the simulation, and a digital-to-analog converter (DAC) converts the digital signal from the simulation to an analog signal that is provided to the controller hardware [4].

B. Power Hardware-in-the-Loop

For power hardware-in-the-loop (PHIL) simulations, power hardware is interfaced with a power system simulation executed on a DRTS, as shown in Figure 1b. This allows the power hardware, including its embedded control, to be tested under realistic but simulated conditions [3], [4], [6]. The power hardware needs to be supplied with operational power (AC power, DC power, or both) that is consistent with conditions in the power system simulation. For example, a bidirectional AC power amplifier, also referred to as a grid simulator, is used to supply the AC power required by the power hardware, based on a voltage signal from the power system simulation. Sensors measure the AC current supplied by the grid simulator and return that data to the power system simulation as feedback, thereby closing the loop. To ensure a stable and accurate PHIL simulation, compensation needs to be added to the loop, as described in [9]. Similarly, a DC power amplifier can be controlled to deliver DC power consistent with the power system simulation when necessary.

An experiment with a photovoltaic (PV) inverter is an example of a PHIL configuration with both AC and DC power connections. A PV inverter is connected to a DC amplifier, also known as a PV simulator, and to a grid simulator. The PV simulator is configured with models for PV panels and can be controlled with solar insolation data stored in the PV simulator or it can be controlled from the DRTS. The latter option is preferred to synchronize the simulation. The inverter operates as if it were installed with solar panels and connected to a utility grid, while allowing researchers to explore its behavior under a wide range of conditions. This technique is more realistic than simulation only because models that capture the full range of realistic behavior may not exist, and it allows proprietary systems to be tested.

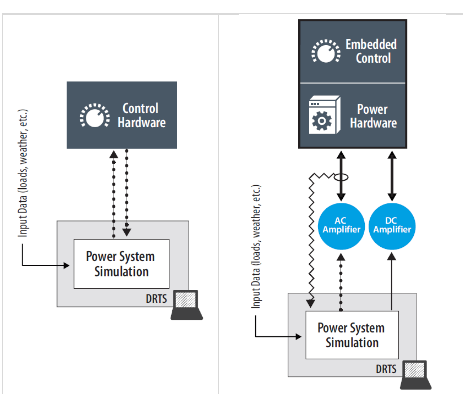

Figure 1. Different configurations of HIL: (a) CHIL and (b) PHIL.

C. PHIL with Multi-Timescale Co-Simulation

For PHIL simulations of large power systems that exceed the capacity of the DRTS, a quasi-steady-state time-series (QSTS) simulation tool, such as GridLAB-D or OpenDSS, can be used to simulate the power system. The QSTS power system simulation can generally run on a PC or workstation. The DRTS is used to convert the voltage phasor data to time-domain waveforms required to control the grid simulator, as shown in Figure 2a. For example, testing two residential PV inverters at separate points of common coupling (PCCs) to the IEEE 8500-node test distribution feeder simulated in GridLAB-D PHIL with multi-timescale co-simulation [10]

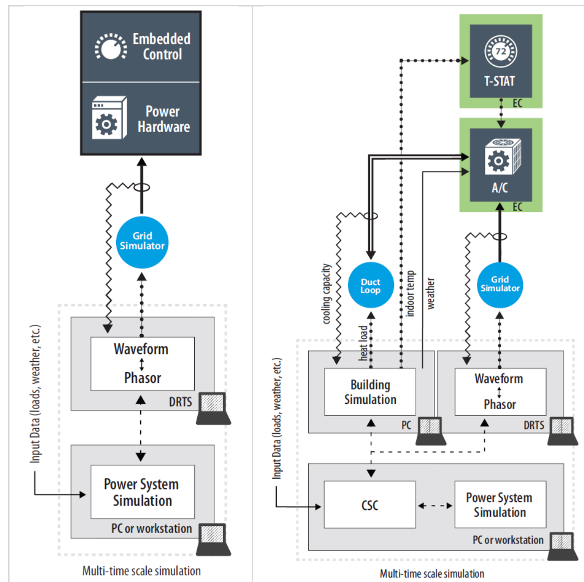

Figure 2. More complex HIL configurations: (a) PHIL with multi-timescale simulation (b) PHIL + thermal HIL.

D. PHIL + Thermal HIL

This HIL configuration combines PHIL with a thermal HIL component, as shown in Figure 2b. The power hardware is an air conditioner (A/C) with a thermostat as the controller. To re-create realistic operation of the A/C, a thermal HIL system was designed to pair a building simulation with the thermostat and A/C hardware. The building simulation uses EnergyPlus software to determine the indoor temperature based on weather, building construction, internal loads, and operation of the A/C [8]. The outdoor component of the A/C is located in an environmental chamber (EC) that is controlled to match the outdoor temperature from the weather file. The indoor component of the A/C is part of a duct loop that imposes the correct heat load on the A/C based on the modeled return air temperature in the building simulation. The thermostat is located inside a second EC controlled to match the indoor temperature from the building simulation. When cooling is needed, the thermostat turns the A/C on, and cooling capacity data is passed to the building simulation to inform the indoor temperature calculation.

The measured electrical load is applied to the power system simulation, either within the DRTS or a QSTS simulation. A co-simulation coordinator (CSC) can be employed to manage the flow of signals between the DRTS, power system and building simulations [11]. In [8], results are presented from an experiment in which the power system simulation was a GridLAB-D simulation of a feeder with multiple houses. The A/C load for one house in the GridLAB-D simulation was replaced with measurements taken from the A/C hardware. In turn, the grid simulator supplying power to the A/C hardware was controlled so that the voltage supplied to the hardware matched the voltage calculated by the GridLAB-D simulation. The DRTS was used to convert the voltage phasor data to a time-domain waveform signal.

E. Smart Home Hardware-in-the-Loop

We have designed and implemented a setup that incorporates PHIL, CHIL, and thermal HIL with multi-timescale simulations, as shown in Figure 3. This capability was developed to evaluate smart appliances and smart home control strategies under multiple utility tariff structures and to quantify the impact of those controls on the power distribution system. This HIL configuration intends to represent all relevant components of a home in hardware, so this configuration is called Smart Home Hardware-in-the-Loop (SHIL). The power system simulation is a GridLAB-D model that includes 20 homes on the IEEE 13-node feeder, with the load for one of those homes replaced by the residential hardware in the laboratory. Each home has multiple controllable appliances and a dedicated home energy management system (HEMS) controller that determines the optimal operation of each controllable appliance.

In this instantiation, the controllable appliances in the homes are an air conditioner, an electric water heater (EWH), and electric vehicle supply equipment (EVSE). The current version of this system also includes an uncontrolled PV inverter, but future iterations will include a controllable PV inverter. Uncontrolled appliances, such as a refrigerator and lights, are also included in the laboratory home. Each home has a separate HEMS controller that executes a multi-objective optimization within a model predictive control (MPC) framework [12] to optimize appliance operations. It sends control signals to either simulated appliances within GridLAB-D or to physical appliances via Wi-Fi or physical signal wire in the laboratory home. The A/C and EWH are controlled by changing the associated set point temperature for the physical appliances. Control of the A/C hardware is implemented via an internet-connected thermostat, and the water heater has a custom controller that was also internet-connected. The charging rate for the electric vehicle (EV) was controlled by changing the duty cycle of the pulse-width modulation signal from the EVSE, a feature enabled by the supported CTA-2045 protocol. The SHIL setup therefore includes a variety of appliances that we can operate either with their built-in controls, or with advanced controls implemented at the appliance level or by a supervisory controller such as a HEMS. This enables us to evaluate the impact of different control strategies.

In order to run multiple HEMS optimizations, parallelization is required; thus they are executed on a high-performance computer (HPC). The CSC used with the SHIL simulation is an NREL-developed framework called the Integrated Energy System Model (IESM), which was designed to manage timing and data exchange among the GridLAB-D model, the HEMS optimizations, the control signals for the power hardware, and the phasor-to-waveform conversion running on a DRTS [8], [11]. In addition to sending a control signal to the grid simulator, the DRTS also sends insolation and temperature signals to the PV simulator to drive the PV inverter throughout the experiment.

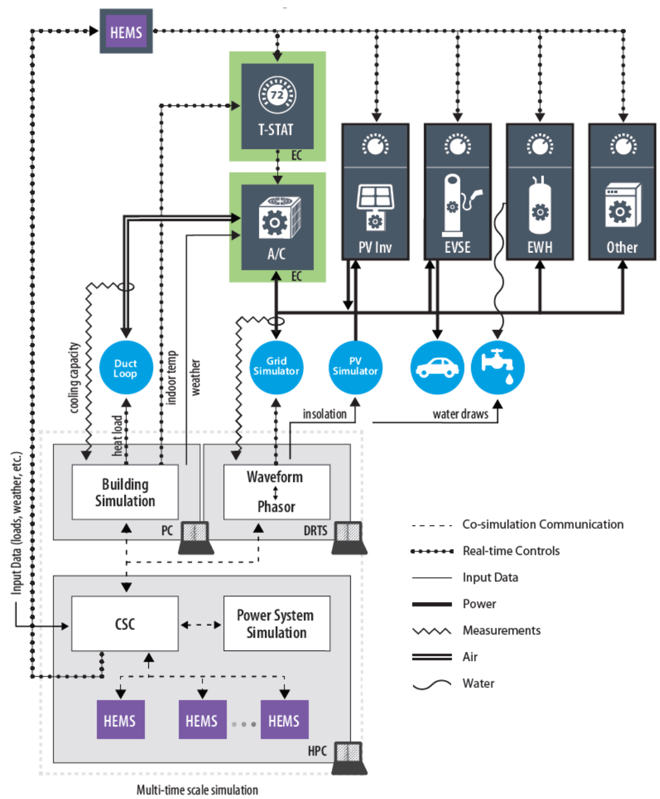

Figure 3. SHIL includes PHIL, CHIL and thermal HIL.

Voltage variations can impact power consumption or can impact the current flow if the device is designed to maintain a constant power draw. In both cases, providing power to the appliances at the voltage determined by the power system simulation (closing the loop on the HIL simulation) is important for evaluating the full impact of HEMS.

III. SHIL SIMULATION APPROACH

We present results from two SHIL experiments that were performed to compare behavior with and without HEMS, each lasting two days. These results demonstrate both realistic operation of individual hardware appliances and the ability to perform analyses based on results from both simulated and hardware appliances.

A. Simulation Parameters

The experiments simulated two days in early June using typical meteorological year (TMY) weather data from North Carolina to inform the outdoor air temperature and solar insolation for the GridLAB-D and EnergyPlus simulations. A time-of-use (TOU) tariff schedule from Duke Energy in North Carolina was used to calculate the cost of electricity. The TOU tariff had a peak price between 1 p.m. - 6 p.m. and shoulder rates for two hours before and after the peak [8].

The baseline experiment did not use the HEMS to dynamically change the operation of the controlled devices; the operation of the appliances was determined by a fixed schedule. The set points for the water heaters were constant at 119°F. The air conditioners were controlled with a simple setback schedule: 76°F during the day (8 a.m.–5 p.m.) and 72°F at other times. The EVs had a charging window between 6 p.m. and 8 a.m. to simulate a typical daily schedule, which was imposed by using a charging schedule in the vehicle.

When the HEMS control was applied to the homes, the operating schedules were adjusted to find an optimal trade-off between electricity cost savings and occupant discomfort (within prescribed comfort bounds) [12]. For this experiment, optimizations were performed and new control signals sent to the appliances every 15 minutes. The A/C and water heater set points were allowed to vary up to ±5°F from the base schedule, and the EV was allowed to charge anytime between 6 p.m. and 8 a.m., as long as it reached full charge by 8 a.m.

For both cases, the appliances were subjected to simulated use to ensure that their operation was consistent with appliances in an occupied home. The air conditioner was driven with the thermal HIL simulation described in section II.D and [8]. The building simulation incorporated the impact of weather, solar insolation, and internal gains on the interior air temperature, which ensured proper cycling of the air conditioner. A water draw schedule was imposed on the 50-gallon water heater using a solenoid valve—which was controlled by the laboratory data acquisition and control system—connected to the hot water line on the kitchen sink. This schedule used an average of 51 gallons per day and was developed using a hot water draw generation tool developed at NREL [13]. A Nissan Leaf EV was charged using the controllable EVSE during the night, but it was not feasible to drive the Leaf during the day to drain the battery. Instead, the A/C for the car was turned on at its highest level and all the seat heaters were turned on for several hours each day. This drained the battery an amount equal to driving approximately 35 miles per day, which is consistent with the average daily driving distance of 36 miles for Americans, per [14].

IV. Results

The following plots show the behavior that was observed. In all figures, the purple lines correspond to the baseline results, and the green lines correspond to results from when the HEMS controls were applied. The vertical pink bands indicate the price according to the TOU schedule: the darker band indicates the peak price period and lighter bands show the duration of the shoulder prices.

To avoid running the A/C during the peak price period, the HEMS raised the set point toward the end of the high price periods (as indicated in Figure 4 by the higher indoor temperature under HEMS control) and then lowered the set point once the price dropped (indoor temperature drops after price drops). Similarly, the HEMS sent a lower A/C set point to precool the house before the price increased (A/C runs and temperature drops before peak price period). However, the A/C needed to operate for a minimal amount of time during the peak price period to meet the comfort requirements. The water heater set point was mostly set to the lowest allowable temperature, as can be seen in Figure 5. The tank temperature in the HEMS case is generally lower than the baseline. However, the EWH set point was raised before the electricity price increased to ensure that hot water was available through the peak period. The charge rate signal, which sets the maximum charge rate for the EVSE, and the actual power consumption of the EVSE are shown in Figure 6.

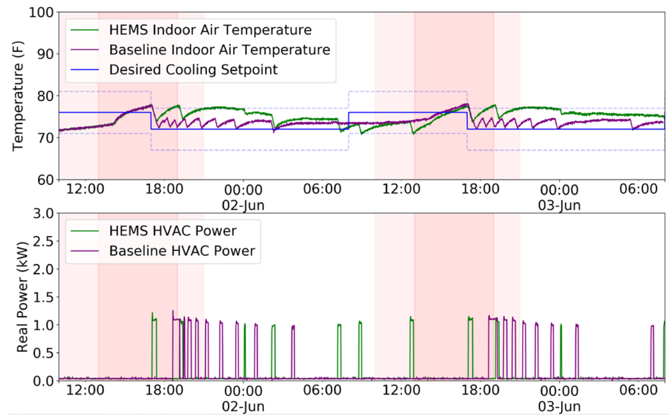

Figure 4. Comparison of temperature and power data from the air conditioner hardware during two days under baseline control and HEMS control. The dashed blue lines indicate the bounds on the set point temperature.

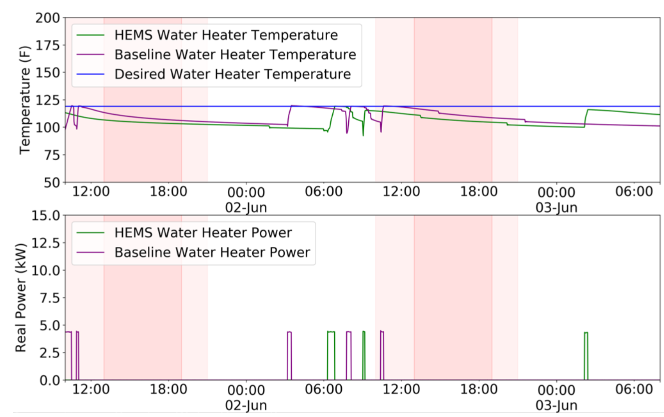

Figure 5. Comparison of tank temperature and power data from the water heater hardware during two days under baseline control and HEMS control.

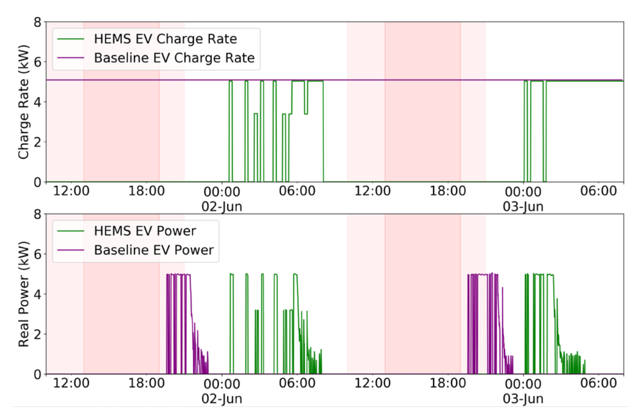

Figure 6. Comparison of charge rate set point and power data for the EVSE hardware during two days under baseline control and HEMS control.

Under HEMS control, charging of the EVSE was delayed until after the utility rate dropped to its lowest price. The charge rate for the EVSE under HEMS exhibited pulsing behavior because battery degradation was not taken into account in the HEMS optimization; future work will include battery degradation in the optimization, based on a linearization of the approach described in [15].

For the house represented in hardware, these controls resulted in 4.6 kWh or 8% energy savings during two days and 14% cost savings; however, there was an adverse aggregate impact on feeder voltage, with the GridLAB-D simulation showing slightly more variation from the nominal voltage when the HEMS controls were applied. In the baseline case, the largest voltage deviation from nominal (120 V) was 0.75 V, or 0.6%; whereas the HEMS controls resulted in 2.0 V, or 1.6% deviation from nominal.

Another way to view the aggregated impact of the HEMS is shown in Figure 7. The top plot shows the average indoor temperature from all the homes (simulated and hardware) for the HEMS and baseline cases. The blue line indicates the desired set point. The lower plot shows the total power from all the homes for both cases. The baseline case shows a higher indoor temperature at the beginning of the peak period because no precooling took place, which causes significant cooling at the end of the peak period after the set point decreases. The HEMS case shows a lower temperature earlier in the day because precooling was used to avoid the need for cooling during the peak price period.

V. Conclusions and Future Work

Building on established CHIL and PHIL techniques, the SHIL system is a robust, powerful tool for evaluating smart home technologies and how they impact the grid and its consumers. The ability to customize the feeder model, utility tariff structure, building models and weather data means that this test bed can be used to simulate smart grid systems from different regions. In this paper, we presented results from simulations that compare behavior with and without HEMS; however, the SHIL capability will accommodate a wide range of experiments that could help inform utility rate designs and policies, customization of HEMS algorithms, and research and development related to smart appliances and other DERs.

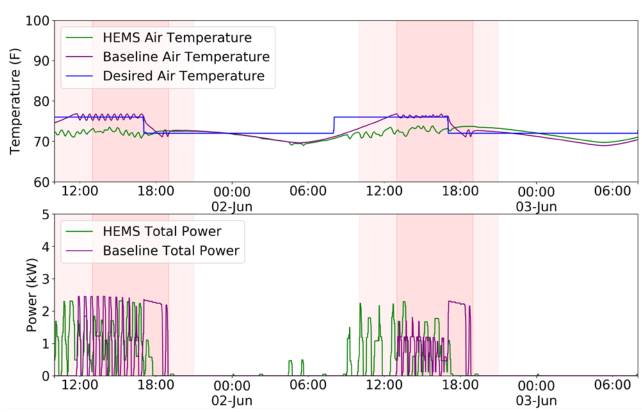

Figure 7. Summary of indoor air temperature and real power consumption for all 20 homes on the simulated GridLAB-D feeder.

In future work we will incorporate new HEMS algorithms and apply this framework to homes in different climate regions with different feeders, including some that exhibit more voltage variability. We will develop more complex residential appliance and building models for GridLAB-D to improve the accuracy of HIL simulations and larger scale simulation-only studies. We also plan to add an aggregator module that can coordinate HEMS through transactive energy and other techniques to flatten the aggregated load shape and avoid unintended coincident operation.

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