PHEVs Charging Stations, Communications, and Control Simulation in Real Time

Luis Herrera, Robert Murawski, Feng Guo, Ernesto Inoa, Eylem Ekici, and Jin Wang
Department of Electrical and Computer Engineering
The Ohio State University
205 Dreese Labs; 2015 Neil Avenue
Columbus, Ohio, 43210
E-mail: wang@ece.osu.edu

Abstract- **This paper introduces a platform for real time simulation and its contribution towards smart grid related research, with focus on Plug-in Hybrid Electric Vehicles (PHEV) charging stations. The current system is able to simulate in real time key elements of a smart grid such as: high speed power electronics, distributed energy resources (DER), and communication networks. A description of the platform for real time simulation is presented along with the integration of communication emulation; achieved through OPNET's System in the Loop (SITL) package. In addition, an introduction to Networked Control Systems (NCS) is presented and a case study of PHEV charging stations which displays the latest results accomplished with the current setup.**

I. INTRODUCTION

The smart grid refers to the digitalization of the power grid in order to further improve it in terms of efficiency, reliability, and automation. Some of the main characteristics of this intelligent grid include two-way communication, self-monitoring, adaptive, and allowing customer choices. Although the necessary technology to achieve this modernization of the power grid exists, sufficient research and validation of the technologies and methods is necessary in order to speed up their adoption [1][2]. However, real environment tests are usually expensive and difficult to achieve in a laboratory setting, for this reason, real time hardware in the loop (HIL) simulation becomes a fundamental tool in order to test controllers, power electronics circuits, and communication methods to effectively incorporate them in the power grid.

PHEVs are becoming dynamic elements not only requiring large amounts of power from the grid, but also supplying power in times when localized distribution faces overload capacity [3]. In addition, PHEVs can supply supplementary services to the grid such as frequency regulation by controlling the active power flow [4]. Communications thus play a key role in managing the distribution of energy. It is necessary for a charging station to know the state of the grid in terms of demand, pricing, and health in order to better estimate the times for charging [5]. In [6], an overview of different communication methods applicable to PHEV charging stations such as Power Line Carriers (PLC), IEEE 802.15.4 (Zigbee), ZWave, and cellular networks were summarized. Furthermore, a Zigbee based communication platform for testing optimization parameters in a PHEV charging station was proposed in [7].

The integration of communication in different applications of power systems and power electronics can be considered part of Networked Control Systems (NCS) [8]. A NCS is a type of closed loop control in which there is communication between the remote controller and the plant. NCS have found many applications ranging from: robotics, aircraft, automobiles, and now could be applied to power electronics and power systems. Nevertheless, there are several communication factors which affect the performance of NCS such as: latency, unreliable communications (packet losses), bandwidth and packet size constraints, and packet disordering. In terms of power electronics, in [9] different topologies for applications of interconnected converters, while generalizing types of control requirements and delays for each topology were studied. In [10], a wireless PWM control for parallel dc-dc buck converters was modeled using a state space representation, in which the characteristics of communication delays were considered. Lastly, a method for modeling wide area measuring systems (WAMS) in power grids have been proposed in [11] for a NCS.

A co-simulation of real time HIL of continuous (power systems) and discrete (communication) models, provides a more tangible method for simulating real world NCS systems. Focusing on PHEV charging stations, some examples of real time HIL simulation for testing different characteristics of PHEVs have been proposed in [12], where a model of a PHEV was developed and run in real time to test a Vehicle Control Unit (VCU). When integrating both power and communication simulations, Nutaro *et al.* [13] developed a software simulation of a 17 bus power network with communication between the loads and generators; investigating the effects of factors such as bandwidth and latency on the overall system stability. This work provides an example of combining discrete and continuous models to study communication requirements and its influence to a power system.

Although real time HIL simulation platforms have been developed, most focus on one aspect in modeling, either continuous (power electronics, power systems) or discrete (communication networks). A joint effort is proposed in this paper in order to effectively model these two types of

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networks together to evaluate different scenarios within the distribution level; such as PHEVs load demand managements and control, intentional islanding, and load dynamics. In section II, the overall system is discussed in detail, while section III provides a survey of different communication emulation software available, along with a description of the software currently used. In section IV, a brief review on NCS is presented for characterizing delays and simulation methods. In section V, a case study is shown to demonstrate the capabilities of the current system. Lastly, a conclusion and future work is presented

II. REAL TIME SIMULATION FOR POWER NETWORKS

A real time simulator can run a large and complex model at the same rate as physical time. This feature can bring advantages such as faster development time, and lower costs when it is incorporated with HIL and SITL simulations. For example, a prototype controller can be tested using real time HIL simulation under different conditions and scenarios, such as normal or fault situations which could be otherwise costly or difficult to test with a physical plant.

The real time platform developed at The Ohio State University is composed of four target machines, each connected together through a high speed, low latency Dolphin link [14]. In total, there are 8 CPUs running Linux operating system, 48 cores, 4 Field Programmable Gate Array (FPGA) Spartan-3 chips, 1 Virtex-6 FPGA, and more than 500 analogue and digital input/outputs. The complete system is shown in Fig. 1.

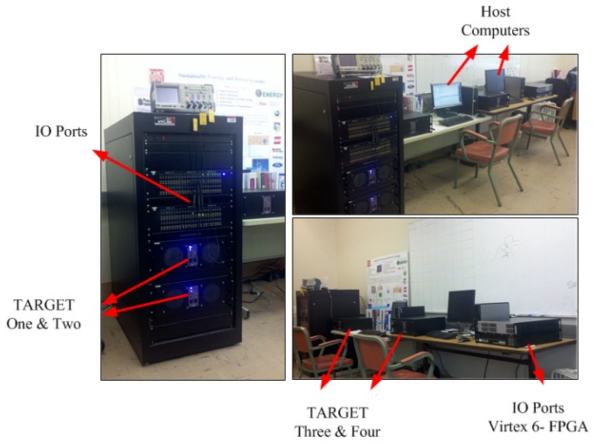


Fig. 1 Real time HIL Machines for power systems and power electronics research.

This system can execute large scale distributed real-time Matlab Simulink models in parallel. As an example, a plant model can be distributed on four processors while the controller model can be run on a fifth processor. All subsystems are synchronized together with very high precision, allowing multiple devices under test to be connected to the system simultaneously. Furthermore, this configuration permits multiple users to connect concurrently to the system to perform collaborative simulations. For instance, one master simulation can contain the main power grid model and then multiple clients can attach simulation components to the grid such as photovoltaic (PV) array models, PHEV models, etc. Different control strategies can then be tested at the same time to study the behavior of a fully integrated environment including real devices. Fig. 2 illustrates a possible setup utilizing all target machines to work together in a combined simulation.

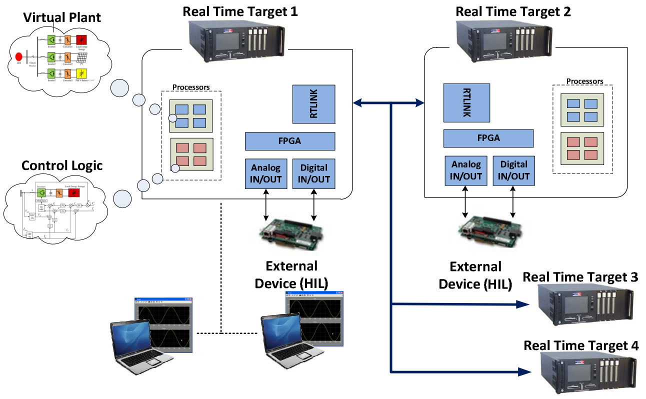


Fig. 2 Example of a platform setup for integrated modeling of complex models.

III. COMMUNICATION NETWORK SIMULATION

Current network emulators offer the capability to be integrated with real hardware and devices under test. In academia, one of the most prevalent tools is NS2 [15]. NS2 is an open-source network simulation package which has the capability to operate as a system-in-the-loop (SITL) emulator. It is able to accept real-time network traffic and simulate either a wired or wireless network. In addition, the live traffic can either be interpreted as opaque data packet (opaque mode) or protocol data packets which can be manipulated by the simulation software (protocol mode). Another type of network emulator is Exata [16], developed by Scalable Network Technologies (SNT) based on the popular QualNet network simulator. Exata is able to simulate parameters such as terrain, cyber-attacks, scalability, and static parameters. While Exata can be used in SITL applications, it is mainly directed towards the military industry. Furthermore, the university licensing of Exata offers mainly precompiled code with little adaptability or flexibility compared to the open source solutions presented.

OPNET [17] is a well-developed commercially available network simulator that has been used extensively in research. There is a large community of support available for OPNET modeler comparable to NS2, however, being a commercial product, corporate support through OPNET Technologies is available as well. A SITL package is available for use with OPNET that can bridge the OPNET network simulation with the hardware simulation described in section II. The university license for OPNET allows for significant flexibility in terms of network development, this combined with the integrated support of many well-known communication protocols, makes OPNET an excellent option for implementation of the proposed communication network.

Fig. 3 shows an example model using SITL gateways to link the model with external hardware. In the simulation environment, multiple gateways can be connected to a single physical Ethernet port. Each gateway is assigned a filter to allow network traffic from a specific IP address, TCP or UDP port, or even for a specific application to enter the OPNET simulation at the desired location. In Fig. 3, three gateways are defined which accept traffic from three external servers. Each server is configured to be on a separate IP subnet. The three simulated routers accept traffic from a single machine, and route the packets based on predefined static IP routing tables. In this example, the packets are routed through a virtual Ethernet switch, however, more complex scenarios can are being developed for future studies which route packets through different virtual network types such as wireless, fiber optic, satellite, etc. By placing each network node at different distances from each other, the delays which would occur in an actual system can be simulated depending on the types of link used. Factors such as bandwidth limitation, jitter, and packet losses can also be controlled as well.

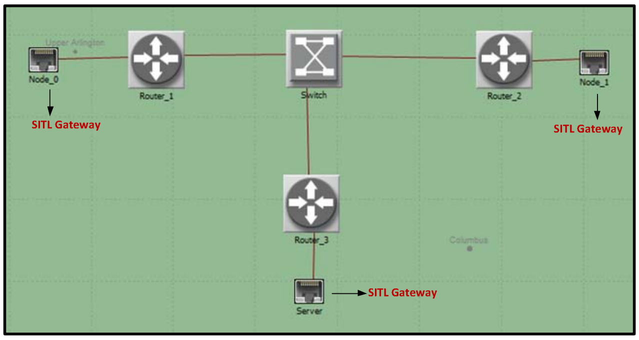


Fig. 3 OPNET's System in the Loop (SITL) model example.

IV. COMMUNICATION EFFECTS IN CONTROL SYSTEMS

One of the main reasons to model a control system that includes communication in the loop is to be able to design better controllers; a NCS may be stable when the effects of the network are not taken into account but may be unstable in real life conditions. Tipuswan and Chow [18] categorized different topologies of NCS into two main types of structures: direct and hierarchical. An example of a direct structure NCS is shown in Fig. 4. In this figure, it is possible to see characteristics of a NCS in which the controller is separated from the plant, and united by communication links.

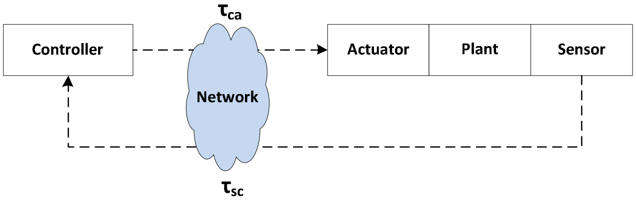


Fig. 4 Direct structure representation of a networked controlled system.

A. Natures of Delays

One of the key factors in NCS is the delays introduced by the communication network. It is known that this latency can degrade the performance of the NCS and even destabilize the system. This delay can be decomposed into two parts as shown in Fig. 4: controller to actuator (τ_{ca}), and sensor to controller (τ_{sc}). Furthermore, it is important to know the characteristics of these delays in order to properly choose or derive methods which can model the system. In [19], the latency introduced by the network was classified different categories such as: random, time varying, or constant and bounded or unbounded, depending on the Medium Access Control (MAC) protocol.

Common multiple access protocols for wired or wireless networks include Carrier Sense Multiple Access (CSMA), Time Division Multiple Access (TDMA), token bus, token ring, and token passing. NCS using CSMA protocols such as Controller Area Network (CAN) or Ethernet, involve uncertain or random delays, while TDMA or token types involve a more deterministic type of latency.

B. NCS Modeling

Different types of control methods can be used for modeling a NCS, where some procedures require previous knowledge of the nature of the delay. Stochastic processes such as Poisson or Markov have been discussed in [20] in order to model random types of latency in a control system. Walsh, *et al.* [8] developed a continuous state space representation model for static or dynamic schedulers. This control method used non-linear and perturbation theory in order to study the effects of delays to a NCS. However, the networks in this method are limited to *priority-based* networks and priority scheduling algorithms such as token-ring and a novel try once and discard (TOD) protocols. Halevi and Ray [21] proposed an augmented discrete-time methodology to grasp the dynamics of NCS over a periodic delay network. Lastly, Branicky *et al.* [22] studied the stability of NCS using deterministic delays in a discrete approach:

$$x[(k+1)h] = \Phi x[kh] + \Gamma_0(\tau_k)u[kh] + \Gamma_1(\tau_k)u[(k-1)h], \tag{1}$$

where, h is the sampling period and

$$\tau_k = \tau_{ca} + \tau_{sc}$$

$$\Phi = e^{Ah}$$

$$\Gamma_0 = \int_0^{h-\tau_k} e^{As} B ds$$

$$\Gamma_1 = \int_{h-\tau_k}^{h} e^{As} B ds.$$

Furthermore, augmenting the system in the form:

$$\bar{x}[k+1] = \bar{A}\bar{x}[k] + \bar{B}\bar{u}[k] \tag{2}$$

where, $\bar{A} = \begin{bmatrix} \Phi & \Gamma_1 \\ 0 & 0 \end{bmatrix}$, $\bar{B} = \begin{bmatrix} \Gamma_0 \\ 1 \end{bmatrix}$, and $\bar{x}[k] = \begin{bmatrix} x[k] \\ u[k-1] \end{bmatrix}$.

For a total periodic delay $\tau < h$, the system is still time invariant and the stability of the system could be evaluated when using a regulator such as; $u[k] = -Kx[k]$, by computing the eigenvalues of the matrix $(\bar{A} - \bar{B}[K\ 0])$ [23].

The methods presented in this section will serve as a reference for future studies in smart grid and PHEV applications. With the platform discussed in section II and III, it is possible to simulate the models developed.

V. CASE STUDY

In this section, a case study of a modern distribution network is presented. The purposes of this model are to test the effects of islanding, which refers to the ability of distributed energy resources (DERs) to continue energy supply to a section of the grid after losing the power from the utility, and to test the influence of the communication during a three phase fault which occurs at grid side.

A. *Model Description*

An example of a distribution network consisting of a PHEV charging station, Local Energy Storage (LES), and a renewable energy resource (PV) is built with the proposed system discussed in sections II and III.

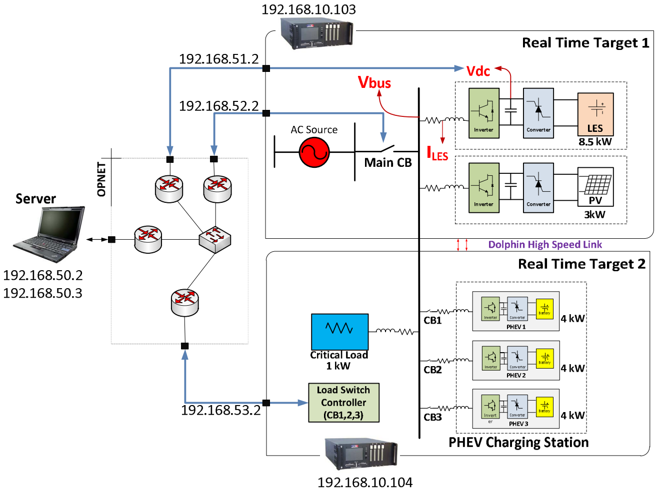


Fig. 5 Integrated communications and power system model for PHEV charging station.

The closed loop control of the power electronics circuits in each renewable energy source has been implemented similar to [24]. In overall, there are two modes for the controllers: grid connected and islanding. During grid connected mode, the aim of the LES connected inverter is to keep the dc bus voltage stable, and the goal of the dc-dc converter is to control the current level of the battery, either charging or discharging. During islanding mode, the LES inverter will change its mode in order to keep a constant grid voltage, while the LES converter will change to voltage control mode in order to maintain a constant DC bus voltage.

When a three phase fault occurs at gird side, a signal from the main CB is sent to the PHEV charging stations in order to disconnect the loads. After 0.1 seconds, the loads are then reconnected to the system one by one. During this process, a measurement of the LES dc bus voltage is packaged and sent to the PHEV charging station through OPNET's simulated network. Within the network, parameters such as latency, bandwidth limitation, and packet losses are introduced. As the PHEVs are added to the system, a drop on the dc bus voltage signifies that there are more loads than the DERs can support. The last load added to the system is then disconnected and no more loads are added.

B. *Model Distribution*

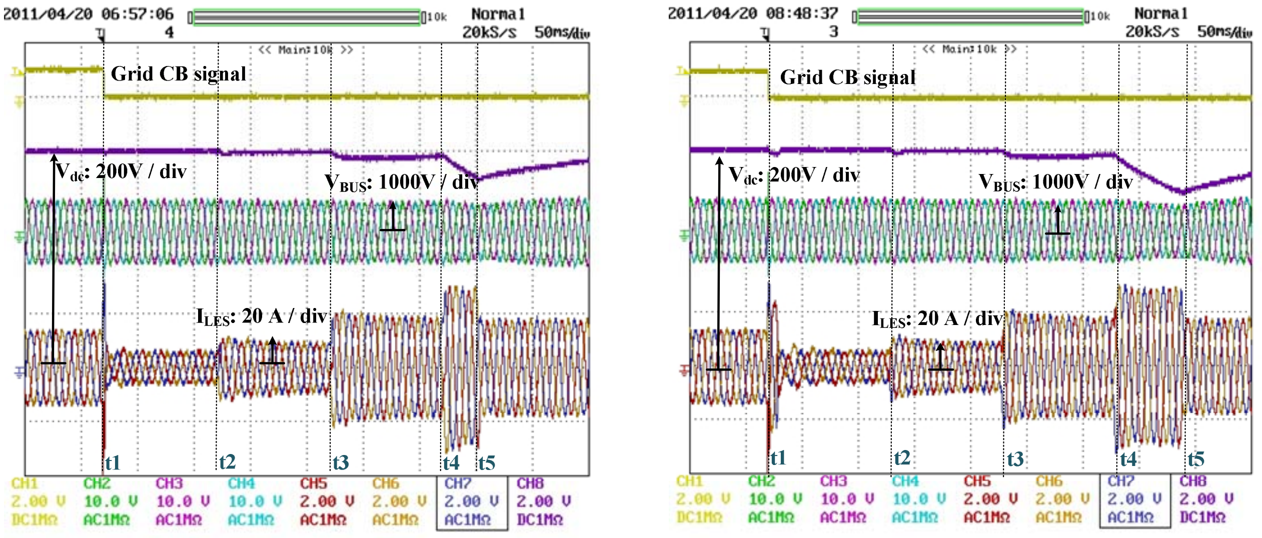
The distribution network model is split into two targets: RT1 contains the grid source along with the DERs, while RT2 contains the PHEV charging station and critical load. A communication infrastructure is built in order for the PHEV charging station to determine when there is loss of main, and whether the new island is able to sustain all the loads. OPNET is implemented in an external desktop as well as a server to distribute the traffic in the network.

C. *Simulation Results*

Real time simulation results are presented which show the influence of the communication network on the model. The details of the power capacity of each unit within the system are shown in Fig. 5. The LES and PV can supply a total of 11.5 kW, while the PHEV charging station and the critical load require 12 kW (4 kW/battery) and 1 kW respectively. The normal dc bus voltage is 800 V and the threshold level is 700 V. These values were chosen based on approximations for a level 2 charging facility.

Fig. 6a shows the results for a model in which the communication between the two targets is ideal (no delays), whereas in Fig. 6b the simulated network requires the data to travel through a specified length in order to obtain a total latency of 28ms. For the first case, an interruption from the grid side occurs at t1 due to a three phase fault which causes the main CB to open and all the noncritical loads are disconnected. At t2, the first PHEV battery is connected to the system, while the rest are attached every 0.1s afterwards. At t3, the second PHEV battery is reconnected. At t4, switch CB3 is closed and the last PHEV battery added to the system causes the dc bus voltage on the LES side to drop, since the DERs do not have enough power to supply the entire system. When the voltage drops below 700V, the last load added to the system is re-disconnected and the model re-stabilizes.

In the second case, the effects introduced by the communication network are more noticeable. The same scenario is run, however due to the delay introduced by the network, two things are noticeable. First, during the disconnection of the grid, the signal from the main CB takes time to reach the PHEV charging station and thus larger and longer transients appear when compared to the first case. Second, the dc bus voltage drops below the threshold value, since the measured dc bus voltage takes a longer time to reach the charging station. This drop in voltage could case problem to the LES and critical load since there is a bigger disturbance on the ac side voltage when compared to the first case.



a) b)

Fig. 6 Simulation Results of two cases: a) ideal communication (no delays), b) 28ms delay in signal communication.

VI. CONCLUSION AND FUTURE WORK

This paper discusses a joint simulation of power and communication networks for the smart grid and PHEV related research. A description of the setup for the complete platform is presented in sections II and III. Section IV presents a review of networked controlled systems, through which is possible to model different types of applications related to smart grid or PHEV scenarios.

A case study for a micro grid model consisting of a PHEV charging station is presented while studying cases more specific to protection and islanding managing. The results confirm the importance of taking into account communication factors such as latency, bandwidth, packet losses, etc., when modeling and simulating micro grids. In the future, different PHEV applications such as vehicle to grid (V2G) and frequency regulation will be studied and modeled.

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