Journal of Network and Computer Applications ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Network and power-grid co-simulation framework for Smart Grid wide-area monitoring networks ☆

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ARTICLE INFO

Keywords:
Smart Grid
Wide area monitoring
Network simulation
Power grid simulation
Co-simulation framework

ABSTRACT

This paper presents a co-simulator framework for wide-area Smart Grid monitoring systems based on phasor measurement units (PMU). The communication network framework is based on the North American Synchrophasor Initiative Network (NASPInet) specification. To understand the performance and to facilitate design of wide-area monitoring based Smart Grid applications, there is a need for a simulator that has both power system and communication system capabilities. In this paper, we present a co-simulation framework developed using two existing public-domain simulators (OpenDSS and OMNET++ for power systems and communication networks simulation respectively). This framework has been implemented at IIT Madras for public use. A hybrid state estimation application, a voltage monitoring application and a renewable energy integration application are implemented over this framework, as example of simulator usage. The simulator software has been made available for public download on http://sourceforge.net.

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1. Introduction

The term "Smart Grid" refers to the enhanced electric power grid that is more reliable, secure and automated using Information and Communication Technologies (ICT) (NIST, 2010). Wide-area monitoring, a part of this framework, utilizes Phasor Measurement Units (PMUs) placed on different buses of the grid. These units report the quality of power in terms of voltage magnitudes, angles and frequency at the rate of 30–120 samples per second. The North American Synchrophasor Initiative Network (NASPInet) has provided a basic framework and specifications for wide-area monitoring systems (Hu et al., 2010; Bakken et al., 2010). Various Smart Grid applications use these data for automated decisions. To understand and evaluate the performance of such monitoring systems, there exists a need for a simulator that incorporates monitoring and communication network functions (Hopkinson et al., 2006; Nutaro et al., 2007; Lin et al., 2011; Godfrey et al., 2010). This can be achieved by developing a simulation framework that uses existing simulators (monitoring system and communication system), supplemented with appropriate message passing and synchronization capabilities.

One of the challenges faced is that power system simulators are based on continuous-time whereas communication network system simulators are event-driven discrete-time simulators. Thus, time synchronization between the two simulators is an important technical challenge to be overcome. Discretizing the continuous system and synchronizing the two simulators at regular intervals results in *accumulation error*. There exist co-simulation frameworks such as EPOCHS (Hopkinson et al., 2006), ADEVS (Nutaro et al., 2007) and the simulator described in (Godfrey et al., 2010). These systems are prone to accumulation error and have been designed for a specific application.

In this paper, we propose a generic co-simulation architecture that uses the existing OpenDSS simulator, a power distribution system solver (Electric Power, 2014), and OMNET++ (The OMNeT++, 2015), an existing communication network simulator. The framework has been implemented at IIT Madras and different grid applications have been tested on the framework. The framework can also be used as a platform for testing different state estimation algorithms, Smart Grid Communication architectures and other applications such as microgrid integration and dynamic pricing. The simulator framework has been made available for public download on sourceforge.net (Bhor et al., 2015), and has already been downloaded by more than 680 users, as of June 2015.

Cyber-physical testbeds represent an alternate approach for conducting similar studies. For instance, the Experimentation

☆This work was supported in part by an Open Collaboration Research (OCR) grant from IBM. Part of this paper was presented at Sixth International Conference on COMmunication System and NETworkS (COMSNETS) 2014, Bangalore, India, January 2014.

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http://dx.doi.org/10.1016/j.jnca.2015.06.016
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Platform for Internet Contingencies (EPIC) project (Siaterlis and Genge, 2014) has been developed using an Emulab-type infrastructure for studying several applications including the Smart Grid. Other testbeds include PowerCyber (Hahn et al., 2013), DEFT (Yardley et al., 2013) and NSTB (U.S. Department of Energy, 2009). Such testbeds are indeed very valuable. However, they require sharing of system resources by users worldwide and hence not very scalable in terms of number of users; also, their lifetime depends on continuous research funding support. Software co-simulators can be used simultaneously by multiple researchers and hence is a more scalable approach; further, they play an important role in initial system analysis before experimenting on a testbed. Thus, co-simulators can be viewed as a useful complement to cyber-physical testbeds.

2. Related work

This section presents the relevant background and related work in co-simulation framework for power systems.

2.1. Simulation basics

In continuous-time system simulation, the changes in system state variables are continuous with respect to time. The state variables are specified in the form of a mathematical equation. Commonly used continuous-time power system simulators include OpenDSS and PSLF. The OpenDSS (Electric Power, 2014) distribution system simulator is a differential equation solver that solves the harmonics and dynamics based on the power generation and load.

A discrete-event simulation framework is used to model system behavior as a series of events occurring at discrete instants of time. Each event can result in the generation of new events in the future. The simulation system maintains an event list, sorted by monotonically increasing order of event times. The system state is changed as each event is sequentially processed in this list. Computer network systems are typically modeled using discrete event simulators such as ns2/ns3 and OMNET++ (http://www.omnetpp.org).

2.2. Smart Grid co-simulation

Co-simulation is a technique where two different simulation environments are combined to create a collaborative system with data exchange between the two simulators. Figure 1 shows a conceptual framework where two different simulator types are integrated. Since the simulation environments of power system and communication network are different, synchronizing between them without errors is a challenging task. We next describe some of the existing co-simulators for power systems.

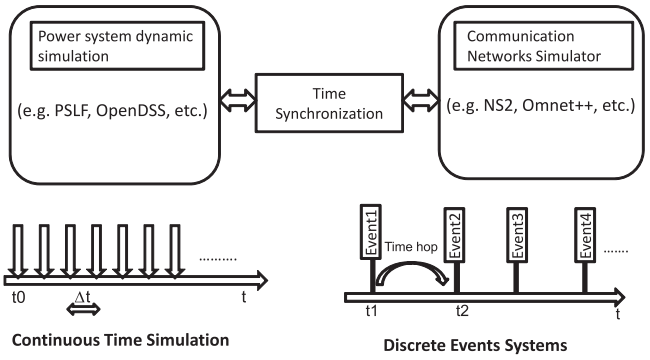

Fig. 1. Time synchronization between continuous-time and discrete-time simulators.

In Godfrey et al. (2010), a co-simulation framework that integrated OpenDSS and NS2 network simulator has been presented. This has been done for a specific application of controlling sudden voltage drops in Photo-voltaic cells due to transient cloud conditions. The IEEE 802.11 wireless network is used for communication and is modeled using ns2. However, it does not provide a generic Smart Grid simulator framework.

EPOCHS (Electric Power and Communication Synchronizing Simulator) (Hopkinson et al., 2006) is a co-simulation system that links PSCAD, an electromagnetic transient simulator, PSLF, a power distribution simulator and NS2 a communication simulator. EPOCHS provides a Run Time Environment (RTE) that transfers messages between the simulators and also maintains the time synchronization across all components. EPOCHS uses a simple time-stepped model for synchronization.

In the framework presented in Lin et al. (2011), the continuous time simulator is solved by discretizing the differential equations and then integrating them to yield approximate results at every point of synchronization. The state variables and network boundary variables are calculated and finally integrated. This forms a *round* in the continuous time simulator and the process is repeated continuously. The synchronization is achieved using an approach that is similar to EPOCHS.

The framework presented in Liberatore et al. (2011) combines ns2 and Open Modelica, a power distribution system with several electrical and electronic libraries. This also implements the time-stepped model for synchronization; however, the synchronization points are not decided earlier. It uses the real-time clock for synchronization between the simulators and ensures that Modelica will never overtake ns2. The communication between the two systems is based on UNIX pipes.

The objective of this paper is to provide a more generic co-simulator framework with explicit support of network protocols.

2.3. EPOCHS synchronization

The main challenge in a co-simulation development is to accurately synchronize the time between the two different simulators. In EPOCHS, a middleware package called the Real-time infrastructure (RTI) provides data access from both the simulators (Hopkinson et al., 2006). RTI decides the synchronization points at which the data transfer between the simulators takes place. These points are evenly spaced along the timeline (Hopkinson et al., 2006). As shown in Fig. 2, the top timeline presents the power system rounds. These are generated continuously in time. The bottom timeline presents the discrete events of communication

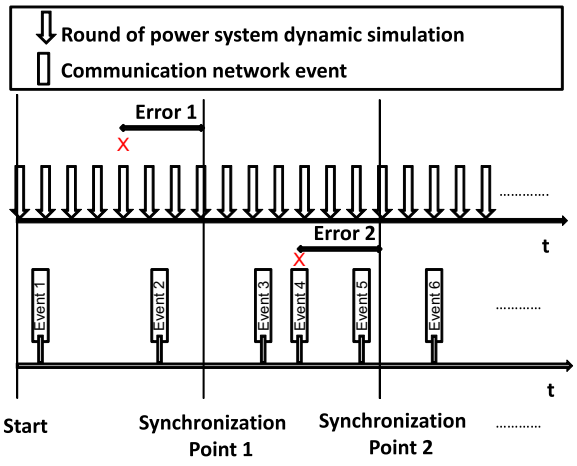

Fig. 2. Error handling in EPOCHS.

Please cite this article as: Bhor D, et al. Network and power-grid co-simulation framework for Smart Grid wide-area monitoring networks. Journal of Network and Computer Applications (2015), http://dx.doi.org/10.1016/j.jnca.2015.06.016

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