

Real-time Co-simulation Platform using OPAL-RT and OPNET for Analyzing Smart Grid Performance

D. Bian, *Student, IEEE*, M. Kuzlu, *Senior Member, IEEE*,
M. Pipattanasomporn, *Senior Member, IEEE*, and S. Rahman, *Fellow, IEEE*
Advanced Research Institute
Virginia Tech
Arlington, VA, USA 22203

Y. Wu, *Student, IEEE*
Industrial Information and Control
System Department
KTH Royal institute of technology
Stockholm, Sweden 10044

Abstract— The objective of this paper is to present a real-time co-simulation platform for analyzing electric power grid operation, taking into account integrated communication systems. This paper discusses how a co-simulation platform can be set up using OPNET and OPAL-RT as communication and power system simulators, respectively. A simplified distribution automation case study is demonstrated to show how the co-simulation platform can be used to analyze performance of the smart grid operation in real-time.

Keywords— real-time, co-simulation, Java Eclipse, OPNET, RT-LAB, OPAL-RT, System-in-the-Loop, smart grid applications.

I. INTRODUCTION

A smart grid is regarded as a complex network where electric power systems and communication systems are interdependent [1]. Relying on communication technologies, many smart grid applications can be implemented in electric power grids, such as demand response, distribution automation, etc. Since communication systems have intrinsic characteristics, such as latency, data error and package lost, this will affect the reliability and security of smart grid operation. In [2, 3, 4], benefits and potential impacts that communication networks have introduced to a smart grid are discussed. Because smart grid operation relies on communication technologies, analyzing its performance needs to consider operation of both power and communication systems.

PowerWorld, MATLAB/Simulink, GridLAB-D, RT-LAB are popular power system simulation tools. OPNET, NS2/NS3 and OMNeT++ are popular communication and network simulators. Nonetheless, neither simulation tools for power system analysis consider the impact from communication systems, nor can communication system simulators provide power system analysis. By combining both power system and communication network simulators, a co-simulation platform can be developed that enables simulations of electric power systems that take into account communication network

properties, such as Quality of Service (QoS), latency, etc. This will allow realistic studies of smart grid operation integrated with communication systems.

There are several co-simulation platforms presented in the literature, including VPNET, OpenDSS-NS2, ADEVS-NS2 and NMLab. The VPNET platform – the combination of VTB (Virtual Test Bed) and OPNET – is used to analyze the influence of data blocking on the output voltage of a boost converter in [5]. A co-simulation platform based on OpenDSS and NS2 network simulator is presented in [6], and this platform has been used to examine the effect of communication failures on smart grid operation. NS2 cooperated with ADEVS (A Discrete Event System simulator) is also used to simulate the communication delay on power system monitoring and control in [7]. In [8], a co-simulation framework called NMLab, which is a combination of MATLAB and NS2, is introduced. This paper introduces a real-time co-simulation platform using OPNET and OPAL-RT. This platform is unique in that it allows simultaneous simulations of power system and communication networks in real-time.

Section II summarizes popular simulators for both communication and power system analyses. In Section III, the classification of co-simulation platforms is discussed, and then the process to set up a real-time co-simulation platform based on OPNET and OPAL-RT is described. In Section IV, a distribution automation test case based on a remote control of a switch is simulated on this real-time co-simulation platform. Simulation results are then discussed.

II. SIMULATION TOOLS FOR POWER AND COMMUNICATION SYSTEMS

In this section, widely used power and communication system simulators are summarized, including PowerWorld, OpenDSS, SimuLink, RTDS and OPAL-RT for power system analysis, and NS2/NS3, MONeT++ and OPNET for communication system simulation.

A. Simulation tools for Power System Analysis

PowerWorld from PowerWorld Corp. is an interactive power system simulation package designed to simulate high voltage power system operation. This software contains power flow analysis package capable of efficiently solving power system models [9].

OpenDSS, an open-source simulator from EPRI, is a comprehensive electrical power system simulation tool for analyzing power distribution systems. OpenDSS supports nearly all frequency domain analyses commonly performed on electric utility power distribution systems. Additionally, it supports many new types of application analyses, which are designed to meet future needs related to smart grid, renewable energy research, etc. [10].

Simulink, developed by MathWorks, is data-flow graphical programming software for modeling, simulating and analyzing dynamic systems. It supports simulation, automatic code generation, continuous test and verification of embedded systems. Integrated with MATLAB, it can incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis [11].

Several kinds of real-time hardware-based simulation platforms are available, i.e., Real-Time Digital Simulator (RTDS) and OPAL-RT. These platforms enable model execution at the same rate as actual time.

RTDS is a real-time power system simulator. High-speed simulation, closed-loop testing of protection and control equipment and hardware-in-the-loop applications are supported by RTDS [12].

OPAL-RT can be used to design, test and optimize control and protection systems for power grids, power electronics, etc. In addition, the RT-LAB, core OPAL-RT software, enables users to develop models suitable for real-time simulation. RT-LAB models are fully integrated with MATLAB/Simulink [13].

B. Communication System Simulators

Network Simulator versions 2 and 3 (NS2/NS3) are open-source discrete event network simulators, targeting communication and network research. They support simulations of IP-based applications (including TCP, UDP, etc.), routing and multicast protocols over all kinds of networks (both wired and wireless). NS2 core is written in C++ programming language. Therefore, C++ is needed to create new network models or protocols. NS3, the successor of NS2, includes some new features, such as support for the Python programming language, improved scalability, and etc. [14].

OMNeT++, as a discrete event simulation environment, is an open-source software. Since OMNeT++ is component-based and provides a generic and flexible architecture, it is widely used to simulate complex information technology systems, queuing networks, and etc. Communication network simulation is one of the most popular applications of OMNeT++ [15].

OPNET Modeler is a commercial discrete event network simulator which focuses on network performance simulation. OPNET provides toolsets, such as: node models that specify interface of a network component; process models that abstract the behavior of a network component; a project window that defines network topology and link connections; and a simulation window that captures and displays simulation results. OPNET Modeler has a high-level user interface offering access to a large library of blocks, which represents different models and functions. In addition, OPNET Modeler provides System-in-the-Loop (SITL) that allows physical hardware devices and a simulator to interact as a unified system. SITL can also allow multiple physical networks to communicate through a simulation [14].

C. Choosing Simulators for Real-Time Co-Simulation

In this paper, OPNET and OPAL-RT are chosen to develop a real-time co-simulation platform. OPNET is chosen because it is well designed and widely used commercial software that provides more standard packages than other communication simulators discussed above. It also offers a user-friendly interface. For power system real-time simulation, OPAL-RT is chosen because RT-LAB, coming with OPAL-RT, has a number of ready-to-use models and it can be integrated with MATLAB/Simulink. Having access to a number of standard packages and ready-to-use models will facilitate simulations of a number of smart grid applications.

III. CO-SIMULATION PLATFORM

In this section, the classification of co-simulation platform is discussed. Components of the real-time co-simulation platform are presented, together with discussion on the co-simulation platform set up.

A. Co-Simulation Platform Classification

The co-simulation platform can be classified into non real-time (off-line) and real-time, as discussed below.

1) Offline Co-Simulation (Non Real-time)

In a non real-time co-simulation, two simulators are generally runs separately. In order to realize accurate information exchange between power and communication systems, it is necessary to synchronize the simulation time step, while the operation of two simulators does not need to be synchronized. For a non real-time platform, a communication simulation runs and simulation results are saved into a file, which is shared with the power system simulator. This file is used when the power system simulator needs information about communication simulation results. Easy setting up is the advantage of this non real-time co-simulation platform. However, the accuracy of simulation results can be limited due to asynchronous operation of two simulators.

2) Real-Time Co-Simulation

A real-time co-simulation platform needs an interface that can enable the information exchange between two simulators. The synchronization of two simulators relies on this interface,

which serves as a data buffer that allows real-time packet exchanges using protocols, like TCP or UDP. In a real-time co-simulation platform, two simulators run synchronously. As an advantage, a real-time co-simulation platform can handle large and complex systems without manual intervention. However, the initial set up is time-consuming and multiple PCs along with the real-time simulator are necessary to set up a real-time co-simulation platform.

B. Components of a Real-Time Co-Simulation Platform

The following components, as shown in Figure 1, are necessary to establish a real-time co-simulation platform for simulating smart grid operation. This paper discusses this real-time co-simulation platform in the context of a distribution automation application.

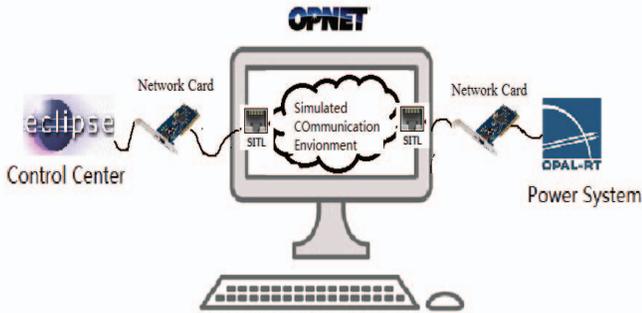


Figure 1. Connection among OPAL-RT, OPNET and Java Eclipse.

1) Control Center Model

A distribution automation control center is simulated using a PC that has Java Eclipse installed. This control center is responsible for monitoring voltage levels and controlling selected devices in a distribution system. Based on the voltage information monitored, the control center makes a decision and sends control commands to selected devices.

2) Electric Power System Simulator

To set up an electric power system, OPAL-RT and a PC

that has RT-LAB installed are used. The power system model is built using readily available blocks from RT-LAB library. Once the simulated model is compiled successfully in RT-LAB, the power system model can be loaded into the real-time simulator, i.e., OPAL-RT.

3) Communication System Simulator

A PC with OPNET installed is used to simulate the communication system. The communication system model is configured to enable information exchanging between the control center and the power system model. Simulation results can provide communication latency, data dropping, etc.

4) Connections among the Control Center Model, and the Electric Power and Communication System Simulators

The connection between the power system simulator (i.e., OPAL-RT) and the communication system simulator (i.e., the PC that has OPNET installed) is set up using an Ethernet interface. Similarly, the connection between the OPNET PC and the control center (i.e., the PC that has Java Eclipse installed) is also set up using an Ethernet interface.

SITL, a model provide by OPNET is used to enable exchange of packets between OPNET and OPAL-RT/Java Eclipse. As shown in Figure 1, the PC with OPNET installed requires two sets of a SITL model and a network card. Each set, i.e., one SITL model and one network card, functions as the data exchange interface. With this interface, the data exchanging between Java Eclipse and OPNET can be realized. Similarly, OPAL-RT and OPNET are connected through another set of data exchange interface.

C. Network Configuration and Operation of the Real-time Co-simulation Platform

The detailed IP and Subnet Mast set up of the real-time co-simulation platform are illustrated in Figure 2. The operation sequence of this platform can be divided into two steps.

In the first step, building and compiling the power system model in the PC with RT-LAB installed; and loading the

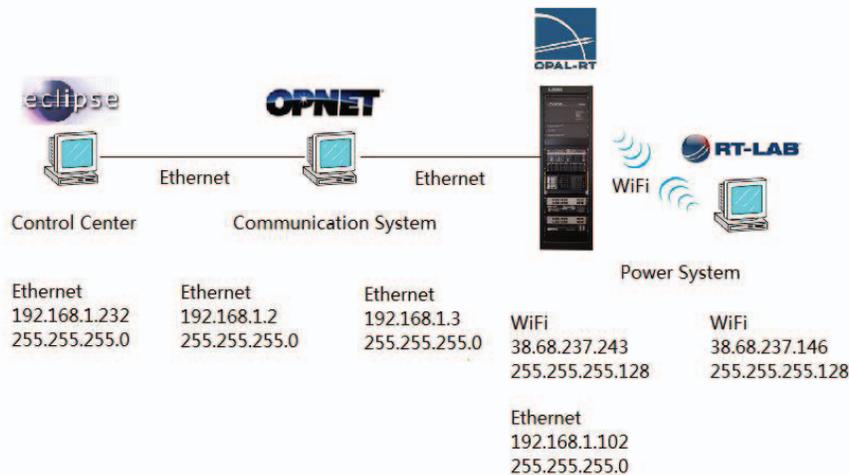


Figure 2. Real-time Co-simulation Platform with detailed IP and Subnet Mask

compiled power system model into OPAL-RT. In this experiment, the connection between OPAL-RT and RT-LAB is established using Wi-Fi interface. See Fig. 2.

The second step is to run control center, OPNET and OPAL-RT at the same time to co-simulate smart grid operation. Simulations performed in this step run in real-time. The package exchanging among these three components uses the UDP protocol.

IV. CASE STUDY

In this section, a case study of a simplified distribution automation application is simulated using the real-time co-simulation platform discussed in Section III.

In the simulation, a simplified distribution system model is set up in RT-LAB, whose single-line diagram is shown in Figure 3. As shown, a capacitor bank is connected at Bus 4 through a switch, which is remotely controlled by the control center located 100 km away. The control center monitors voltage at Bus 4 and sends control commands to switch ON/OFF the capacitor based on the voltage level.

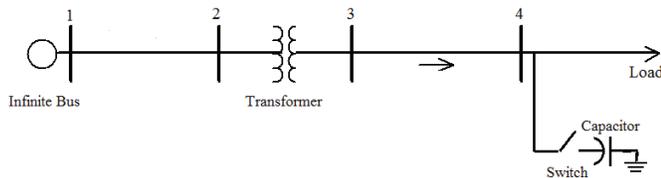


Figure 3. Single-line diagram of the simulated power system model

Two scenarios are simulated in this study. In the first scenario, the control center monitors the voltage at Bus 4, but there is no control command sent to the switch. In this case, the switch keeps its open status, implying that the capacitor bank is always disconnected. In the second scenario, the voltage at Bus 4 is monitored, and a control command is sent to switch ON the capacitor bank if the monitored voltage is lower than 0.95 per unit (*pu*). When the monitored voltage is higher than 0.98 *pu*, a control command is sent to switch OFF the capacitor bank.

In order to simulate the system in the developed real-time co-simulation platform, a communication model associated with this power system model is developed in OPNET, as shown in Figure 4.

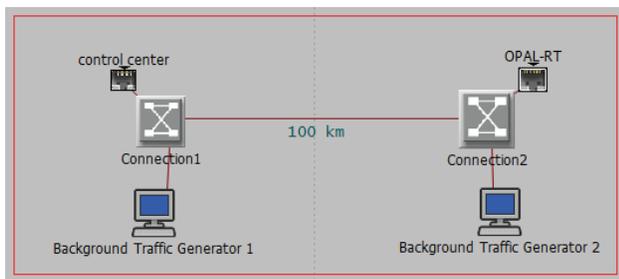


Figure 4. Communication system model in OPNET

It is assumed that the transmission medium between the control center and the switch for capacitor bank control is a fiber-optic cable. This is typical for any distribution automation application. This connection is modeled as a 100-km fiber-optic cable that connects the control center and the power system model developed in OPAL-RT, as shown in Figure 4. In this simulation, two background traffic generators (one is attached to the control center; the other is attached to the OPAL-RT node) are used to create background traffic representing communication traffic of other smart grid applications that shares the same channel.

Load data used in the case study is derived from a real-world distribution substation of an electric utility in Virginia. The data resolution is in one-minute intervals. The load profile at Bus 4 used in this study is shown in Figure 5 for a 24-hour period.

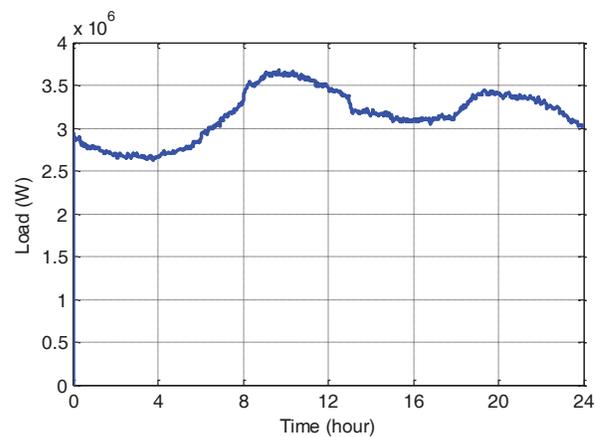


Figure 5. Load profile at Bus 4

The real-time co-simulation platform is used to simulate the two scenarios discussed above. Simulation results showing voltage profiles at Bus 4 are shown in Figure 6.

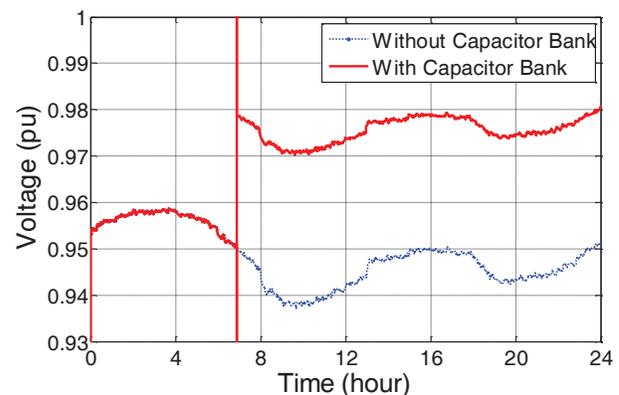


Figure 6. Voltage profiles at Bus 4 w/ and w/o the capacitor bank

For the first scenario, the capacitor bank is always disconnected. Voltage at Bus 4 without the capacitor bank is shown as the dotted blue line in Figure 6. The voltage is

lower than 0.95 pu during the morning peak period, which begins at 7 am.

In the second scenario, voltage at Bus 4 is shown as the solid red line in Figure 6. The voltage drops below 0.95 pu at around 7:30 am. Therefore, the switch is closed to connect the capacitor bank when the command from the control center is received. The recorded latency is around 0.002 seconds. This represents the duration from when the voltage is measured at Bus 4 to when the switch receives the command from control center. Once the switch is closed, voltage at Bus 4 is increased above 0.95 pu as expected. Note that this 0.002-second latency is obtained assuming that the occupied bandwidth of the fiber-optic communication channel is less than 50% using the background traffic generators.

Figure 7 illustrates communication latencies for the switch to receive commands from the control center. Using the background traffic generators, three cases with different background traffic are simulated, i.e., 0%, 50% and 100% of the channel bandwidth.

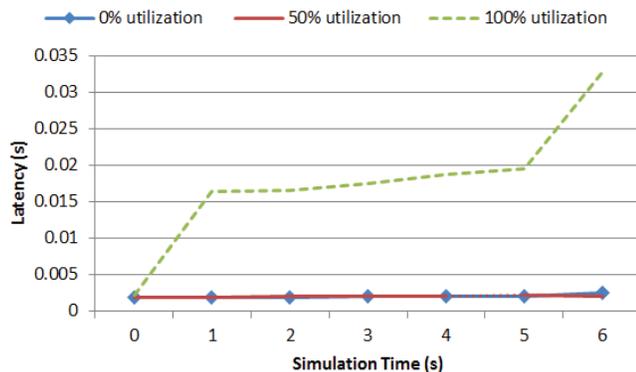


Figure 7. Communication latency

When the background traffic is lower than the channel bandwidth, the latency relies on the channel length. It can be seen that with 0% and 50% bandwidth utilization, the latencies are around 0.002 seconds, as shown as the solid line and the line with dots in Figure 7.

With smart grid development, communication channels may need to be shared with many other smart grid applications. In some situations, the channel utilization can be close to 100% of its capacity during certain peak periods. The latency may also increase due to the queueing delay caused by high data transfer. An example of latency with 100% channel utilization is shown as the dashed line in Figure 7. Under this situation, poor communication performance may potentially have negative impacts on the operation of the smart grid, depending on criticality of smart grid applications. Therefore, the real-time co-simulation platform is helpful for analyzing the impact of communication failure on smart grid operation.

V. CONCLUSION

This paper discusses a real-time co-simulation platform set

up using OPNET and OPAL-RT. In this platform, the simulation of power system operation takes into account the communication system performance. The detailed network configuration and operation of this platform are discussed. A simplified distribution automation case study is simulated on this real-time co-simulation platform. Results of the case study verify that this platform can provide a real-time co-simulation analysis for smart grid applications, such as the impact of communication system failures.

REFERENCES

- [1] Fang, Xi; Misra, Satyajayant; Xue, Guoliang; Yang, Dejun, "Smart Grid -The New and Improved Power Grid: A Survey," *Communications Surveys & Tutorials*, IEEE, vol.14, no.4, pp.944-980, 2012.
- [2] U.S. Department of Energy, "A survey of wireless communications for the electric power system" [Online], Available: https://www.pnnl.gov/nationalsecurity/technical/secure_cyber_systems/pdf/power_grid_wireless.pdf. Retrieve: Nov. 2014.
- [3] ABB North America, "Power systems automation and communication protection and control for reliable and optimized power delivery" [Online], Available: [http://www05.abb.com/global/scot/scot400.nsf/veritydisplay/ae01e7a2e47c7a9fc1257bf3004681e9/\\$file/9AKK105713A8759_LoRes_en_Power_Systems_Automation_and_Communication_ABB_North_America.pdf](http://www05.abb.com/global/scot/scot400.nsf/veritydisplay/ae01e7a2e47c7a9fc1257bf3004681e9/$file/9AKK105713A8759_LoRes_en_Power_Systems_Automation_and_Communication_ABB_North_America.pdf). Retrieve: Nov. 2014.
- [4] Karlheinz Schwarz, "Monitoring and control of power systems and communication infrastructures based on IEC 61850 and IEC 61400-25" [Online], Available: http://www.nettedautomation.com/download/pub/dt-tampa-paper_2010-03-24.pdf. Retrieve: Nov. 2014.
- [5] Li, W.; Monti, A.; Luo, M.; Dougal, R.A., "VPNET: A co-simulation framework for analyzing communication channel effects on power systems," *IEEE Electric Ship Technologies Symposium (ESTS)*, pp.143-149, April 2011.
- [6] Godfrey, T.; Mullen, S.; Dugan, R.C.; Rodine, C.; Griffith, D.W.; Golmie, N., "Modeling Smart Grid Applications with Co-Simulation," *IEEE Smart Grid Communications (SmartGridComm) Conference*, pp.291,296, Oct. 2010.
- [7] Nutaro, J.; Kuruganti, P.T.; Miller, L.; Mullen, S.; Shankar, M., "Integrated Hybrid-Simulation of Electric Power and Communications Systems," *IEEE Power Engineering Society General Meeting*, pp.1-8, June 2007
- [8] Heimlich, O.; Sailer, R.; Budzisz, L., "NMLab: A Co-simulation Framework for Matlab and NS-2," *Advances in System Simulation (SIMUL) Conference*, pp.152-157, Aug. 2010
- [9] PowerWorld Corporation, [Online], Available: <http://www.powerworld.com/products/simulator/overview>. Retrieve: Nov, 2014.
- [10] Electric Power Research Institute, [Online], available: <http://smartgrid.epri.com/SimulationTool.aspx>, Retrieve: Nov, 2014.
- [11] RTDS Technologies, [Online], Available: <http://www.rtds.com/hardware/hardware.html>. Retrieve: Nov, 2014.
- [12] OPAL-RT Technologies, [Online], available: <http://www.opal-rt.com/product/rt-lab-professional-real-time-digital-simulation-software>. Retrieve: Nov, 2014.
- [13] Jianli Pan, "A Survey of Network Simulation Tools: Current Status and Future Developments", [Online], Available: <http://www.cs.wustl.edu/~jain/cse567-08/ftp/simtools/index.html>
- [14] "Introduction to SITL" [Online], Available: https://support.riverbed.com/bin/support/static/doc/opnet/17.5.A/online_modeler_17.5_PL5/Tutorials/wwhelp/wwhimpl/common/html/wwhelp.htm#href=sitl_tut_1.html&single=true Retrieve: Nov, 2014.
- [15] OMNeT++, [Online], Available: <http://www.omnetpp.org/models> Retrieve: Nov, 2014.