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A Comparison of Wireless Sensor Networks Co-Simulation Platforms for Smart Grid Applications

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ABSTRACT

In the past few years, the smart grids have attracted more and more attention. The fact that these systems are based on the pervasive use of new Information and Communications Technologies (ICTs) opens new perspectives in an aim to improve the electrical grid performances. One of the most commonly deployed technologies in such a real environment is the wireless sensor networks (WSNs) technology. WSNs are thus used to monitor and control the electrical grid components. In this paper we will give an overview on WSNs applications and challenges for smart grids. One promising research topic, when speaking about WSNs in smart grids, is the co-simulation which allows studying and evaluating any new technique in a near real grid behavior. Hence, in this paper, we will also present and discuss the architectures, the advantages and the drawbacks of the most important smart grids co-simulation platforms used to combine the network behavior with the power grid systems models.

KEYWORDS

Co-simulation, network simulation, electric power simulation, smart grid, wireless sensor networks.

1 INTRODUCTION

The huge development of consumer electronics (PDAs, cell phones, laptops, etc.) and the increase of the world population make the techniques used in the electricity generation, transmission and distribution of the current power grids –conceived more than a century ago- inappropriate to meet the new power consumption needs. In fact, the energy consumption is expected to double by 2020 [1]. Other factors such as the wear of the used components/equipments prompt depletion of the fossil energy used in the electric energy generation process also affect the current power grids efficiency. Due above mentioned causes; many countries have experienced, in the last years serious blackouts causing considerable financial losses. Therefore, the power renovation grids renovation process becomes a real need to meet the efficiency and reliability requirements. The renovation process targets: *i*) the electric equipments construction and modernization, *ii*) the renewable energy integration (wind, photovoltaic, etc.), *iii*) the available grid resource management to avoid the energy wasting, and *iv*) the efficient grid components control and monitoring.

A major power grid objective is to ensure the permanent electricity availability regardless all the conditions (weather, component failure, hacking attacks, etc.). This objective can be reached by foreseeing the power consumption, monitoring the grid components, the grid self-healing improving and adjusting automatically the electricity distribution. All these functionalities become feasible thanks to the advent of Information and Communications Technologies (ICTs). ICTs guarantee the efficient communication and coordination between all power grid participants (suppliers, consumers, equipments, etc.). The power grids equipped with ICTs are called "*smart grids*".

One of the most appropriate technologies for the smart grids control and monitoring is the wireless sensor networks (WSNs) technology [2]. Hence, WSNs are deployed all over the electricity grid parts (generation plants, substations, power lines, consumers' side, etc.). Then, in this paper, we propose to present the different challenges to be raised by WSNs to meet the smart grids requirements. We also undertake a study on how a WSN based smart grid solution is validated through what we call the co-simulation process (i.e. combining the network behavior with the power grid systems models in order to assess the performance in both network communication side and efficient power management side).

The rest of this paper is organized as follows. In the section II, we focus on the different WSNs' applications in the smart grids [3] [4] and we present the new challenges facing the WSNs to satisfy the smart grids requirements. In section III, we present the need of using co simulation to evaluate the performance of WSNs communication behavior in the context of the smart grids by considering the characteristics of the electrical components. Different co-simulation platforms will be presented with a discussion on the advantages and the drawbacks of each platform. Finally, we conclude the paper in section IV.

2 WSNS' APPLICATIONS AND CHALLENGES IN SMART GRIDS

Considering their autonomy, their ease of deployment, as well as the sensor node sensing and communication capacities, new opportunities had raised in the past decade in the Wireless Sensor Networks (WSNs) domain. These opportunities are not linked to specific applications, and WSNs can be deployed in an outfit of applications (military applications, industry, e-health, environment, security, etc.).

On the other hand, in the smart grids field, the power generation, transmission, distribution and consumption processes require more and more control and monitoring to improve the (power) resource management and to optimize the electricity consumption by adapting the energy distribution to the consumers' needs. Such a monitoring and control can be done only by deploying a sensing device in each grid component (transformers, generators, etc.) and transmitting the gathered information to either other components (regulator, actuator, etc.) or to a control center. This latter will be in charge of taking adequate decisions. WSNs are the natural choice to fulfill the sensing and communication tasks. Then, new types of sensors can be conceived to satisfy the smart grid needs such as:

- Basic measurements sensors: voltages, currents, temperature;
- Smart voltage sensors;
- Smart sensors for fault or failure detection;
- Smart sensors for transformers monitoring;

- Temperature sensors for high voltages lines;
- etc.

2.1 Applications of WSNs' in Smart Grids

The electrical power grid can be partitioned into three main conceptual segments: the energy generation, the power transmission & electricity distribution, and the consumption side.
1) *WSNs for energy generation segment*: In the conventional power grids, energy generators are monitored by a limited number of high-cost wired sensors deployed in some critical locations. One of the main objectives of smart grids is the usage of intensive renewable energy sources (wind, photovoltaic cells, etc.) and their ease of integration in the generation process. These generation sources are generally situated in remote and hard to reach areas within harsh environment which requires a continuous monitoring of such zones via low-cost sensors. Then WSNs represent the ideal technology to monitor such energy generators [5] [6] [7] [8].
2) *WSNs for transmission and distribution segment*: The transmission system (towers, overhead and underground power lines) and/or distribution system (substations, transformers and wiring to the consumers) failure may cause blackouts and may even present a danger to the public security. Hence, these components must be monitored in near real time to troubleshoot any problem. In addition to the continuous monitoring, this segment must be protected against external attacks due to the ease of access to any component. Once again, WSNs provide promising solutions for the electrical power grids monitoring and securing [9] [10] [11] [12].
3) *WSNs for the consumer side*: For the conventional electricity grids, the substations have been the last mile of the grid. Indeed, the consumer premises are not included in the power grid. In smart grids, a two-way flow of electricity and information between the supplier and the consumer become possible with the usage of smart meters and an Advancing Metering Infrastructure (AMI). It becomes then possible to monitor, to control the energy consumption of each consumer, and even to react automatically by using advanced tools for home automation based on WSNs capacities. Then, each appliance in the modern house can be equipped by some sensors to determine the energy consumption cost and communicate it to a local control center [3] [13].

2.1 WSNs' Challenges in Smart Grids

The WSNs deployment in the smart grids introduces new challenges which sensor networks must overcome. These challenges are related to communication, reliability & robustness, and real time constraints.
1) *Communication challenges*: The use of usual communication technologies for the WSNs such as ZigBee on IEEE 802.15.4 does not allow taking into consideration the hostile environment in which the smart grid components operate. These components are a target to noise and important interferences to which the ZigBee technology is not adapted since Zigbee shares the same frequency band with the wireless LANs using IEEE 802.11 and the Bluetooth technology.
This may degrade considerably the network communication performance.

2) *Reliability and robustness of WSNs*: WSNs failures arising in power grids may create serious problems. In fact, the environmental conditions (interferences, humidity, dust and vibration) may cause the sensor nodes defection and affect the network topology. The problems in WSNs can be caused by the sensor nodes constraints (limited battery and CPU, and reduced memory capacity).
3) *Real time constraints*: Considering the real time requirements in smart grids which must react very quickly to a failure situation, the communication network must transmit the data in a near real time to correct the anomaly arising in the network and restore the normal functioning of the electricity grid.
After giving an overview of WSNs' applications in smart grids and some challenges related to the sensor networks deployment, the following section will be dedicated to the description of smart grids co-simulation platforms.

3 SMART GRIDS CO-SIMULATION

The electric power grid is among the most critical infrastructures for a nation. In fact, this infrastructure is interdependent with other vital infrastructures and disruptions in the power grid can have severe consequences for other critical systems such as the natural gas and the water supply systems. To avoid any disruption in that grid, any new mechanism must be well studied and experimented before deploying it in the real infrastructure which is the role of simulation.

3.1 Necessity of Co-Simulation for Smart Grids

In smart grids, the more accurately a simulation platform emulates the behavior and performance of the smart grid architecture, the better we could improve this grid. The problem in a smart grid is to simulate two completely different systems interacting with each other. On the one hand, the electric power system has a continuous time dynamic behavior. On the other hand, the communication network including many types of networks (wireless sensor, wired, LAN, and WLAN networks) has a discrete event behavior. Therefore, simulators conceived for conventional power grids or only for networking are unable to emulate the real behavior of smart grids. This incapability rise the need for new platforms that can reflect the real smart grids behavior and provide tools for the researches to simulate any new technique or mechanism specific to these grids. The term co-simulation is used to define a simulation of two different systems, which needs the cooperation of more than one simulator (the power simulator and the network simulator in the case of smart grids) to fulfill the simulation task.
Co-simulation supports many different methods for connecting simulators. One method is that each simulator runs separately from the other and when an interaction is needed it can send or receive information by using third tier (for example pipes). In this method, the synchronization is a key factor to guarantee the simulation success. The second method is to implement new interface in each simulator ensuring the interaction with the other simulator without need of a third tier. Another method is to integrate one simulator's

functionalities in the other as a module. This can avoid the problem of synchronization and gives a perfect emulation of the real world.

3.2 Smart Grid Co-Simulation Platforms

In the literature, many co-simulation platforms were proposed to allow smart grid efficiency simulation. For the networking side the most used simulator is the well known *ns-2* (*Network Simulator-2*) [14]. For instance, ns-2, allows the simulation of a large panel of communication technologies in particular the IEEE 802.11 or IEEE 802.15.4 medium access layers that can be used to ensure communication in WSNs.

For the power systems side, many simulators are experienced in the co-simulation process (*adevs*, *OpenDSS*, *PSLF*, and *Modelica*).

1) *The ns-2/adevs co-simulator*: The well known network simulator *ns-2* provides a rich set of techniques and protocols for WSNs. So selecting it as the network simulator in the most co-simulation platforms is explained by its functionalities covering different types of sensor networks. In [14], the authors presented a new co-simulation technique to integrate power systems models with the network-based wide area control schemes. In fact, the difference between a power system and a network system is that the physical laws dictating the power system behavior are defined by differential-algebraic equations (continuous models) with few discrete events, while the network behavior is described by chains of significant events (discrete models). The integration technique is based on formal semantics provided by *DEVS* (*Discrete EVent System Specification*) [15] which offers a large set of mathematical basis for building and simulating hybrid systems. *adevs* (*A Discrete EVent System simulator*) [16] is used to implement discrete events and continuous processes that do not need communication using the C++ language. Other processes using communication are modeled with *ns-2*. The events and processes modeled by *adevs* are then integrated into the *ns-2* simulation model using the *adevs* simulation control API. The *adevs* simulation tool is encapsulated as an *ns-2* TclObject and used directly by the ns-2 simulation. The *ns-2* module invokes the *adevs* module if one of two events occurs: an internal *adevs* event or a message receipt at a process modeled within *adevs*. When the first type of events occurs, the *ns-2* simulator queries *adevs* for any message needed to be sent, schedules *ns-2* events to send messages returned by the query, instructs *adevs* to update its internal state and queries *adevs* for its next event time to schedule a corresponding *adevs* event in *ns-2*. The second type of events causes *ns-2* to inject information into the *adevs* module. It injects events into the *adevs* simulator, instructs this simulator to update its internal state according to the injected events and asks it for its next event time. *ADEVS* structure is used to simulate the continuous processes. A good *DEVS* formalization of the power behavior is essential to reflect the real power dynamics. The simulation of WSNs deployment can be evaluated in this platform thank to the different *ns-2* techniques and modules (MAC protocols, Routing protocols. . .). The small scale WSNs' applications such as home automation can be well simulated in this platform.

2) *The ns-2/OpenDSS co-simulator*: In 2010, Godfrey et al. proposed a co-simulation platform [17] using the *ns-2* and the *OpenDSS* (*Open Distribution System Simulator*). They studied the impact of "*cloud transient*" (solar ramping) phenomenon, when clouds pass in front of photovoltaic (PV) panels, on the voltages variation. The communication network is needed to discharge distributed storage batteries to compensate the voltage reduction.

OpenDSS is a simulation tool for electric utility distribution systems. It provides energy analysis tools for power delivery and is designed to simulate discrete events.

In the co-simulation, when the storage controller detects the solar ramping, it will attempt to dispatch the storage units to maintain a smooth voltage. *OpenDSS* provides the time of the PV ramp event, the topology of the storage batteries and the power load profile for the storage units. *ns-2* simulates the arrival of controller messages to each storage unit, which is assumed to respond immediately. The arrival times are sorted and fed back to the *OpenDSS* engine as a script. The system voltage can be computed at any time according to the storage units' reaction determined by message arrival times.

The PV panels form a WSN that communicates using the IEEE 802.11 standard. The model used in the ns-2 is configured to simulate the IEEE 802.11 operating in 915 MHz Industrial, Scientific and Medical (ISM) band.

Figure 1 gives an overview of the data flow between the *OpenDSS* and the *ns-2* during the co-simulation. The messages sending time and the storage units' coordinates are transmitted to the *ns-2* module, which computes the messages arrival times. These times are merged with the load profiles and then injected in the *OpenDSS* engine. The process is repeated until the storage batteries are fully discharged.

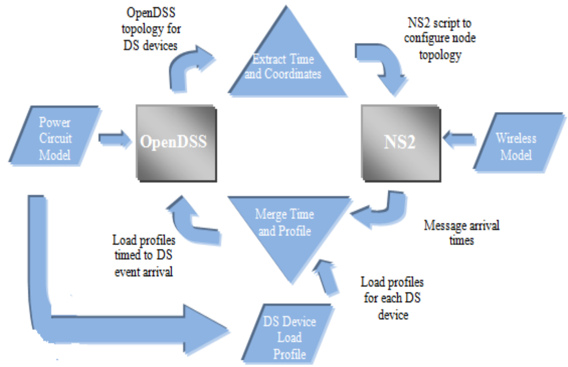

Figure 1. OpenDSS/ns-2 co-simulation.

The study undertaken in [17] shows how, using the *ns-2/OpenDSS* co-simulation, we can evaluate the solar ramping phenomenon in smart grids using photovoltaic panels and monitored by a wireless sensor network.

3) *The ns-2/Positive Sequence Load Flow (PSLF) co-simulator*: In [18], Lin et al. integrate the *PSLF* (*Positive Sequence Load Flow*) and the *ns-2* to implement a co-simulation framework improving the practical investigation of smart grid and evaluating wide-area measurement and control schemes.

The authors explained their choices of simulators by the fact that the two simulators are proven in their domains and have good supports for used defined extensions. *PSLF* provides steady state and dynamic power system simulations. It has an extensive library of electromechanical dynamic models and can simulate a system with up to 60000 buses. *PSLF* offers also a graphical user interface to facilitate the interactions with the users.

The co-simulation is provided by implementing new interfaces in both *PSLF* and *ns-2* sides. The *ns-2* network event scheduler is adopted as the global scheduler. In the *ns-2* side, a new class is implemented as a *PSLF* interface that initializes the power system dynamic simulation rounds in *ns-2*. This class collects power system data from *PSLF* after each dynamic round and saves it in *ns-2* for future use by other network components. In *PSLF*, a new stand-alone dynamic model implemented and attached to the simulated system. It has two functionalities; the first is reporting back the power system state data to the *ns-2* after a demand. The second functionality is suspending *PSLF*'s simulation after each dynamic round and waiting for *ns-2* commands to continue. The second function is crucial for scheduling co-simulation by a global scheduler.

Besides the new interface, other components are implemented in *ns-2* to facilitate the power system applications management. Slave agents are implemented in application layer that stand agents interacting with power system and communication infrastructure (intelligent electronic devises or digital relays). A master agent is also implemented in the same layer to coordinate the slave agents' tasks. This agent can stand for a central control module or an operation center. Classic transport protocols are modified to support power data transmission. After describing their co-simulation platform, the authors studied an agent-based supervisory backup relay protection scheme on this platform. This case study allows the co-simulation framework and the protection scheme validation.

4) *The ns-2/Modelica based-on simulator*: In [19], the co-simulation is used to evaluate a new communication network for smart grids named *PowerNet*. This network includes interoperable heterogeneous networks and aims to provide adequate degrees of QoS, reliability, and security for the networked control. It attempts to exploit the previous deployed networks to reduce the cost of deploying new networks (LANs, WLANs, WiMax, WSNs, etc.).

The co-simulation evaluation benefits from the communication functionalities offered by *ns-2*, the extensive set of power devices available in *Modelica* libraries, and from the graphical interfaces of both simulators. The intercommunication between the two simulators is achieved by UNIX pipes. The synchronization between the two simulators is a key feature for the interconnection to success. The inter-simulator connection proceeds as follows: *ns-2* and *Modelica* start at the same time (t_i). While *Modelica* is pausing, *ns-2* runs until the first event needing communication occurs at time (t_{i+1}). *ns-2* pauses running and instructs *Modelica* to run until (t_{i+1}). At this time is the event needs information to be communicated from *Modelica* to *ns-2*, this latter instructs *Modelica* to write the information to a named pipe and then *ns-2* reads it from this pipe. If the information is from *ns-2*, it informs *Modelica* to read this information from the named pipe. The process repeats until the end of the simulation. At any given time, we can notice that one simulator is running, while the other is pausing. In this co-simulation, *ns-2* is responsible of determining the communication times. Therefore, this co-simulation cannot support sending data between the two simulators in response of events occurring inside *Modelica*. Furthermore, the mechanism of running and pausing reduces the exploitation of parallelism available in co-simulation.

The simulator choice is explained by the fact that *ns-2* provides tools to model different networks (wired, wireless, local and wide-area networks) and it can evolve easily. For the power side, *Modelica* is an object-oriented modeling language for large-scale complex physical systems.

5) *Other co-simulation libraries*: In addition to the co-simulators presented above, many other tools are available for building new co-simulation platforms, such as the Toolkit for *HYbrid Modeling of Electric power systems* (*THYME*) [20] which is a C++ library for building simulator that integrates power system modules with existing network simulators (*OMNET++*, *ns-2*). *THYME* applications include: the study of control system based on demand/response, the impact of specific communication technologies and intelligent sensors on situational awareness, control or both, and the design and analysis of wide area diagnosis technologies that depend critically on communication networks. This tool includes an extensive set of modules representing the power system elements and behaviors.

THYME is not a simulator but a set of libraries integrated in the *adevs* simulator. As it is presented in Figure 2, *THYME* provides the power model and the power flow data, while adevs gives the simulation environment (algorithms and interfaces). The unlimited set of network simulators that can be integrated with *THYME* offer the possibility of evaluating WSNs performance deployed in different environments and with different network sizes.

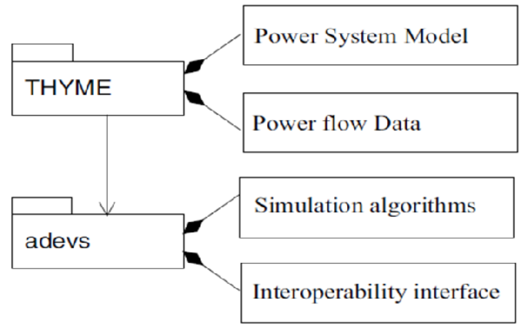

Figure 2. Integration of THYME in adevs simulator.

Table 1 summarizes the advantages/drawbacks of each co-simulation platform described above. Before choosing which co-simulation platform is adapted to a given smart grid application using WSNs as ICT, we first have to determine the requirements of such an application based on the advantages and drawbacks of each co-simulation platform.

For instance, if we choose *ns-2/adevs* co-simulation, we avoid the synchronization problem given that *adevs* is integrated as a module in *ns-2*, but the complexity of the power behavior formalization decreases drastically the performance of such a platform. Moreover, in the case of large scale sensor nodes deployment, the *ns-2* simulator is not appropriate.

In *OpenDSS/ns-2* co-simulation, the scripts' writing is facilitated by the separate simulators running. But the intercommunication technique is not defined. In the *ns-2/PSFL* platform, the use of new interfaces in both simulators facilitates the communication of simulators in spite of the large number of modules to implement.

The *ns-2/Modelica* platform can integrate WSNs with existing networks technologies -such as WIMAX, WHANs, WPANs, etc.- which reduces the deployment cost. Finally, co-simulation with *THYME* offers a large number of WSNs deployment opportunities using different network simulators.

Table 1. A comparative table of co-simulation platforms.

Platforms	**Advantages**	**Drawbacks**
NS2/adevs	Adevs is integrated as a module in ns-2 which avoids the synchronization need.	Complexity of power behavior formalization
NS/ OpenDSS	Each simulation is implemented separately which facilitate the scripts writing	The inter-communication technique is not defined and must be manually
NS2/PSLF	The use of inter-communication interfaces in both simulators	Many new modules must be implemented in ns-2
ns-2/ Modelica	Proven simulation for the most existing communication networks (WSNs, WIMAX, WiFi, WHAN, WPAN…)	Modileca cannot determine when to send data to ns-2; Aperiodic control and alarm signals that are generated in response to events triggered exclusively inside Modelica are not accounted for
THYME/ OMNET++ or NS-2	An extensive set of network simulators can be used with THYME. THYME will permit the accurate simulation of network-centric systems with continuous & discrete-event components.	THYME is a library and not a stand-alone simulator, it must be implemented with adevs

4 CONCLUSION

Due to the importance of the power grids and the impact of their failure on the Human life, new researches attempt to modernize and smarten these grids so as to avoid all the problems experienced with the conventional electric power systems. The so called "*smart grid*" is a combination of the existing power grid with new Information and Communications Technology (ICT).

In this paper we presented the application of a technology extensively used to monitor and control the smart grids' behavior: the wireless sensor networks technology. We then enumerated the different challenges that should be met by the WSNs to satisfy the smart grids requirements.

In the second part of the paper, we focused on the smart grids co-simulation platforms. For instance, in the particular context of the smart grids, two simulations engines have to cooperate together to take into consideration the communication and the power components characteristics when evaluating the performance of smart grid applications. Then, we described the way of function of the most well known smart grids co-simulation platforms and dressed the advantages/drawbacks of each platform especially for the particular case of WSNs deployment.

5 REFERENCES

1. Garrity, T. F.: Getting Smart. IEEE Power and Energy Magazine, April-March, pp. 38-45 (2008).
2. Akyildiz,I. F., Su, W., Sankarasubramaniam, Y., Cayirci, E.: A Survey on Sensor

Networks. IEEE Communications Magazine, pp.102–114 (2002).

3. Erol-Kantarci, M. H., Mouftah, T.: Pervasive Energy Management for the Smart Grid: Towards a Low carbon Economy. Pervasive Communications Handbook, Eds. S. I. A. Shah, M. Ilyas, H. T. Mouftah, CRC Press (2011).
4. Isaac, S. J., Hancke, G. P.: A Survey of Wireless Sensor Network Applications from a Power Utility's Distribution Perspective. AFRICON (2011).
5. Lu, B., Habetler, T.G., Harley, R.G., Gutierrez, J.A., Durocher, D.B.: Energy evaluation goes wireless. IEEE Industry Applications Magazine, vol.13, no.2, pp.17-23 (2007).
6. Shen, L., Wang, H., Duan, X., Li, X.: Application of Wireless Sensor Networks in the Prediction of Wind Power Generation. 4th International Conference on Wireless Communications, Networking and Mobile Computing, vol., no., pp.1-4 (2008).
7. Ipakchi, A., Albuyeh, F.: Grid of the future. IEEE Power and Energy Magazine, vol.7, no.2, pp.52-62 (2009).
8. Al-Anbagi, I., Mouftah, H. T., Erol-Kantarci, M.: Design of a Delay-Sensitive WSN for Wind Generation Monitoring in The Smart Grid. IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), Niagara Falls, ON, Canada (2011).
9. Leon, R. A., Vittal, V., Manimaran, G.: Application of Sensor Network for Secure Electric Energy Infrastructure. IEEE Transactions on Power Delivery, vol.22, no.2, pp.1021-1028 (2007).
10. Lim, Y., Kim, H.M., Kang, S. A.: Design of Wireless Sensor Networks for a Power Quality Monitoring System. Sensors 2010; 10(11):9712-9725 (2010).
11. Ullo, S., Vaccaro, A., Velotto, G.: The role of pervasive and cooperative Sensor Networks in Smart Grids communication. 15th IEEE Mediterranean Electro-technical Conference (MELECON), pp.443-447 (2010).
12. Yang, Y., Lambert, F., Divan, D.: A Survey on Technologies for Implementing Sensor Networks for Power Delivery Systems. IEEE Power Engineering Society General Meeting, vol., no., pp.1-8 (2007).
13. Sood, V. K., Fischer, D., Eklund, J. M., Brown, T.: Developing a communication infrastructure for the Smart Grid. IEEE Electrical Power & Energy Conference (EPEC), pp.1-7 (2009).
14. Nutaro, J., Kuruganti, P. T., Miller, L., Mullen, S., Shankar, M.: Integrated Hybrid-Simulation of Electric Power and Communications Systems. In: Proceedings of the 2007 IEEE Power Engineering Society General Meeting, pp. 1-8 (2007).
15. Zeigler, B. P., Praehofer, H., Kim, T. G.: Theory of Modeling and Simulation. 2nd Edition. Academic Press (2000).
16. adevs: A Discrete Event system Simulator, online at http://www.ornl.gov/~1qn/adevs/.
17. Godfrey, T., Mullen, S., Dugan, R. C., Rodine, C., Griffith, D. W., Golmie, N.: Modeling Smart Grid Applications with Co-Simulation. The 1st IEEE International Conference on Smart Grid Communications (SmartGridComm 2010), pp. 291-296, Gaithersburg, MD (2010).
18. Lin, H., Sambamoorthy, S., Shukla, S., Thorp, J., Mili, L.: Power System and Communication Network Co-Simulation for Smart Grid Applications. Innovative Smart Grid Technologies (ISGT), IEEE PES (2011).
19. Liberatore, V., Al-Hammouri, A.: Smart Grid Communication and Co-Simulation. IEEE Energytech conference (2011).
20. THYME: Toolkit for HYbrid Modeling of Electric power systems, online at http://www.ornl.gov/~1qn/thyme/docs/index.html.