# A Flexible Smart Grid Co-Simulation Environment for Cyber-Physical Interdependence Analysis

Jawad Haider Kazmi*, Aadil Latif*, Ishtiaq Ahmad*, Peter Palensky† and Wolfgang Gawlik‡

*Energy Department
Austrian Institute of Technology (AIT)
Vienna, Austria

†Intelligent Electric Power Grids
Electrical Sustainable Energy
TU Delft, Netherland

‡Institute of Energy Systems
and Electrical Drives
TU Vienna, Austria

*Abstract*—**The ongoing transformation of the traditional power system into a more intelligent *Smart Grid* has many benefits. However, it also brings numerous challenges. The system is becoming more complex, making the existing domain specific tools less relevant. This paper presents a flexible co-simulation framework that supports multiple simulators, including multi-agent platform, for a detailed evaluation of the impact and inter-dependencies between the *cyber* and *physical* components of the system. Two case studies have been evaluated with different Smart Grid applications, modeled and simulated with different simulators and coupled into the developed co-simulation framework. The results show the flexibility and useability of the proposed co-simulation framework.**

***Keywords*—*cyber-physical systems, co-simulation, smart grid, communication, distributed controls, mulit-agents, active power curtailment***

## I. INTRODUCTION

Due to technological breakthroughs in communication technology, power grid is currently transitioning into a Smart Grid - an intelligent power grid capable of digital data processing and real-time monitoring of the system to perform automation and control of the remote and local sub-systems. The vision is influenced by many technical, political, socioeconomic and environmental challenges. The traditional fossil-fuel based power generation is expensive and no longer considered environmental friendly in many countries. Greenhouse gas emissions due to the traditional fossil-fueled power generation plants are widely a major cause of environmental pollution. An estimated 40% of carbon dioxide emission is due to their use [1]. In EU, the Smart Grid initiatives is strongly backed by the EU Vision H2020.

Smart Grid aims at addressing these challenges by suggesting reduction on the dependence of fossil fuel for electricity generation, increasing share of distributed energy resources (DERs), increased monitoring and control, active demand response (DR), intelligent and decentralized controls and other similar initiatives. By this modernization of the tradition power system and the integration of new technologies, Smart Grid promises to bring enhancements like improved power quality, increased monitoring and control, better system awareness, better availability, improved system reliability, cheaper generation, economic benefits to the customers, and improved asset management.

The resulting system comes at a cost of being highly complex cyber-physical system with many more, yet to be known, sources of uncertainty and errors. Obviously, the existing tools and analysis methods, for traditional power systems, will not be suitable anymore for analyzing Smart Grids as they were not designed for such systems. The next logical step thus would be to research and design the methods, tools and test beds which can handle such complexities arising with the mergers and inter-dependencies in discrete and continuous domains [2], [3].

Comprehending such need, a co-simulation (coupling multiple simulators together to perform a single system simulation) test-bed is developed for evaluating the interdependence of cyber and physical systems in a Smart Grid solution.

Major contributions of the paper can be summarized as:

- The concept and implementation of the proposed flexible co-simulation environment for cyber-physical inter-dependencies and impact evaluation for different Smart Grid applications (Section III).
- Description of two case studies selected for the co-simulations modeled with different simulators (Section IV).
- Simulation details and results for the case studies (Section V).

In the next section (Section II), the state of the art is presented while Section VI concludes the paper with a presentation of the major conclusions drawn from the work.

## II. RELATED WORK

Development of the co-simulation framework for getting insight into the power system, communication and control for some Smart Grid applications is an active research area. There are many very useful and good such frameworks available in the literature.

In [4], a microgrid co-simulation environment is presented based on OMNeT++ and MATLAB. The simulators are coupled with ADEVS atomic model interfaces. A medium voltage distribution network (MVDC) microgid is used for the evaluation of the environment. A High Level Architecture

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(HLA) federate based co-simulation environment for power transmission system, communication and control is presented in [5]. GridDyn power transmission simulator is coupled with communication simulator ns-3 through their simulation kit to test a IEEE 39-bus test system. In [6], a co-simulation environment called EPOCHS is presented. In this environment PSCADE/EMTDC, PSLF and NS2 are coupled together with multi-agents system (MAS). Run-Time Infrastructure (RTI) was used to route all messages between simulation components and manages simulation times while distributed wide area control and protection schemes were implemented through agents. Based on OMNeT++, as communication modeler and simulator and OpenDSS as distribution system simulator, a co-simulation environment is presented in [7]. The electrical vehicles charging control using wireless meshed network is investigated using the environment. Another co-simulation environment for the investigation of the electric vehicles charge control was presented in [8]. This environment uses OMNeT++ and MATLAB for co-simulation. In [9] a co-simulation environment VPNET is proposed capable of simulating power system, communication networks and MAS. The data exchange and time synchronization between the other two simulators were carried out using co-simulation coordinator. The co-simulation coordinator is also used for the MAS integration. In [10], the proposed co-simulation environment utilizes NS2 and PSLF for communication and power system simulation respectively while agents were modeled as relay protection units running different algorithms. Effectiveness of different remote relay protection strategies were investigated. INSPIRE is introduced in [11] where power system simulator PowerFactory is coupled with communication simulator OPNET Modeler to carry out power system and ICT impact analysis in real time.

Another power system automation and control co-simulation environment is presented in [12] and [13]. An enhancement of the environment with communication simulation was presented in [14], with MAS in [15] and further with MAS and communication simulation in [16]. The proposed simulation framework is an further extensions of this work with the addition of narrowband and broadband power line communication (PLC) models, improved simulation scheduler and MAS platform support. Furthermore, the added flexibility in coupling makes it possible to couple different tools together with the communication simulation and the inclusion of the option for the calculation of the key performance indices . All these features in a single co-simulation framework are uncommon.

## III. CO-SIMULATION CONCEPT AND TOOLS

### A. Power System Model

The power system modeling and simulation in the proposed co-simulation environment was implemented with DIgSILENT PowerFactory [17], a commercial power system tools. It is a modeling and simulation suite for distribution, generation and transmission grids and provides the capabilities of carrying out different analysis as well. It further provides the facilities to extend its functionalists with custom functions and models.

An overview of the employed PowerFactory co-simulation interfaces is depicted in the Fig. 1.

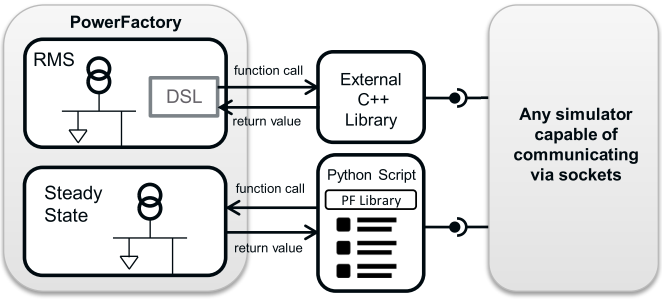


Fig. 1. PowerFactory co-simulation interfaces overview

### B. Communication System Modeling

For the modeling and simulation of the communication system, OMNeT++ and INET Framework is utilized. OMNeT++ [18] (Objective Modular Network Testbed in C++) is an open-source discrete event simulator that provides the basic modeling and simulation facilities by providing the simulation kernel, utility classes, user interface, NED (Network Description Language) and result analysis functionalists while the INET Framework provides the models for different wired and wireless protocols like TCP, UDP, Ethernet, PPP, IEEE 802.11 etc. OMNeT++ supports a hierarchically architecture composed from the reusable components called the modules. The modules can communicate with each other through gates connected via channels. Two or more modules can be combined to form a compound module [19].

Fig. 2 presents an overview of the custom interface and its interactions with the simulation components within OMNeT++. In this work, only the socket interface is used, due to the compatibility with the participating simulators, but it is equally possible to use other interfacing methods (e.g. shared memory). The simulation coupling is achieved with the implementation of a custom OMNeT++ simulation scheduler, customization of some of the INET Framework modules and creation of some new ones to support narrowband (G3, PRIME) and broadband (HomePlug IEEE 1901) Powerline Communication standards.

### C. Control System

*1) Centralized Control:* A centralized coordinated controller is implemented using the Python [20] scientific programming language. Python is a high-level, interpreted, interactive and object-oriented scripting language.

*2) Distributed Control:* To model and simulate distributed controls, MAS paradigm is utilized. In a MAS the agents are some computer programs that are executed autonomously, governed by a set of rules. The agents interact with each other across open and distributed environments to solve some complex problems. In other words, in a MAS the computational resource and capabilities are distributed across a network of connected agents that act on behalf of their users. JADE (Java Agent Development) [21] is used to model and simulate the distributed control algorithms in a Smart Grid environment. JADE is an open source middleware used for developing MAS through basic functionalists like agent and

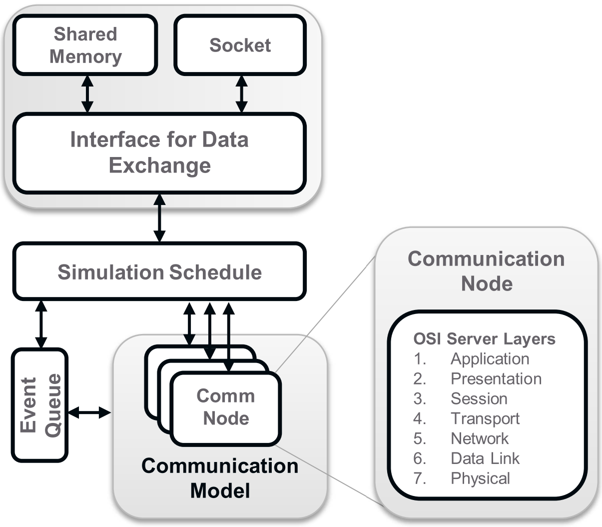


Fig. 2. The OMNeT++ co-simulation interface overview

behavior classes, inter-agent communication methods. A GUI tool is also available for monitoring, agent execution and communication additionally with the debugging capabilities. It is FIPA (Foundation for Intelligent Physical Agents) compliant and supports standards such as FIPA-ACL. At runtime, each instance environment is called a container and multiple containers form a platform. First container is called `main` container and it hosts Agent Management Services (AMS) and a Directory Facilitator (DF). Each container can contain various agents and a typical agent consist minimal of a `setup()` method, one or more behaviors or rules and a `takedown()` method.

## IV. CASE STUDIES AND IMPLEMENTATIONS

This section describes the two case studies selected for the evaluation of the proposed co-simulation environment. The choice is influenced by the fact that the case studies should use different simulators so that the flexibility and useability could be shown. For each case study, first an overview of the problem addressed is presented and then the modeling and simulation setups are described.

### *A. Coordinated voltage regulation in LVN using active power curtailment (Case Study I)*

*1) Problem overview:* The voltage at the point of common coupling (PCC) is a function of the active and reactive power being injected at that point and the grid impedance as seen by the inverter at PCC. As the electrical distance from a transformer increases so does the voltage sensitivity to active power. At times of high generation inverters connected at PCC with higher voltage sensitivity may violate voltage limits. As a result, the inverters that are violating voltage limits have their output curtailed. Essentially, PV (photovoltaic) owners located at the end of the feeder are more susceptible to voltage violations and getting their power curtailed resulting in loss of revenue as illustrated in Fig. 3.

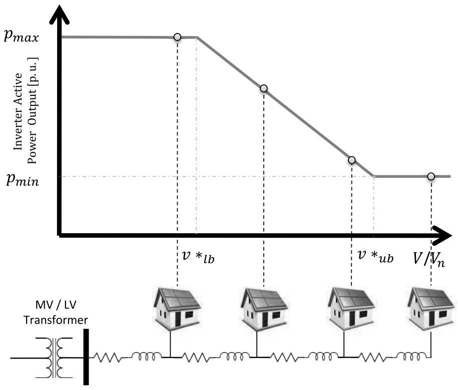


Fig. 3. As the electrical distance from the transformer increases inverter active power output [p.u.] decreases due to curtailment.

Two perspectives of fairness in active power curtailment (APC) have been presented in [22]. Additionally, a coordinated voltage controller has been implemented with two variations (depending on the perspective of fairness). The proposed scheme requires a coordinating controller capable of communicating with every PV inverter on the LVN (low voltage network). In such a control scheme, the cyber and physical layers are tightly coupled and the impact of cyber on physical layer can not be neglected. The communication infrastructure parameters, like bandwidth, congestion, node failure etc. could contribute to a divergence in the normal performance pattern of the overall system. In this example the impact of communication delay and node failure have been studied.

*2) Simulation setup:* The test case chosen for this work consists of a low voltage residential network connected to medium voltage network through a 75 KVA transformer. The low voltage network consists of two feeders connecting 27 consumers. 16 consumers have a rooftop PV system installed with installation capacity varying between 4 and 9 KVA. PV inverters and local controllers have been modeled in PowerFactory and provide voltage support using active power curtailment. The secondary voltage controller has been implemented in Python. During RMS simulation it is possible for controllers modeled in DSL (DIgSILENT Simulation Language) blocks to call functions from an external C++ library. A C++ library has been used to implement sockets to communicate with OMNeT++, which is used for network simulation. Fig. 4 is a graphical illustration of coupling scheme used. Local controllers estimate voltage sensitivity to active power and communicate it to the coordinating controller along with the current voltage at the PCC. The coordinating controller uses this information to generate and communicate set points for active power curtailment for each of the inverter.

### *B. Voltage regulation in distribution network using MAS (Case Study II)*

*1) Problem overview:* Increased use of distribution generation in distribution network has effected the voltage profile of the feeder. When multiple DGs are connected to the distribution network and serve considerable part of the load, it becomes difficult for voltage regulator to correctly estimate the voltage drop/rise through the local current measurements. This

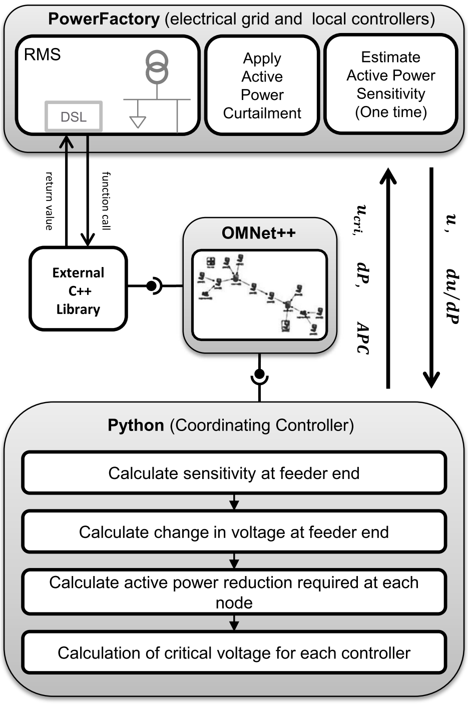


Fig. 4. Graphical representation of the simulation setup in LVNs.

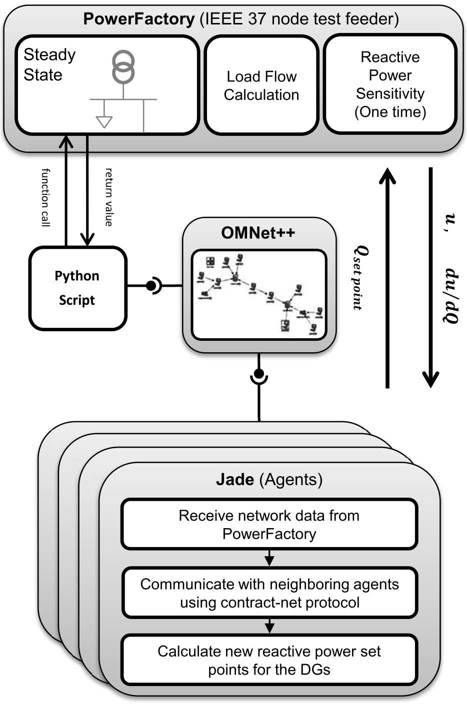


Fig. 5. Overview of the coupling in Co-simulation Framework

problem becomes worse in long feeders. In such scenario DGs can be used to provide voltage support. Voltage regulation in distribution network using Multi-Agent System was taken as an example application of the proposed framework. Voltage support can be provided by the Distributed Generation by increasing/absorbing the reactive power in case of violation of allowable voltage limits.

*2) Simulation setup:* IEEE 13 node test feeder was taken as electric network and developed in PowerFactory. MAS was developed in JADE which includes different types of agents i.e. monitoring agent, DG agents etc. CNP (Contract-Net-Protocol) was used for agent interaction. An overview of the simulation setup is depicted below in Fig. 5. The details of the algorithm and agent modeling are the same as presented in our previous work [15]. Three tools run in parallel and exchange data as and when required. PowerFactory simulation was controlled through a python script which uses PowerFactory API. JADE communicate with PowerFactory and OMNeT++ over sockets.

## V. SIMULATIONS AND RESULTS

### A. *Case Study I*

In base case scenario, an ideal bi-directional communication channel has been assumed. The proposed algorithm performs well by limiting the voltage to the prescribed band as can be seen from Fig. 6. For real world application however, the impact of cyber layer on the control scheme can not be ignored.

*1) Impact of communication delay:* The impact of communication on the proposed algorithm has been tested with public WAN (Wide Area Network) communication scheme with star topology using TCP/IP protocols. Since the chosen network is public, background traffic has been added to create a congestion scenario. The $PV_x$ in Fig. 7(a) represents the PV units with local voltage controller that periodically transmits the measurement readings to a central controller. The coordinating controller then performs calculations and generates set points for each PV unit. The set points generated are communicated to local controllers via WAN. In a situation where communication delay causes coordinating controller to lag behind the current state of the power network, over voltage might occur as is evident from Fig. 8.

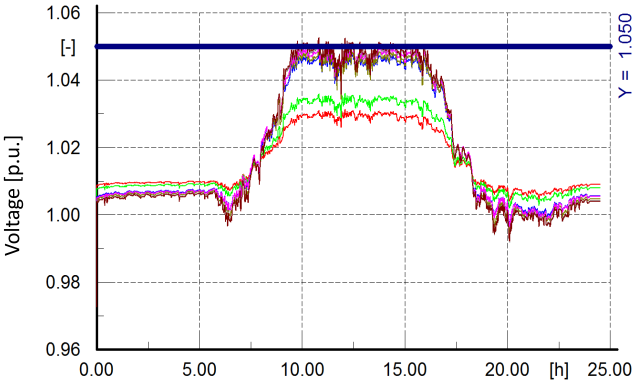
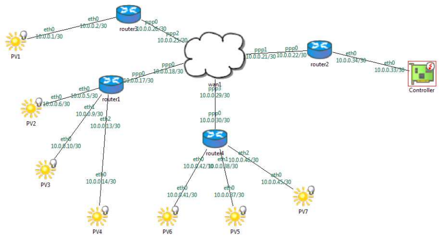
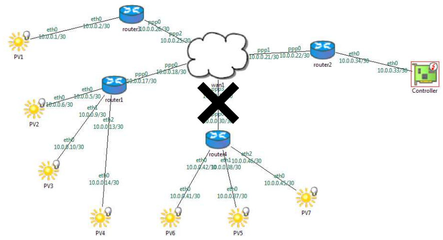


Fig. 6. Base case voltage profiles at PV connected nodes.

*2) Impact of communication failure:* In the final scenario, the control scheme has been tested to evaluate its robustness to communication failure. At time $T = 13.5h$ the communication link between the router connected to PV 5, 6 and 7 and the WAN is severed making the states of the disconnected PVs unobservable (Fig. 7(b)). The coordinating controller generates



(a) A communication delay scenario



(b) A node failure scenario

Fig. 7. Two communication scenarios used for the evaluation of the impact of cyber layer on the physical layer for the case study I (a) communication delay due to background traffic and public network (b) a node failure which causes the interruption of the communication between the controller and PV5, PV6 & PV7.

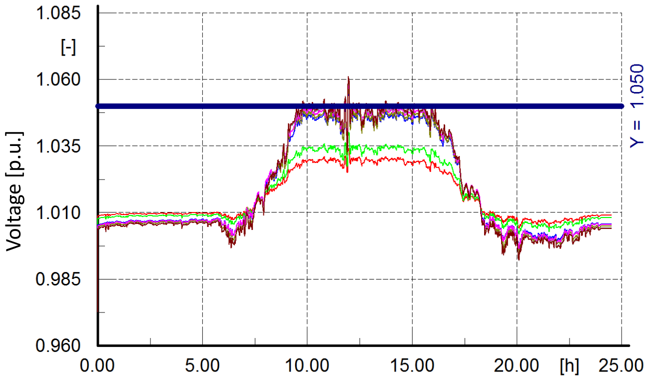


Fig. 8. Impact of communication delay on voltage profiles

new set point on the bases of the available information. Incomplete system information results in incorrect calculation of set points for local controller, which in turn results in over voltage in the feeder. The results have been presented in Fig. 9

### B. Case Study II

The simulation is carried out for two scenarios to test a MAS voltage stabilization algorithm. The two scenarios are designed to measure the effects of communication delay between the agents, coordinating with each other, on the underlying power system.

*1) The base case scenario:* In the base case scenario, an ideal bi-directional communication between the agents is simulated. The results in the Fig. 10 shows that the control algorithm performs the voltage stabilization effectively.

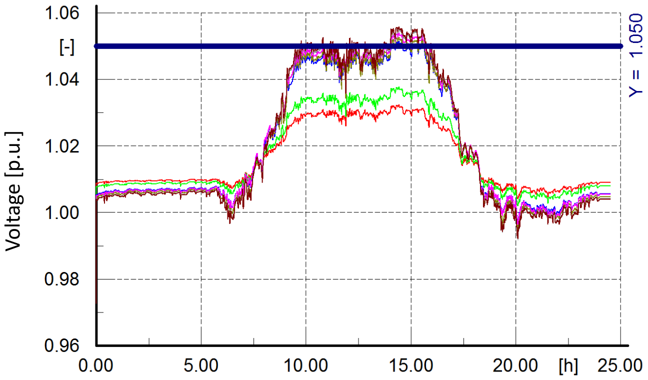


Fig. 9. Impact of communication channel failure on voltage profile.

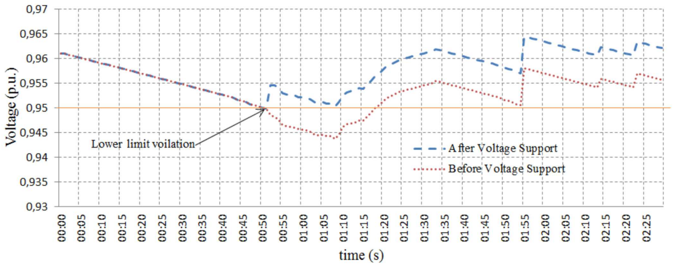


Fig. 10. Distributed voltage regulation control algorithm with ideal communication channel [16].

*2) Impact of communication delay:* In the second scenario, the impact of communication delay between agents in the distributed voltage regulation control algorithm is simulated. Since the chosen network is public, background traffic has been added to create a congestion scenario (Fig. 11). The effect of communication delays on voltage regulation algorithm can be seen as shown in the Fig. 12. As can be seen, between time 00:51 to 00:54, the effects of communication delays are very much visible. In this study the voltage deviation is within the limits prescribed by standards such as EN501660 standard but, for larger networks containing a large number of agents, delay in communication can result in longer time of voltage limit violation. Further, while designing the voltage algorithm time constant of control action is chosen in such a way that it must not interfere with other control action i.e. tap changer etc. In case of delay in control action as shown in figure, there are more chances for control interference and which may have adverse effect on the system.

## VI. CONCLUSIONS

The main contribution of this paper is the development of a co-simulation environment that is capable of simulating a whole cyber-physical system. The architecture of the proposed setup is flexible, reusable and simulator independent. The framework presented in this work enables rapid interfacing as it reduces time and effort required to develop interfacing modules for different simulators. In this paper two test cases have been presented using different simulation tools for controller implementation namely Python and Jade. The drive towards a 'Smart Grid' entails more communication which in turn means a tighter coupling between the physical (power network) and

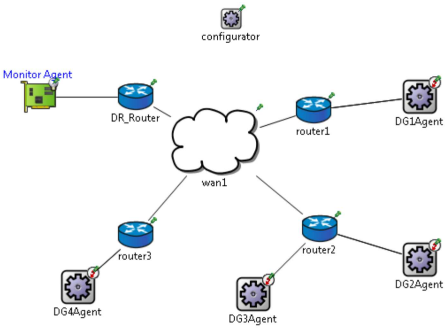


Fig. 11. The communication model for the MAS case study [16].

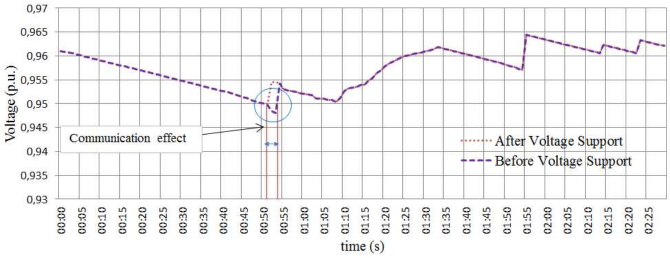


Fig. 12. Impact of communication delay between agents in the distributed voltage regulation control algorithm [16].

the cyber (communication and control) layer. The proposed framework allows researches to better analyze the impact of these inter-dependencies on the stability of the electrical grid.

## REFERENCES

[1] F. Bouhafs, M. Mackay, and M. Merabti, *Communication Challenges and Solutions in the Smart Grid*. Springer Publishing Company, Incorporated, 2014, pp. 1–9.

[2] P. Palensky, E. Widl, and A. Elsheikh, "Simulating cyber-physical energy systems: Challenges, tools and methods," *Systems, Man, and Cybernetics: Systems, IEEE Transactions on*, vol. 44, no. 3, pp. 318–326, March 2014.

[3] J. Momoh, *Smart Grid. Fundamental of design and analysis*. Wiley-IEEE Press, 2012.

[4] V. Kounev, D. Tipper, M. Levesque, B. Grainger, T. McDermott, and G. Reed, "A microgrid co-simulation framework," in *Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2015 Workshop on*, April 2015, pp. 1–6.

[5] B. Kelley, P. Top, S. Smith, C. Woodward, and L. Min, "A federated simulation toolkit for electric power grid and communication network co-simulation," in *Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2015 Workshop on*, April 2015, pp. 1–6.

[6] K. Hopkinson, X. Wang, R. Giovanini, J. Thorp, K. Birman, and D. Coury, "Epochs: a platform for agent-based electric power and communication simulation built from commercial off-the-shelf components," *Power Systems, IEEE Transactions on*, vol. 21, no. 2, pp. 548–558, May 2006.

[7] M. Levesque, D. Q. Xu, G. Joos, and M. Maier, "Co-simulation of pev coordination schemes over a fiwi smart grid communications infrastructure," in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Oct 2012, pp. 2901–2906.

[8] K. Mets, T. Verschueren, C. Develder, T. Vandoorn, and L. Vandevelde, "Integrated simulation of power and communication networks for smart grid applications," in *Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2011 IEEE 16th International Workshop on*, June 2011, pp. 61–65.

[9] W. Li, M. Luo, L. Zhu, A. Monti, and F. Ponci, "A co-simulation method as an enabler for jointly analysis and design of mas-based electrical power protection and communication," *Simulation*, 2013. [Online]. Available: http://sim.sagepub.com/content/early/2013/03/04/0037549712472939

[10] H. Lin, S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili, "Power system and communication network co-simulation for smart grid applications," in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, Jan 2011, pp. 1–6.

[11] H. Georg, S. Muller, N. Dorsch, C. Rehtanz, and C. Wietfeld, "Inspire: Integrated co-simulation of power and ict systems for real-time evaluation," in *Smart Grid Communications (SmartGridComm), 2013 IEEE International Conference on*, Oct 2013, pp. 576–581.

[12] F. Andren, M. Stifter, and T. Strasser, "An environment for the coordinated simulation of power grids together with automation systems," in *PowerTech (POWERTECH), 2013 IEEE Grenoble*, Jun. 2013, pp. 1–6.

[13] M. Stifter, E. Widl, F. Anrn, A. Elsheikh, T. Strasser, and P. Palensky, "Co-simulation of components, controls and power systems based on open source software," in *General Meeting, Annual Conference on IEEE Power and Energy Society*, July 2013, pp. 1–5.

[14] M. Stifter, J. Kazmi, F. Andren, and T. Strasser, "Co-simulation of power systems, communication and controls," in *Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2014 Workshop on*, April 2014, pp. 1–6.

[15] I. Ahmad, P. Palensky, and W. Gawlik, "Multi-agent system based voltage support by distributed generation in smart distribution network," in *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on*, Sept 2015, pp. 329–334.

[16] I. Ahmad, J. Kazmi, M. Shahzad, P. Palensky, and W. Gawlik, "Co-simulation framework based on power system, ai and communication tools for evaluating smart grid applications," in *Smart Grid Technologies - Asia (ISGT ASIA), 2015 IEEE Innovative*, Nov 2015, pp. 1–6.

[17] `http://www.digsilent.de`, DIgSILENT GmbH Homepage.

[18] `http://www.omnetpp.org/`, OMNeT++ Homepage.

[19] A. Varga and R. Hornig, "An overview of the OMNeT++ simulation environment," in *Simutools '08: Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*, 2008, pp. 1–10.

[20] `http://www.python.org/`, Python Programming Languge Homepage.

[21] `http://jade.tilab.com/`, JADE JAVA Agent DEvelopment Framework Homepage.

[22] A. Latif, P. Palensky, and W. Gawlik, "A controller for fair and coordinated active power curtailment of low voltage pv inverters," 2 2016, unpublished. [Online]. Available: https://dx.doi.org/10.6084/m9.figshare.2074474.v1