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Cyber-Physical Co-Simulation Testbed for Real-Time Reactive Power Control in Smart Distribution Network

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***Abstract*—Existing electric power distribution systems are evolving and changing as a result of the high renewable energy sources integration. Hence, future smart distribution networks will involve various technical challenges; one of them is real-time monitoring and controlling the network to operate it effectively and efficiently. This paper develops and analyzes a cyber-physical co-simulation testbed for real-time reactive power control in the smart distribution network. The testbed is a two-layer system, with Typhoon HIL 604 representing the physical layer and the other layer as a cybernetic layer. The cybernetic layer is used to model a test system and control reactive power from smart inverters in real-time. The implementation of real-time reactive power control of smart inverters on a CIGRE MV distribution network is shown in this study. The proposed testbed's usefulness in real-time reactive power control is demonstrated through simulation results.**

***Keywords*— Cyber-physical testbed, Reactive power control, Real-time co-simulation, Smart distribution networks**

I. INTRODUCTION

Renewable energy sources (RESs) are considered one of the potential solutions to make a significant contribution to solving the world's energy problem [1]. As a result, in recent years a significant number of photovoltaic (PV) power generation systems have been integrated into the distribution networks [2], [3]. This integration will lower distribution system operational costs and promote RES usage [4]. However, due to the fluctuating nature of power from PV, many technical challenges are observed in the distribution system. Among many challenges, voltage variations in distribution networks are one of the major problems that affect the operation of distribution networks [5]. Voltage fluctuations are in particular responsible for degrading the power quality in the distribution network [6]. In most of the existing distribution networks, voltage regulation is achieved by using conventional voltage regulating devices (VRDs) [5] like On load tap changing transformers (OLTCs), Switched Capacitor banks, and STATCOM [7]. These VRDs have a limited number of switching operations and have a slower response time [8]. So, they may not regulate the fast varying voltage. With the recent technological advancement in smart inverters together with the regulatory requirement set by IEEE 1547-2018 [9] standard, the utilization of smart inverters to regulate the voltage is gaining more attraction [10].

Distributed energy resources (DERs) have now been designed to provide scalable and reliable reactive power support to resolve these voltage concerns [11], [12]. Existing reactive power control systems based on PV inverters are mainly divided into three types. The first is centralized control methods, which decide the requirement of reactive power from PV by solving an optimal power flow issue to achieve the highest network performance [13]. The centralized techniques imply that a thorough network model is provided, that all network buses are appropriately evaluated, and that loads profile are known in advance. However, this method requires a high-reliability communication infrastructure which may not be feasible in all cases. On the other hand, local control actions are selected only based on local measurements [14]. The local controller acts locally and hence they are fast to respond [15]. The local controller can act as a self-sustained unit to maintain the reactive power requirement [16]. However, the fundamental disadvantage of local control is that the maximum available capacity may not be utilized optimally because of the lack of globally optimal solutions. Some of the literature combines the advantages of both approaches and make the control action in a distributed way [17]. In a distributed control, the local control and centralized control are acted in multiple time steps making the control action more robust [18], [19]. Whatever method of voltage regulation is implemented, in most of the cases in previous studies, the analysis is performed offline and presented as the expected solution and methodologies.

The future distribution network is subject to large voltage fluctuations due to the dramatic rise in PV integration in the network. As a result, distribution system researchers should investigate moving away from the traditional offline mode and toward real-time mode. The use of smart devices to enable real-time control and monitoring is also another essential aspect of future distribution network digitization. Developing a transparent, comprehensive, and implementable platform to test theoretical concepts, computational tools and techniques, and emerging technologies is an urgent need to address the upcoming challenges in the digitization of the future distribution network. Most of the similar domain cyber-physical testbeds available in the literature [20] focus on power system models. And some of them are only online simulation-based without having a real-time simulator in connection. To the authors' best knowledge, this type of co-simulation testbed is the pioneer of its kind. The testbed is more suitable for analysis even in an unbalanced distribution and the real-time simulator.

This paper is devoted to presenting preliminary results of a cyber-physical co-simulation testbed for real-time reactive power control. The testbed is designed to regulate the reactive power of smart inverters using a real-time simulation approach. As a result, the goal of this scientific paper is to create a novel cyber-physical co-simulation testbed for real-time reactive power control in smart distribution networks. The list below summarizes the most important contributions of this study.

1. Develop a co-simulation testbed for real-time reactive power control in the smart distribution network.
2. Develop a methodology to implement a co-simulation testbed for Typhoon HIL and OpenDSS.
3. Obtain the voltage response on each bus of a smart distribution network due to reactive power variation of PV in real-time

The remaining sections of the paper are organized as follows. Section II explains the theoretical concept of modelling the cyber-physical testbed. The detailed implementation process is shown in section III. Section IV describes the results and outlines the benefits of the proposed scheme. Finally, the last section summarizes the main contribution of the work done in this analysis and suggests future directions for research.

II. MODELING OF CYBER-PHYSICAL TESTBED

To realize the application in real-time, several essential components are required for monitoring and regulating smart distribution networks [21]. The tool to compute the three-phase unbalanced power flow is one of the most basic requirements. The centralized control system and its SCADA implications are some other criteria. Also required are the infrastructure for real-time enhanced metering and remotely controllable devices and the necessary communication infrastructure. Some of the needs will be created in the co-simulation testbed's cybernetic layer. However, some of them are in the physical layer as well. The suggested cyber-physical co-simulation testbed is made up of two layers: (A) the cybernetic layer and (B) the physical layer. It is designed to enable real-time reactive power control. Monitoring and controlling elements, software to interact with the physical layer, and software to interact with the distribution system simulator (OpenDSS in this case) make up the cybernetic layer. The Host PC runs all of the software in the cybernetic layers for convenience. The physical layer includes the testbed's virtual and physical hardware. **Fig. 1** shows the framework for the cyber-physical co-simulation testbed. The red line represents the communication between the cybernetic and physical layers. And, the black line represents the communication within the cybernetic layers. The subsections that follow go through each component of the cyber-physical testbed in greater depth.

A. *Modeling of Cybernetic Layer*

The cybernetic layer is the main core of the cyber-physical co-simulation testbed. The cybernetic layer is housed within the Host PC, as previously stated. In addition, the necessary software for modelling and managing the real-time digital simulator is installed on the host PC. A detailed description of modeling each component of the cybernetic layer is described in the following subsections.

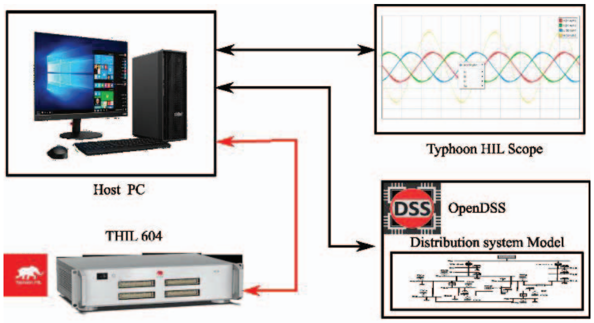

Fig. 1 Framework for cyber-physical co-simulation testbed for real-time

1) Modeling of test systems

To develop the cyber-physical co-simulation testbed for a smart distribution network, information about the distribution network and the program to model them is an important aspect [22]. The main idea of developing a cyber-physical co-simulation testbed is to mimic the real distribution system in a cybernetic layer. The program for modelling distribution systems must be able to do three-phase unbalanced power flow analyses. In the literature, there are numerous distribution system modelling tools. GridLAB-D [23], CYME-DIST [24], PowerModelDistribution.jl [25], and OpenDSS [26] are some of the most used tools. OpenDSS, on the other hand, is regarded as a modeling tool due to its ease of use, intractability, openness, and possibility for a wide spectrum of investigation. One of the advantages of utilizing OpenDSS is the ability to interface directly with Python using the opendssdirect.py module. OpenDSS can model and solve almost any type of distribution system analysis.

The proposed testbed is equipped with measuring/monitoring devices to obtain the required parameters such as voltage magnitudes and total power loss in the network, as the main interest of the proposed testbed is to mimic an entire system during voltage fluctuations events and the effect of reactive power of PV smart inverters on total power loss. The voltage profile reaction to the injection/consumption of reactive power from smart PV inverters can be seen in real-time by altering the reactive power. Also, the total power loss in the network can be observed for the same case. The reactive power injection/consumption can be changed dynamically using a monitoring and control system developed in Typhoon HIL SCADA. In the following section, monitoring and control method are described.

B. *Real-Time Monitoring and Control System*

The cyber-physical testbed's real-time monitoring and control system is a graphical user interface (GUI) that allows the simulation to be visualized and controlled in real-time. Specifically, the GUI is tailored to display the signals generated by the measurement devices connected to the test system during real-time simulation. The GUI also either graphically or digitally displays the current status of the bus voltages, the total active and reactive power loss of the network, and the power exchanged with the upstream network. The GUI, on the other hand, is designed to execute control commands in the test model in real-time by sending the appropriate control signal. The GUI is developed in this paper using the Typhoon HIL SCADA system. The HIL SCADA interacts with the cybernetic layer and the physical layer using python API.

C. Physical Layer

The physical layer is where actual co-simulation takes place. Typhoon HIL Inc.'s HIL 604 has been used as a physical layer in this investigation. The HIL 604 has eight computing cores, two ARM cores, and digital and analog I/O. The Host PC controls the physical layer simulation, which runs the relevant proprietary software (discussed in the next section). The host PC is a workstation with a Ryzen 9 3900X (12 cores) processor, 16GB of RAM, and a 1TB SSD GeForce RTX 2070 SUPER GPU running in Windows 10.

III. IMPLEMENTATION OF TYPHOON HIL AND OPENDSS CO-SIMULATION FRAMEWORK

The overall process to implement the co-simulation between Typhoon HIL and OpenDSS is shown in **Fig. 2**. First, the test distribution system is modelled in OpenDSS. The PVs are placed on the distribution network in the OpenDSS model. The OpenDSS modules are executed through a Python interface. A Python program is written inside the SCADA of Typhoon HIL to interact with the OpenDSS. In a schematic editor on Typhoon HIL, a communication interface between the SCADA and the Typhoon HIL real-time simulator is modelled. This model in the schematic editor can interact with the SCADA and the Typhoon HIL Real-Time Simulator. The SCADA of Typhoon HIL consists of a python program to get the signals from OpenDSS, process the signal, and display them as real-time outputs. The SCADA also consists of different sliders for sending the real-time signal to the OpenDSS. At each change, the signal is fed to the OpenDSS, and the load flow is executed inside the OpenDSS and the outputs are fed into the Typhoon HIL.

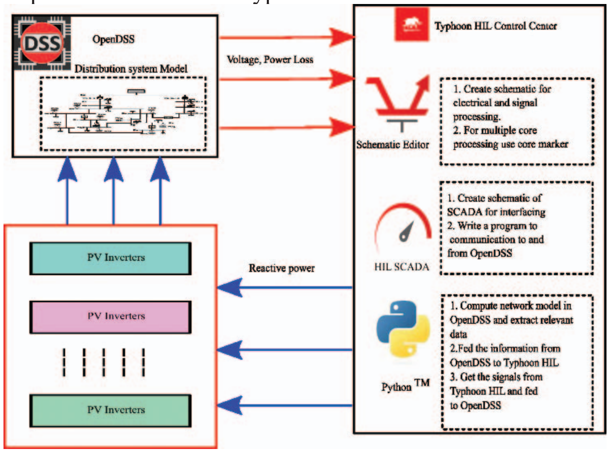

Fig. 2 Overall frameworks for co-simulation between Typhoon HIL and OpenDSS

Another important aspect of real-time monitoring and controlling of reactive power control is a centralized SCADA system to interact with the test system and the monitoring and control unit. In this study, OpenDSS and Typhoon HIL are the two major parts of the cyber-physical co-simulation testbed. The important part of this work is to create a Typhoon HIL schematic and the SCADA. Typhoon HIL schematic editor is a graphical user interface-based modelling system. The model in the schematic works as a bridge between the Typhoon HIL and the OpenDSS simulator. Variables to be controlled from the SCADA of Typhoon HIL are passed to the model in the schematic editor and the output signal from the schematic editor is fed to the OpenDSS. This process continues with the width of the simulation

In the Typhoon HIL schematic editors, various components are available as a built-in function. However, in this paper, the schematic editor is used to communicate the control signal from the SCADA to OpenDSS and vice-versa. Hence, a simple model for the interacting signal between SCADA and OpenDSS is formulated. **Fig. 3** shows the schematic for bridging the control signal for controllable objects. The schematic is designed inside the Typhoon HIL real-time simulator. The controller for the smart inverter is designed inside the PV_control block. Enable, PV_in and PV_out are the signal processing blocks that are used to communicate between the Typhoon HIL SCADA and the Typhoon HIL real-time simulator and vice-versa. When real hardware for the smart inverter is implemented, the signal processing block is used to communicate with the hardware. In this study, the controller for the smart inverter is designed virtually using the model-based system engineering toolchains of Typhoon HIL. For multiple controllable objects, a similar type of schematic needs to be developed to represent the controller for each smart inverter. One thing to note is the use of a CPU marker in case we want to build more controllers in the schematic editor.

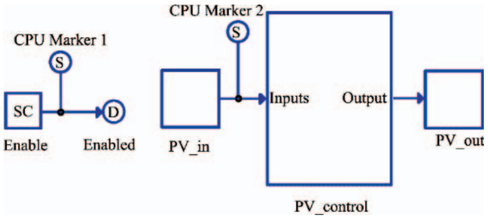

Fig. 3 Schematic of PV control

Typhoon HIL SCADA is a very important component in realizing real-time co-simulation. SCADA contains different panels to initialize co-simulation, control, and monitor expected outputs. The beautiful part of designing SCADA is the python program can be utilized effectively. Three important factors to be considered while designing the Typhoon HIL SCADA for co-simulation are listed below.

1. Initializing Co-Simulation framework between Typhoon HIL and OpenDSS.
2. Development of panel to execute real-time control.
3. Development of a panel for monitoring the output in a real-time framework.

To initiate the co-simulation between Typhoon HIL and OpenDSS, First, the OpenDSS shared library to an interface is imported using Python. OpenDSSDirect.py [27] is the python interpreter to interact with Python from Typhoon HIL.

Then, import most of the Python-based modules in Typhoon HIL SCADA to execute the desired work. More details on how to import python based modules to Typhoon HIL python core can be found in Typhoon HIL operating manual [28]. Second, a program to communicate with the OpenDSS on startup and during real-time simulation is required.

To run the co-simulation in real-time, real-time signals must be given from the SCADA to the OpenDSS. For this purpose, different panels with widgets are designed. And, to monitor, the output variables in SCADA in real-time, a panel needs to be designed. An appropriate widget to show the desired signal is selected from the library. In the widget, a program is written to gather an appropriate signal to be monitored.

IV. SIMULATION AND RESULTS

This section shows HC computation results obtained from different scenarios of topologies of operation by appropriately and intentionally controlling the interconnecting switches available in the network and the effect of reactive power support from DERs. The study was conducted in the Digital Energy Systems Laboratory (DIgEnSys-Lab) (for more information, check https://fglongattlab.fglongatt.org). DIgSILENT PowerFactory is a primary modelling and simulation computational tool.

A. Test System

European MV distribution feeders can be used for DER integration studies [12]. Hence, the European medium voltage distribution network developed by CIGRE Task Force C6.04 in their report "Benchmark Systems for Network integration of Renewable and Distribution Energy Resources" is considered in this study. The network is assumed to be symmetrical and balanced. The test system consists of two typical European MV distribution at 20kV, 50 Hz, three-phase feeders named feeder 1 and feeder 2 as shown in **Fig. 4**. The feeder can be operated in radial or meshed topology by turning ON or OFF the switch S1, S2, and S3. However, in this analysis, all the switches are considered closed.

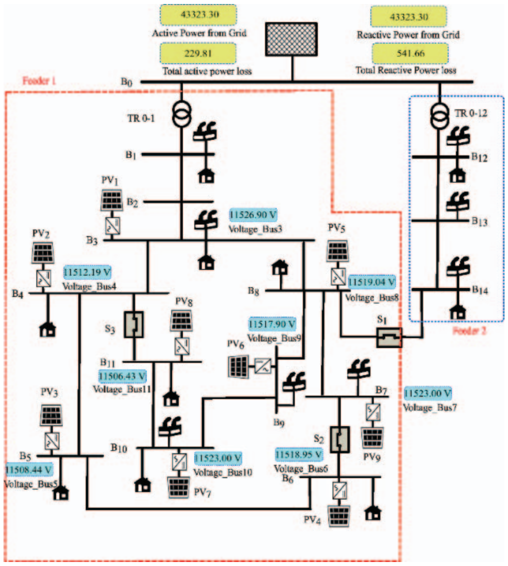

Fig. 4. *Test system*: Modified CIGRE MV DN [29]

To study the effectiveness of real-time reactive power control with smart inverters of PVs in this case, we modify the wind source considered in the original study with a PV of the same size. The wind turbine on node 7 is replaced by PV of the same rating to study the case of a PV-dominated system And, the load size is kept as it is in the original study.

To realize the reactive power control in PV systems in OpenDSS, the fundamental concept of the PV capability curve needs to be precise. The rating of the PV systems in OpenDSS should be assigned in such a way that the reactive power from the PV can be changed to the permissible limit. As per [9] the reactive power limit can be ± 44% of the rated capacity.

B. Real-Time simulation results

To perform the real-time simulation studies in the proposed co-simulation testbed, the SCADA of Typhoon HIL is equipped with different types of widgets like digital display, gauge display, phasor graph, trace graph, etc. available in the Typhoon HIL SCADA library. In the figure the result is for a particular instant, these values keep on changing as per the real-time change in the reactive power of the PV. Similarly, **Fig. 5** shows a detailed demonstration of how the reactive power affects the bus voltage. The slider in the figure can regulate the reactive power of the PV connected to that bus. The gauge shows the reactive power provided by the PV. In the figure, the graphical display for monitoring the variation in reactive power from the PV is shown. It is observed that the voltage profile varies with the change in reactive power. Since the testbed considered in this analysis is symmetric and balanced in nature, the magnitudes of all the phases are almost the same. One situation to note is that the reactive power for each PV is limited by rated capacity. In this particular analysis, we have set the reactive power for PV to be in the range [-0.45*Prated, 0.45*Prated]. A similar type of analysis can be shown for other PVs and buses. However, to follow the page limits of the paper, only one analysis is shown in the figure.

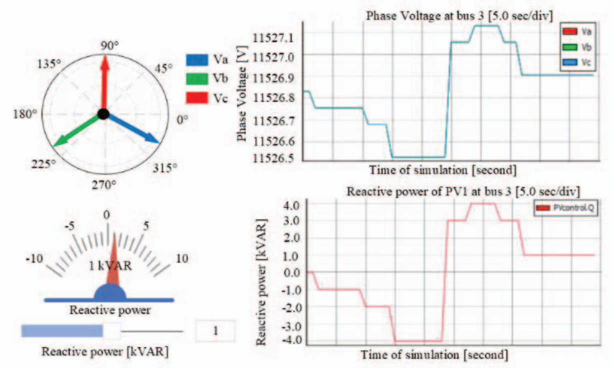

Fig. 5 Voltage response on bus 3 with reactive power change of PV at bus 3

V. CONCLUSION

This scientific paper develops and analyzes preliminary results on a cyber-physical co-simulation testbed for real-time reactive power control in the smart distribution network. This analysis opens the multi-dimensional horizon for real-time testing in cyber-physical co-simulation. This study develops a new method for controlling the reactive power of smart inverters in smart distribution networks with a high level of PV power systems. As per the authors, the main conclusions are as follows

1. A co-simulation testbed for real-time reactive power control in the smart distribution network is developed and tested to show the preliminary observation of the analysis.
2. A detailed methodology to implement a co-simulation testbed between Typhoon HIL and OpenDSS is explained and demonstrated. The voltage response on each bus of a smart distribution network due to reactive power variation of PV in real-time is shown to validate the efficacy of the proposed cyber-physical co-simulation testbed.

Although, the paper contributes to creating a cyber-physical co-simulation testbed for real-time controlling of the reactive power of smart inverters. However, this study can be extended to perform online optimization of the distribution network with multiple PVs to get the optimal requirements of reactive power for smart inverters to adjust the voltage fluctuations due to changes in loads and PV generations.

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REFERENCES

[1] S. Chen, P. Liu, and Z. Li, “Low carbon transition pathway of power sector with high penetration of renewable energy,” *Renew. Sustain. Energy Rev.*, vol. 130, no. February, p. 109985, 2020.

[2] DNV GL, “Energy Transition Outlook 2020 - A global and regional forecast to 2050,” *Dnv Gl Energy Transit. Outlook*, p. 306, 2020.

[3] H. R. Chamorro *et al.*, “Smart Renewable Energy Communities - Existing and Future Prospects,” in *2021 IEEE 22nd Workshop on Control and Modelling of Power Electronics (COMPEL)*, 2021, pp. 1–6.

[4] D. Sampath Kumar, O. Gandhi, C. D. Rodríguez-Gallegos, and D. Srinivasan, “Review of power system impacts at high PV penetration Part II: Potential solutions and the way forward,” *Sol. Energy*, vol. 210, pp. 202–221, 2020.

[5] V. Astapov, S. Trashchenkov, F. Gonzalez-Longatt, and D. Topic, “Performance Assessment of TSO-DSO using Volt-Var Control at Smart-Inverters: Case of Vestfold and Telemark in Norway,” *Int. J. Electr. Comput. Eng. Syst.*, vol. 13, no. 1, pp. 48–61, 2022.

[6] M. H. J. Bollen *et al.*, “Power Quality Concerns in Implementing Smart Distribution-Grid Applications,” *IEEE Trans. Smart Grid*, vol. 8, no. 1, pp. 391–399, 2017.

[7] R. Wagle, P. Sharma, C. Sharma, T. Gjengedal, and C. Pradhan, “Bio-inspired hybrid BFOA-PSO algorithm-based reactive power controller in a standalone wind-diesel power system,” *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 3, p. e12778, Mar. 2021.

[8] M. B. Liu, C. A. Canizares, and W. Huang, “Reactive Power and Voltage Control in Distribution Systems With Limited Switching Operations,” *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 889–899, 2009.

[9] IEEE, “IEEE 1547 Series of Interconnection Standards,” vol. 19, no. 5, pp. 1159–1162, 2015.

[10] D. Pettersen, E. Melfald, A. Chowdhury, M. N. Acosta, F. Gonzalez-Longatt, and D. Topic, “TSO-DSO Performance Considering Volt-Var Control at Smart-Inverters: Case of Vestfold and Telemark in Norway,” *Proc. 2020 Int. Conf. Smart Syst. Technol. SST 2020*, vol. 1547, no. 2018, pp. 147–152, 2020.

[11] H. J. Liu, W. Shi, and H. Zhu, “Distributed Voltage Control in Distribution Networks: Online and Robust Implementations,” *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6106–6117, 2018.

[12] M. N. Acosta, F. Gonzalez-Longatt, M. A. Andrade, and J. Rueda Torres, “Optimal Reactive Power Control of Smart Inverters: Vestfold and Telemark Regional Network,” *2021 IEEE Madrid PowerTech, PowerTech 2021 - Conf. Proc.*, 2021.

[13] X. Su, M. A. S. Masoum, and P. J. Wolfs, “Optimal PV inverter reactive power control and real power curtailment to improve performance of unbalanced four-wire LV distribution networks,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 3, pp. 967–977, 2014.

[14] S. Pukhrem, M. Basu, M. F. Conlon, and K. Sunderland, “Enhanced Network Voltage Management Techniques Under the Proliferation of Rooftop Solar PV Installation in Low-Voltage Distribution Network,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 5, no. 2, pp. 681–694, 2017.

[15] H. Zhu and H. J. Liu, “Fast Local Voltage Control Under Limited Reactive Power : Optimality and Stability Analysis,” *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3794–3803, 2015.

[16] D. Almeida, J. Pasupuleti, and J. Ekanayake, “Assessing the Performance of Smart Inverter Functionalities in PV-Rich LV Distribution Networks,” *2020 IEEE Student Conf. Res. Dev. SCOReD 2020*, no. September, pp. 90–95, 2020.

[17] Z. Tang, D. J. Hill, and T. Liu, “Distributed Coordinated Reactive Power Control for Voltage Regulation in Distribution Networks,” *IEEE Trans. Smart Grid*, vol. 12, no. 1, pp. 312–323, 2021.

[18] Y. Guo, Q. Wu, H. Gao, and F. Shen, “Distributed voltage regulation of smart distribution networks: Consensus-based information synchronization and distributed model predictive control scheme,” *Int. J. Electr. Power Energy Syst.*, vol. 111, no. October 2018, pp. 58–65, 2019.

[19] S. Maharjan, A. M. Khambadkone, and J. C. H. Peng, “Integration of centralized and local voltage control scheme in distribution network to reduce the operation of mechanically switched devices,” *2019 IEEE Milan PowerTech, PowerTech 2019*, 2019.

[20] M. H. Cintuglu, O. A. Mohammed, K. Akkaya, and A. S. Uluagac, “A Survey on Smart Grid Cyber-Physical System Testbeds,” *IEEE Commun. Surv. Tutorials*, vol. 19, no. 1, pp. 446–464, 2017.

[21] Stuart Borlase, *Smart Grids Infrastructure, Technology, and Solutions*, 1st ed. CRC Press, 2017.

[22] M. N. Acosta, F. Gonzalez-Longatt, M. A. Andrade, J. L. Torres, and H. R. Chamorro, “Assessment of Daily Cost of Reactive Power Procurement by Smart Inverters,” *Energies* , vol. 14, no. 16. 2021.

[23] D. P. Chassin, K. Schneider, and C. Gerkensmeyer, “GridLAB-D: An open-source power systems modeling and simulation environment,” in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, 2008, pp. 1–5.

[24] Eaton, “CYME Power Engineering Software.” [Online]. Available: https://www.cyme.com/software/cymdist/.

[25] D. M. Fobes, S. Claeys, F. Geth, and C. Coffrin, “PowerModelsDistribution.jl: An open-source framework for exploring distribution power flow formulations,” *Electr. Power Syst. Res.*, vol. 189, p. 106664, 2020.

[26] R. C. Dugan, “Reference guide: The open distribution system simulator (OpenDSS),” *Electrical power Research institute*, 2012.

[27] Dheepak Krishnamurthy, “OpenDSSDirect.py,” 2017. [Online]. Available: https://dss-extensions.org/OpenDSSDirect.py/notebooks/GettingStarted.html.

[28] T. HIL, “Typhoon HIL documentation,” 2022. [Online]. Available: https://www.typhoon-hil.com/documentation.

[29] Cigre, “Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources,” 2014.