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Experiences in a Cyber-Physical Co-Simulation Testbed Development for a Smart-er Distribution Network

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Abstract: With the rise of the integration of renewable energy sources, the operating characteristics of existing electric power distribution systems are evolving and changing. As a result, the digitalisation of the distribution network is gaining attention for effective real-time monitoring and control. Cyber-Physical co-simulation is one of the options for implementing and testing novel concepts and ideas before actual implementation on the distribution network. Therefore, this paper presents some experiences on the cyber-physical testbed in the distribution network. Moreover, the methodology, possible challenges and mitigation techniques are also presented for a cyber-physical co-simulation testbed of optimal reactive power control in smart-er distribution network (SDN). The cyber-physical co-simulation testbed is analysed using a Typhoon HIL 604 and OpenDSS on a CIGRE MV distribution.

Keywords - *Cyber-physical co-simulation testbed, Real-time control, Real-time simulator, Smart distribution networks*

I. INTRODUCTION

The complexity of distribution networks is increasing day by day due to the expansion of the network, higher penetration of renewable energy sources (RES), the incorporation of large amounts of controllable devices, and the revolution in operating mechanisms [1]. A modern distribution network's operating scenario demands advanced and sophisticated technology for efficient monitoring and control [2]. Within the next few years, there will be a significant gap in the existing control and monitoring system. The study uses cutting-edge algorithms, and real-time monitoring with advanced hardware and software is required.

With the advancements in cutting-edge information and communication technology (ICT), digitalisation and automation have been intensively affecting several sectors, especially the revolution in monitoring and controlling the power system [3]. The key forces behind this transformation include significant advances in cyber-physical systems (CPSs), the Internet of things (IoT) [4], [5], artificial intelligence (AI) [6], and big data analytics (BDA) [7]. With these developments, it is now possible to continuously accumulate, manipulate, and interpret real-time data streams in conjunction with high-fidelity models to produce a digital mirror of complex systems that offers insightful information on their current and anticipated operating conditions [8]. So, for real-time monitoring and control, a realistic, comprehensive, and adaptive virtual representation of the

system is accessible through cyber-physical co-simulation (CPCS). By connecting the physical and digital worlds, a CPCS enables the system to reflect the physical circumstances in real-time and provides enhanced analytics of the system it represents. CPCS is gaining more and more momentum in academics, research, and industry across all fields [9], [10]. With the assistance of CPCS, control centre operators can respond more quickly to solve operational challenges due to the high integration of RES in real time. Furthermore, CPCS closes the applicational gap in control centres [11]. It creates a novel foundation for increasing the operation and control's flexibility, fidelity, and efficiency.

In recent years, there has been significant interest in using cyber-physical real-time co-simulation to depict the complex behaviour of smart-er distribution networks [12]. The objective of CPCS impacts how cyber-physical real-time co-simulation progresses [13]. Most of the technical literature that has been evaluated so far on CPCS for SDN relates to cyber security, cyber theft detection, and false data detection [14], [15]. Meanwhile, some of them do not include the dynamics of the distribution network and instead only employ the cyber-physical real-time test in small systems, such as single converter systems [16]. The CPCS framework for analysing the grid-forming converter is studied in [17], but the impact of the distribution network is not considered in the corresponding paper. Real-time control using the cyber-physical system has not been the subject of many studies. For example, in [18], OPAL-RT and Matlab Simulink were used to create, build, and simulate a distribution grid model for dynamic performance assessments in the real-time simulator. However, Matlab Simulink is suitable for the dynamic modelling of small systems but may not be regarded as an appropriate modelling software for large distribution system analysis [19]. A method to provide real-time volt-watt control in a smart inverter is proposed in [20]. However, the Volt-Watt settings are obtained from offline optimisation.

Similarly, CPCS is used in [21] to propose extensive investigations of smart-er grid control functions in various power system networks. However, the detailed modelling of the converter is not done in the CPCS framework. A cyber-physical framework considering the complex distribution network topology and multiple converters is presented in [22]. Similarly, in [23], coordinated Volt-Var control of multiple converters with detailed mathematical modelling of the converter is presented. With the advancement of smart converter technology, recent smart converters are equipped

with advanced communication systems. Therefore, centralised optimal power flow (OPF)-based control in a converter-enriched distribution network may be a suitable option [24]. To consider this, the optimal reactive power control in smart-er distribution networks using real-time CPCS is presented in [25].

This paper is devoted to presenting the methodology, possible challenges, and mitigation techniques while developing a CPCS testbed for optimal reactive power control in the smart converter-enriched smart-er distribution network. The following list summarises the most important contributions of this study.

1. Develop a co-simulation CPCS testbed for real-time optimal reactive power control in the smart-er distribution network.
2. The proposed testbed is tested by creating various scenarios of voltage violation, and the effectiveness of the proposed testbed in mitigating such voltage violations using the real-time optimal reactive power control is presented to show the effectiveness of the proposed method. The reactive power set points are obtained after the occurrence of the voltage violations. With the new reactive power set points, the voltage violations are mitigated.

The remaining sections of the paper are organised as follows. Section II explains the theoretical concept of the CPCS testbed in SDN. 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 summarises the main contribution of the work done in this analysis and suggests future directions for research.

II. PERSPECTIVE OF CYBER-PHYSICAL CO-SIMULATION TESTBED FOR SDN

With the increasing integration of high-renewable energy sources, active participation of consumers, advanced energy management systems, and several demand response programs in the distribution network, the existing distribution network

needs to operate in smart-er grid paradigm for greater observability, controllability, and flexibility [26]. The smart-er distribution network, on the other hand, depends on communication and information systems for effective real-time control, operational efficiency, and grid resilience [27]. CPCS is one of the options to represent the smart grid paradigm in SDN [28]. By this, real-time bidirectional interaction between the cybernetic and the physical layer can be achieved. A vital element of the CPCS testbed infrastructures is becoming increasingly prevalent in the operation of SDN. The CPCS testbed is made up of several interrelated physical and digital resources that are used to achieve a specified goal [29]. Fig. 1 shows the CPCS framework for implementing a smart paradigm in the SDN. CPCS consists of various components for reliable and secure operation between different layers with the aim of effective monitoring, metering, automation, and protection [12]. Therefore, it is essentially very important to test any new concept and idea in CPCS prior to real implementation in a physical system.

To increase productivity, dependability, and effectiveness, CPCS relies on two-way interactions between physical components and cybernetic components, as shown in Fig.1. A typical CPCS combines a physical system with a cyber system through advanced communication. For this purpose, the physical system needs to be equipped with advanced metering infrastructure, such as intelligent electronic devices for proper monitoring. Furthermore, the physical system should be equipped with an advanced control and management system capable of fast communication with the cybernetic layer to ensure the safe operation of the SDN. With the advancement of information and communication technology in smart converters, a realistic operational scenario with high-speed data streams can be obtained for successful CPCS implementation. On the other hand, the cybernetic layer of the CPCS system should include various algorithms and methodologies for analysing the states of the physical system with the help of obtained measurements. The CPCS activates the proper control signal to rectify the abnormal operation of the physical system due to unknown disturbances [30].

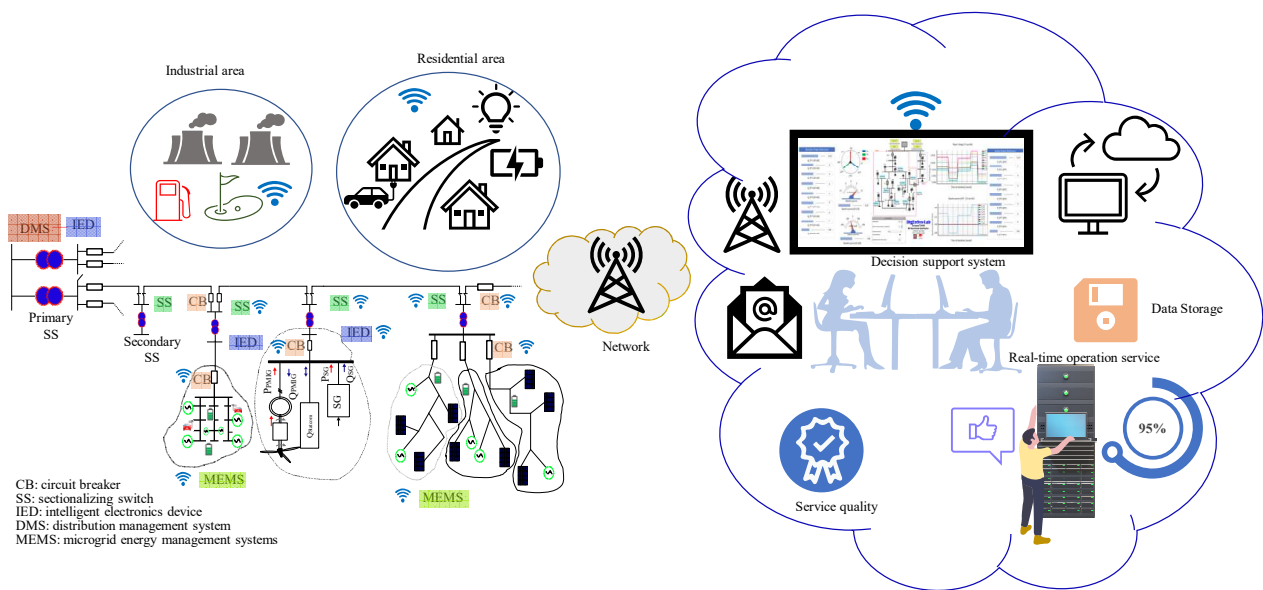


Fig. 1. The architecture of Cyber-physical co-simulation framework in SDN

III. IMPLEMENTATION OF CYBER-PHYSICAL CO-SIMULATION TESTBED FOR OPTIMAL REACTIVE POWER CONTROL IN SDN

Among several applications of CPCS, the optimal reactive power control of smart converters on an SDN is proposed in this paper. The overall process to implement the CPCS co-simulation for optimal reactive power control in SDN is shown in Fig.2. The proposed CPCS testbed is divided into two major parts, the physical system and the cybernetic system. As the main objective of the proposed CPCS is to control the reactive power, the cybernetic system consists of several components, for example, the distribution network solver, the reactive power control centre, the optimisation block to obtain the optimal reactive power set for smart converters, and the supervisory control and data acquisition (SCADA) system. The distribution network solver is operated in co-simulation with the real-time simulator and aids in obtaining the states of the distribution system. The distribution network solver is also utilised for co-simulation-based optimisation for faster convergence of the optimisation problem. SCADA in the cybernetic system is utilised in this testbed to create intentional disturbances in the physical system. SCADA also consists of several graphical user interfaces to display the real-time status of the physical system. On the other hand, the physical system in the proposed CPCS testbed consists of several measurement and monitoring systems, including a controller for the smart converter. In this analysis, the communication between the cyber system and the physical system is achieved by using Ethernet communication. Even though, OpenDSS does not provide a native support for protocols such as DNP3, the OpenDSS and Typhoon HIL cosimulation block in the SCADA of Typhoon HIL acts as a bridge to communicate between the real-time simulator and the distribution network solver. The OpenDSS is utilised as a distribution network solver. Typhoon HIL is the real-time simulator considered in the analysis.

To implement the proposed CPCS testbed for optimal reactive power control in SDN first, the test distribution system is modelled in OpenDSS [31]. The OpenDSS is executed using the Python-based application programming interface (API) of OpenDSS and Typhoon HIL. The OpenDSS API is utilised for co-simulation-based optimisation, and the Typhoon HIL API is for updating the system states in real time. The reactive power control center developed in the SCADA is responsible for creating the reactive power control. The model of reactive power control can be designed in the reactive power control center. The SCADA in the Typhoon HIL control centre is responsible for initiating optimisation in case of abnormal operation in the distribution network, updating the system states of the network system in OpenDSS, and transferring information between the cybernetic system and the physical system.

On the other hand, the smart converters are placed on physical system. The physical system is equipped with measurements and a monitoring system to check the status of the operation of the smart converter and the SDN. Detailed modelling of the controller of the converter is placed in the physical system. The controller is designed to track the optimal setpoints obtained from the cyber system. These setpoints are obtained in the cybernetic system to modify the abnormal operation of the distribution network. The communication between the physical system and the cybernetic system is

achieved by using the built in model-based toolchain of the real time simulator.

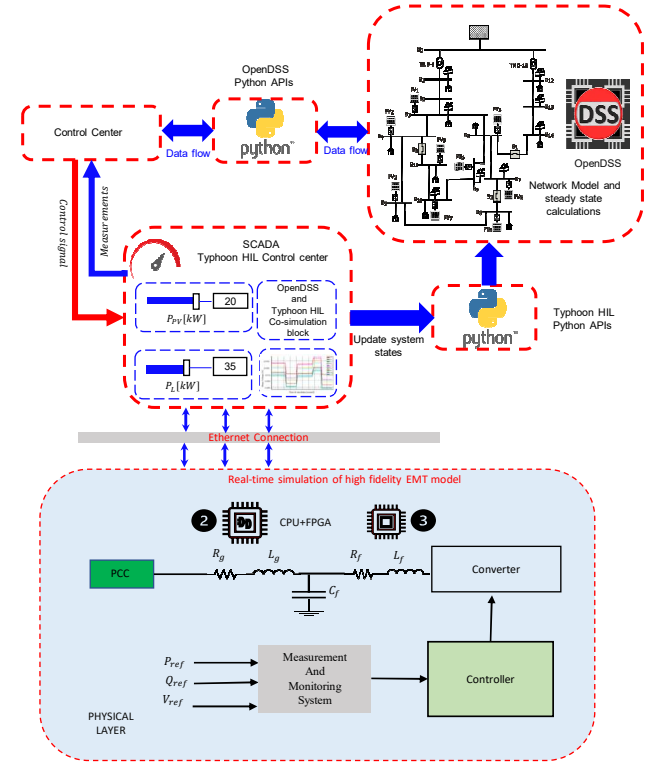


Fig. 2. General methodology for implementation of cyber-physical co-simulation testbed for optimal reactive power control in SDN

IV. SIMULATION RESULTS

This section illustrates the application of the proposed OPF-based optimal reactive power using CPCS. The research was carried out at the Digital Energy Systems Laboratory (DIGEnSys-Lab). The DIGEnSys-Lab has physical equipment for real-time monitoring and control (<https://fglongattlab.fglongatt.org>).

A. Test System

CIGRE MV distribution feeders can be used for DER integration studies [32]. Therefore, the medium voltage distribution network developed by the CIGRE Task Force C6.04 in its report “Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources” [33] is considered in this paper. The feeder can be operated in radial or meshed topology by turning ON or OFF the switches S1, S2, and S3. However, in this analysis, all the switches are considered closed.

B. Real-Time Simulation Results

To perform the real-time simulation studies in the proposed CPCS testbed, the detailed development of the CPSC is done as described in Section III. All the necessary configuration, and real time simulation setup is fixed. Once the real-time simulation starts, SCADA is utilised to create the intentional disturbance in the test system. The SCADA is equipped with different types of widgets like a digital display, gauge display, phasor graph, trace graph, etc. available in the Typhoon HIL SCADA library. By the help of sliders, the intentional disturbance is created on the test network which is responsible for altering the operation of the distribution network. Once the abnormal operation is sensed

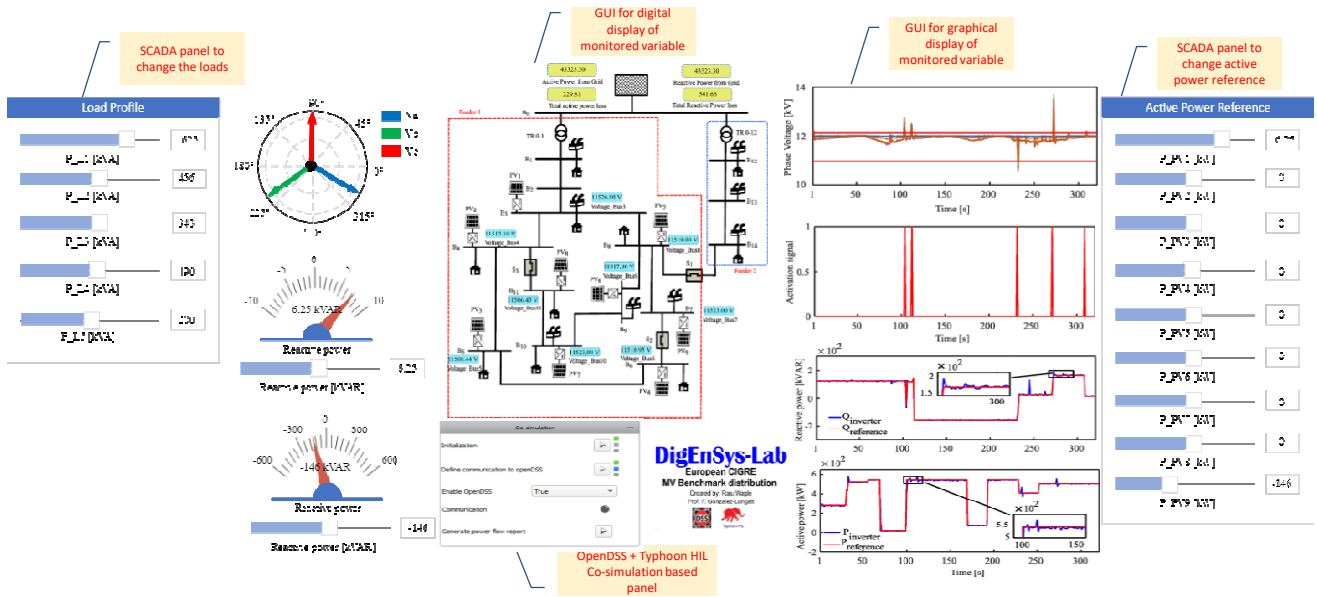


Fig. 3. General layout of the CIGRE MV network with SCADA panel for changing loads, DERs, and GUI implemented on the proposed CPCS

by the monitoring system, the control centre exchanges the information between the physical system and the cybernetic system. Depending on the type of information, the control centre initiates the corrective measures to mitigate abnormal operation of the network. In this case, the control centre initiates the co-simulation-based optimisation to compute the new sets of optimal reactive power set points. These reactive power set points are sent to the physical system where the control of the control tracks these set points to operate the network normally.

In Fig. 3, the GUI shows the voltage profile of the network, the activation signal in case of voltage violations, the active and reactive power from the smart converter. The figure also shows the block for initiating the co-simulation between the distribution network solver and the real-time simulator. The sliders on the sides of the figure are the GUIs in the SCADA panel to change the power generation profile and the load profile of the DERs and loads in the network. Various digital and graphical displays are also placed on the SCADA to show the real-time data of the network.

C. Possible Challenges and solutions of real-time implementation of optimal control in SDN

From the knowledge learned during the development of the proposed method, this technique can be utilised on any form of network, whether balanced or unbalanced, radial or mesh, and single-phase or poly-phase. To implement the suggested approach in any other distribution network, two main challenges must be addressed. First, the challenge is the application of real-time optimisation. To address this challenge, optimisation based on co-simulation is used in this paper. By co-simulation-based optimisation, the extensive mathematical model of the distribution network and convergence concerns can be solved. Therefore, by making use of this co-simulation-based optimisation, the real-time optimisation can be performed in any distribution network. Another challenge in incorporating the proposed framework is to model the converter in the physical layer to implement the correct control strategy. The modelling of converters varies from network to network. So, a suitable converter

modelling is required to consider the size and voltage level of the considered network.

V. CONCLUSION

This scientific paper presents a CPCS testbed for real-time optimal reactive power control in the smart-er distribution network. This analysis opens the multidimensional horizon for real-time testing in CPCS. This study develops a new method to control the reactive power of smart inverters in smart-er distribution networks with a high level of DERs. As per the authors, the main conclusions are as follows:

1. A cyber-physical co-simulation testbed for optimal reactive power control in the smart distribution network is developed and tested.
2. A detailed methodology to implement the proposed methodology is explained and demonstrated.
3. Possible challenges and solutions to the implementation of the proposed CPCS testbed for another type of SDN are presented.

There are numerous approaches to implementing the suggested CPCS framework to test, develop, and validate the smart grid paradigm in the distribution network. Future research with more sophisticated smart grid features is planned.

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