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***Abstract*—With the rise of integration of renewable energy sources, existing electric power distribution networks are facing a variety of technical obstacles, one of which is modelling of the distribution networks for real-time network monitoring and control. This research designs and analyzes a novel cyber-physical test system for real-time reactive power compensation from smart inverters in the active distribution network using cyber-physical co-simulation between the Typhoon HIL and OpenDSS. The testbed is a two-layer system, with a physical and cybernetic layer. The physical layer is represented by Typhoon HIL 604 and the cybernetic layer is represented by software from Typhoon HIL, OpenDSS, and Python. The cybernetic layer is used to model, design, and control the reactive power from the smart inverter in real-time. The distribution network considered is a CIGRE MV distribution network. Real-time simulation results demonstrate the applicability of the proposed test platform in real-time reactive power control.**

***Index Terms*—Cyber-physical co-simulation, reactive power control, real-time control, active distribution networks**

I. Introduction

Renewable energy sources (RES) are one of the possible alternatives to solving the global energy crisis [1]. Therefore, a large proportion of photovoltaics (PV) have been integrated into distribution networks in recent years [2], [3]. However, the distribution system faces significant technological challenges as a result of the fluctuating nature of the photovoltaic. Voltage fluctuations in distribution networks are one of the key difficulties that affect the efficient and efficient operation of distribution [4]. Furthermore, voltage fluctuations are one of the main causes of the degradation of power quality in the distribution network [5]. Voltage regulation is performed in most existing distribution networks using traditional voltage-regulating devices (VRDs) [4], [6], such as on-load tap changing transformers (OLTC), switched capacitor banks, and STATCOM. These VRDs have a limited number of switching operations and a slow response time [7]. As a result, they may not be able to regulate the rapidly changing voltage. Therefore, the use of smart inverters to manage voltage is becoming increasingly attractive [8].

Smart inverters have been designed to provide reliable and scalable reactive power support to resolve these voltage concerns [9]–[11]. Existing reactive power control systems based on PV inverters are divided into three types, namely centralized [12], decentralized [13], and distributed [14]. In most of the voltage control strategies available in the literature, distribution network modeling is performed using the Distflow equation or LinDistflow equations [15], or by sensitivity-based modeling [16]. The linearized form of the distribution network may not represent all of the properties of the network. Furthermore, regardless of which voltage regulation method is implemented, in most cases, the analysis is performed offline and presented as the expected solution or methodologies.

Furthermore, due to the substantial increase in PV penetration in the network, the future distribution network will be exposed to large voltage variations. As a result, studies investigating the control and management of distribution systems should look to move away from the old offline mode and shift toward real-time form. Another important feature of the future digitalization of distribution networks is the use of smart devices to provide real-time control and monitoring. To solve the looming issues in the digitalization of the future distribution network, it is critical to provide a clear, thorough, and executable platform to test concepts and theories, computational tools and methodologies, and new technologies. Most of the research in similar domains focused on power system models [17]. A cyber-physical co-simulation framework is used in many applications, including industrial automation, aeronautical and automotive control, power grid management, and difficult-to-access and dangerous investigations [18]. [19] proposes a real-time cyber-physical test bed for microgrid control, where the power system network is constructed in RSCAD and real-time co-simulation is performed using the real-time digital simulator (RTDS). A real-time simulation test bed between OpalRT and Matlab Simulink is also suggested in [20]. This article incorporates a test bed to verify the microgrid control algorithm and the influence of cyber events on microgrid performance. However, the modeling of distribution network is limited to the user of Matlab only, which may not be a suitable system for modeling large distribution network. The communication network simulation created using OPNET and the Real-Time Laboratory (RT-LAB) is studied in [21]. A detailed analysis of the real-time co-simulation testbed. In earlier research, microgrids or small distribution networks are considered for cyber-physical co-simulation is carried out in [22]. The article [22] focuses mainly on research on the cyber security of the power system. The most comparable cyber-physical testbeds in the domain listed in the literature [23] focus more on power system models. The distribution network solver taken into consideration in the co-simulation testbed should be able to solve all forms of distribution networks in order to assess a realistic distribution network in a reliable and faster way. OpenDSS is a highly potent technology developed specifically to address the distribution network problem. To the best of our authors' knowledge, the proposed co-simulation testbed between Typhoon HIL and OpenDSS for smart inverter control is the first of its kind. The proposed system can be applied on any kind of distribution network, either balanced or unbalanced, single-phase or three-phase. Therefore, the goal of this effort is to provide a framework for cyber-physical co-simulation that will be used to execute a real-time simulation between Typhoon HIL and OpenDSS together.

In this work, we present the preliminary results of a proposed testbed for real-time reactive power control. Using real-time simulation, the purpose of this research article is to develop a new testbed for real-time reactive power control in active distribution networks using cyber-physical co-simulation.The list below summarizes the most important contributions of this study.

1) Develop a testbed for real-time reactive power control in the active distribution network using cyber-physical co-simulation.
2) Obtain the response for the monitoring variable of an active distribution network from the testbed.

The remaining sections of the paper are organized as follows. Section II explains the theoretical concept of modeling the testbed. Section III 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. Development of Testbed

Several critical components for regulation and monitoring are required to complete the test bed for modeling active distribution systems [24]. Among the most basic requirements is software to estimate unbalanced power flow in multiple phases. Other factors include the centralized control system and its implications for SCADA. Infrastructure that enables advanced real-time monitoring and fully controllable equipment, as well as the appropriate connection infrastructure, is also required. Some of the requirements will be developed in the cybernetic layer of the testbed. while some of them are present in the physical layer. The proposed testbed is divided into two layers: the cybernetic layer and the physical layer. The cybernetic layer consists of monitoring and controlling elements, software to interface with the physical layer, and software to interact with the distribution system simulator. The host PC runs all of the software at cybernetic levels. The virtual and physical hardware of the testbed is included in the physical layer. The general process of co-simulation using the proposed test bed is shown in Fig. 1. The connection between the cybernetic layer and the physical layer is done using an Ethernet cable. Each component of the cyber-physical testbed is discussed in detail in the subsections that follow.

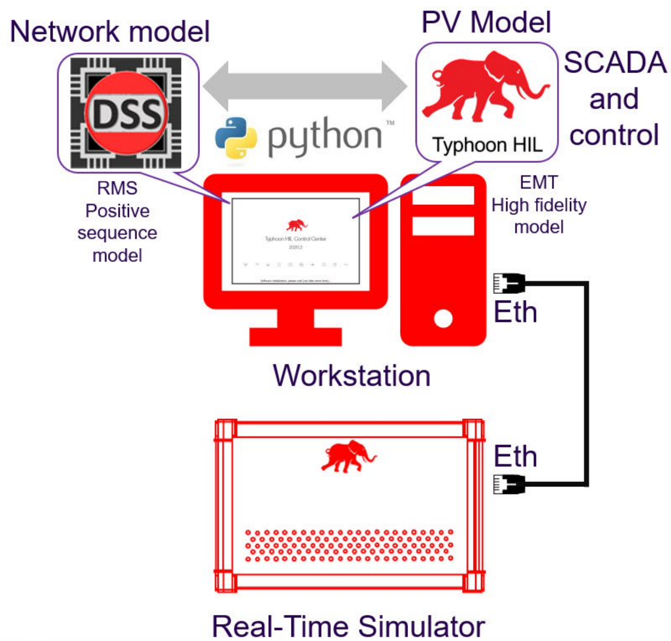

Fig. 1. Overall process of modelling testbed of active distribution system using cyber-physical co-simulation

A. modelling of Cybernetic layer

The cybernetic layer is the fundamental core of the testbed. As indicated previously, the cybernetic layer is contained within the host PC. On the host PC, the required software is also installed to model and operate the real-time digital simulator. The following subsections provide a full description of the modeling of each component of the cybernetic layer.

1) Modelling of Test System: Data about the distribution network and the software to simulate it are a crucial part of the development of the required test bed [25]. The basic goal of creating a testbed is to create a cybernetic layer that mimics the real distribution system. Distribution system modeling software must be able to perform three-phase unbalanced power flow calculations. There are various distribution system modeling techniques in the literature. Some of the most commonly used tools include GridLAB-D [26], CYME-DIST [27], powermodeldistribution [28], and OpenDSS [29]. OpenDSS is considered a modeling tool due to its ease of use, flexibility, openness, and ability to perform a wide range of analyses. One of the advantages of using 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.

The proposed test bed includes measurement and monitoring equipment to obtain network metrics such as bus voltages and total power loss. When the reactive power is changed, the system voltage response to the injection/consumption of reactive power through smart PV inverters may be viewed in real-time. In the same situation, all the power losses in the network can be seen. A monitoring and control system designed in Typhoon HIL SCADA may dynamically modify reactive power injection/consumption. Different sliders on the SCADA are used to deliver the real-time signal to the OpenDSS. The signal is supplied to the OpenDSS at each change and the load flow is carried out inside the OpenDSS, with the outputs being fed into the Typhoon HIL. In the following section, the monitoring and control implementation is explained in brief.

2) Real-time Monitoring and Control System: The real-time monitoring system for the proposed testbed is a graphical user interface (GUI) that allows simulations to be viewed and operated in real time. During real-time simulation, the GUI is specifically designed to show the signals produced by the measurement equipment linked to the test system. The present condition of the voltage magnitude, the overall active and reactive power losses of the network, as well as the power exchanged with the upstream network are also displayed graphically or digitally in the GUI. The GUI is meant to deliver the proper control signal to the test model in order to execute control commands in real-time. This study uses the Typhoon HIL SCADA system to create the GUI.

A centralized SCADA system that interacts with the testbed and the control and monitoring unit is another significant aspect of real-time monitoring and control of reactive power control. The cyber-physical co-simulation in this work is divided into two parts: OpenDSS and Typhoon HIL. The creation of Typhoon HIL schematics and SCADA is a crucial aspect of this work. The Typhoon HIL schematic editor is a modeling system with a GUI. The schematic model serves as a link between Typhoon HIL and the OpenDSS simulator. The variables to be controlled from Typhoon HIL's SCADA are provided to the model inside the schematic editor, and the schematic editor's output signal is fed to the OpenDSS. This process continues with the width of the simulation.

Various components are accessible as built-in functionalities in the Typhoon HIL schematic editors. In this investigation, the schematic editor is utilized to transmit the control signal from SCADA to OpenDSS. As a result, a basic model for signal interaction between SCADA and OpenDSS is developed. The concept of bridging the control signal for one controllable object is illustrated in Fig. 2. A similar style of schematic must be created for several controlled objects. The schematic inside Fig. 2 is shown in Fig. 3.

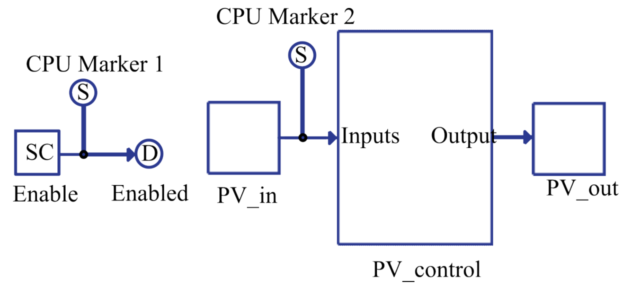

Fig. 2. Schematic of PV control

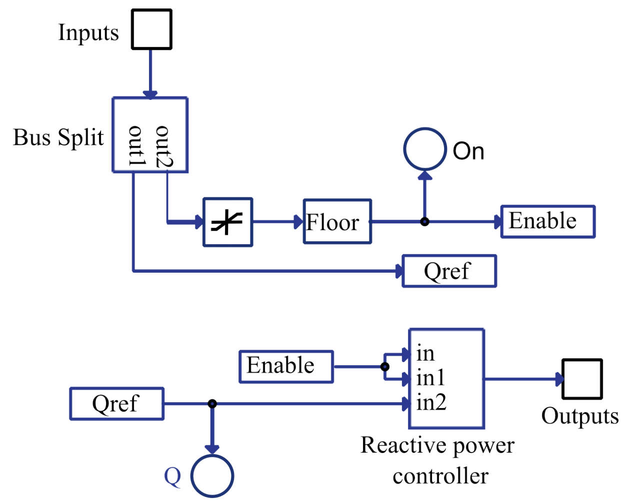

Fig. 3. Schematic inside PV control subsystem

First, import the OpenDSS shared library to start the testbed. The OpenDSSDirect.py Python interpreter [30] is used to communicate with Typhoon HIL. Then, in Typhoon HIL SCADA, it is required to import most Python-based modules to complete the task. The Typhoon HIL operational handbook [31] has more information on how to load Python-based modules into the Typhoon HIL python core. Second, a script is written to communicate with OpenDSS during the real-time simulation and at initialization. Real-time signals from SCADA to OpenDSS are required to execute the co-simulation in real time. For this purpose, the different panels contain widgets. A panel must also be created to monitor the output values in SCADA in real time. A suitable widget to display the output signals is chosen from the library. In the widget, a program is created to gather an appropriate signal to be monitored.

B. Physical Layer

The physical layer is where actual co-simulation takes place. The Typhoon HIL Inc. 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 simulation of the physical layer, 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. Simulation and Results

This section illustrates the application of the proposed testbed. Research was carried out at the Digital Energy Systems Laboratory (DIgEnSys-Lab). The DIgEnSys-Lab has physical equipment for real-time monitoring and control (see https://fglongattlab.fglongatt.org for further information). Each part of the simulation studies is described in the following subsection. Typhoon HIL 604 is used to model the cybernetic and physical layers in this paper. The active distribution system with installed photovoltaics is built using OpenDSS, as shown in Fig. 1. modeling is done with Python.

A. Test system

For DER integration studies, MV distribution feeders can be used [11]. As a result, this study takes into account the European medium voltage distribution network produced by CIGRE Task Force C6.04 in their publication ”Benchmark Systems for Network Integration of Renewable and Distribution Energy Resources.” It is assumed that the network is symmetric and balanced. As illustrated in Fig. 1, the test system comprises two typical 20kV, 50 Hz, three-phase feeders named feeder 1 and feeder 2. By turning on or off switches S1, S2, and S3, the feeder can be operated in a radial or meshed topology. In this analysis, all switches are assumed to be closed.

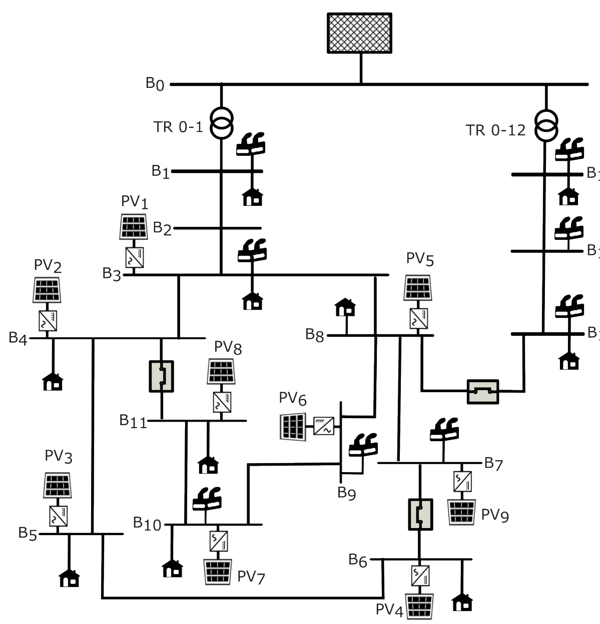

Fig. 4. Test system:Modified cigre medium voltage distribution system [32]

The rating of the PVs is considered the same as in the original test study case, so the location and size of the PV is not considered in this study. The unity power factor is considered for all PVs in the network. The reactive power limits of the inverter are set according to the IEEE 1547-2018 standard [9]. The wind source considered in the original study is replaced with a photovoltaic of the same size to test the effectiveness of real-time reactive power control with smart photovoltaic inverters in this situation. The load and other information of the network is kept the same as in the original study. Table I shows the PV ratings considered in this study.

TABLE I
MV distribution network benchmark application: PV unit parameters [32]

Node	Type of DER	$P_{max}(kW)$
3	Photovoltaic	20
4	Photovoltaic	20
5	Photovoltaic	30
6	Photovoltaic	30
7	Photovoltaic	1500*
8	Photovoltaic	30
9	Photovoltaic	30
10	Photovoltaic	40
11	Photovoltaic	10

The essential concept of the PV capability curve must be implemented to realize the reactive power control in PV systems in OpenDSS. The PV capability curve and the link between inverter size and reactive power are shown in Fig. 5. PV system ratings in OpenDSS should be assigned in such a way that the PV's reactive power can be modified to the acceptable limit. The reactive power limit, according to [9], can be $\pm 45\%$ of the rated capacity.

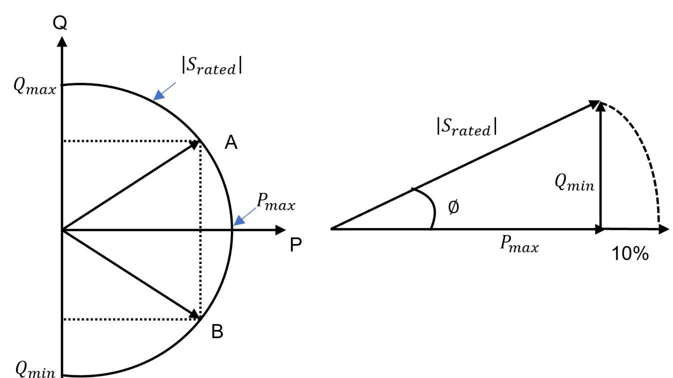

Fig. 5. (a) PV capability curve (b) inverter size and reactive power capability relationship [33]

B. Real-time simulation results

The SCADA of Typhoon HIL is equipped with many types of widgets such as a digital display, gauge display, phasor graph, trace graph, and others available in the Typhoon HIL SCADA library to perform simulation studies in real time on the suggested testbed. Fig. 6 shows the GUI developed in Tyhphoon HIL SCADA designed in this study to monitor different parameters such as bus voltages, total active and

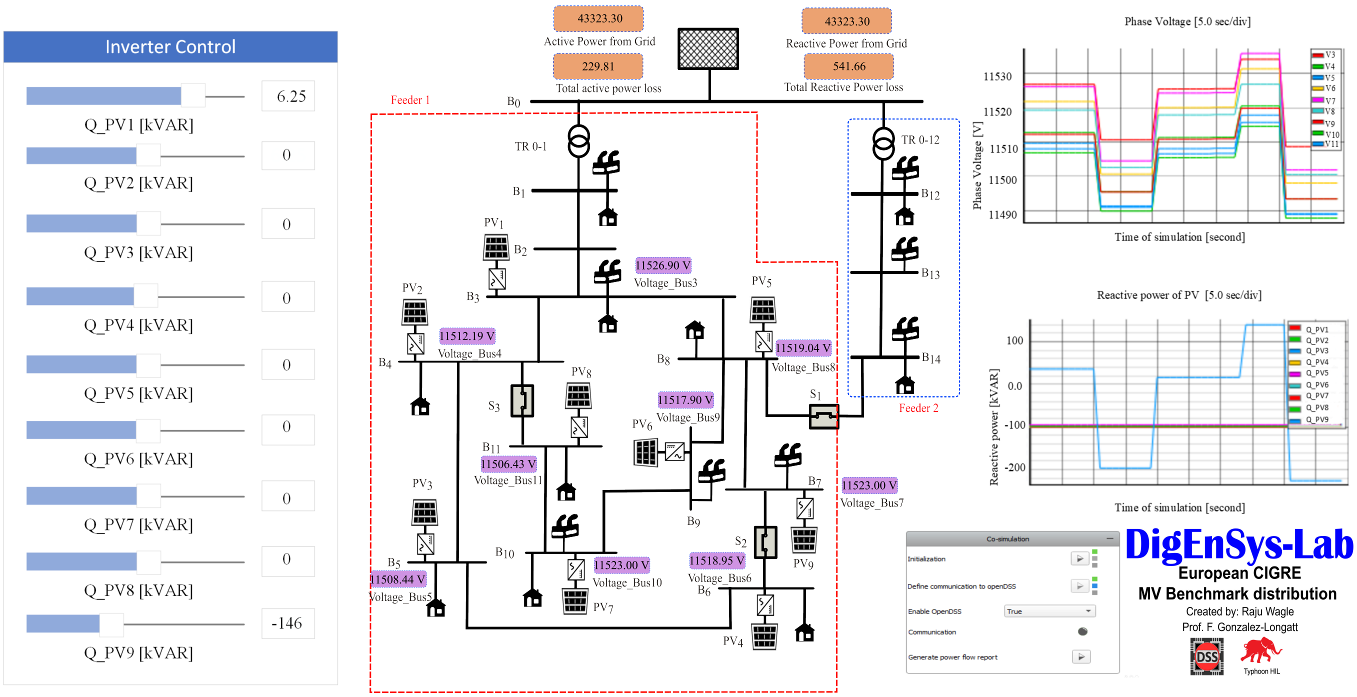

Fig. 6. Test system with monitoring digital display

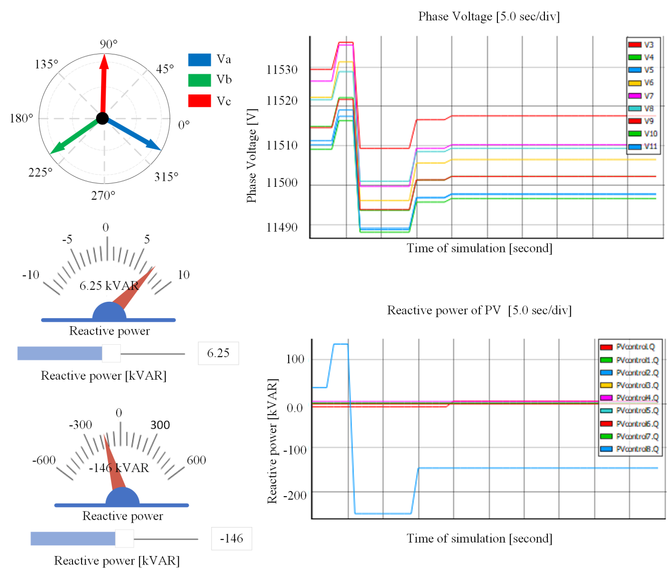

Fig. 7. Voltage response on bus 3 with reactive power change of PV on that bus

reactive power loss, and total power exchanged from the upstream network. The slider on the left shows the mechanism to manually change the reactive power reference of the inverter. For the initial investigation, the mechanism is designed to control the reactive power of the photovoltaic power using a slider. However, further studies are underway to optimally set the reference frequency of the reactive power. The part in the middle shows how reactive power influences bus voltage and network losses in real time. The graphical display on the right shows the voltage profile during the real-time simulation as a result of the changes in the reactive power of the photovoltaic energy. In Fig. 6, the initiation block for co-simulation between openDSS and the HIL SCADA typhoon is also shown. A detailed description of the formulation of the co-simulation is presented in [34]. Fig. 6 shows the overall layout of the real-time output obtained by changing the reactive power of the photovoltaic.

Similarly, Fig. 7 is the extended output with phasor diagrams, the gauge for the reactive power display and the display for the controllable and monitored parameters in the study. The voltage profile fluctuates in response to changes in reactive power. The reactive power of each photovoltaic is limited by its rated capacity. The reactive power of PV in this study is between $[-0.45 * P_{rated}, 0.45 * P_{rated}]$.

IV. Conclusion

This scientific study produces and analyzes preliminary findings from a proposed testbed for real-time reactive power control in active distribution networks using cyber-physical co-simulation. This research expands the multidimensional horizon for real-time control and monitoring studies. This research proposes a novel way to regulate the reactive power of smart inverters in active distribution networks with high penetration of photovoltaics. The following are the authors' primary conclusions.

1) A testbed for modeling an active distribution network using cyber-physical co-simulation is developed and tested to show the preliminary observation of the analysis.

2) A detailed methodology to implement co-simulation between Typhoon HIL and OpenDSS is explained and demonstrated. The voltage response on each bus of an active distribution network as a result of the reactive power variation of PV in real time is shown to validate the efficacy of the proposed testbed.

However, the paper contributes to the development of a testbed for modeling active distribution networks combining cyber-physical co-simulation and real-time control of smart inverter reactive power. This research can be expanded to include real-time optimization of the distribution network to determine the appropriate reactive power requirements for smart inverters and to compensate for voltage fluctuations caused by changes in loads and PV generation. Moreover, a robust testbed considering the IEC 61850 and IEEE C37.118 communication protocols to communicate among the distribution network devices, IoT devices, IEDs, AMI is planned for future works.

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