Real-Time Hardware-in-the-Loop Distributed Energy Resources System Testbed using IEEE 2030.5 Standard

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Abstract—**IEEE 2030.5 standard is drawing special attention among communication protocols for smart inverters and distributed energy resources (DER). Moreover, California Rule 21 mandates new DER must be ready to communicate to a host utility using the IEEE 2030.5 standard. Therefore, development of an effective real-time simulation method for managing DER using IEEE 2030.5 network is crucial. This paper presents a real-time hardware-in-the-loop (HIL) DER system testbed using the IEEE 2030.5 standard. The proposed real-time co-simulation testbed consists of a DER physical system simulation using OPAL-RT real-time simulator and a cyber system simulation including DER gateways and a DER management system (DERMS) cloud server. Custom-built client and server programs are developed to meet the compliant with IEEE 2030.5-2018 standard and implemented in the DER gateways and a DERMS server, respectively. The feasibility of the proposed testbed for DER systems is validated by experiments.**

Keywords—co-simulation, hardware-in-the-loop testbed, cybersecurity, distributed energy resources, distributed energy resources management system

I. INTRODUCTION

Penetrations of distributed energy resources (DER) such as renewable energy systems, energy storage systems, electric vehicles in electric power systems has been rapidly growing [1], [2]. Due to the ever-increasing number of DER, the current power grid is undergoing a transition. Geographically, broadly dispersed DER can make the electric power grid resilient with monitoring and control [3]-[7]. For example, a group of DER can act as a virtual power plant [5] providing grid services such as demand response [6] and mitigating renewable energy oversupplies [7]. However, standardizing communication protocols for interoperability between power system operators and DER equipment is crucial [8]).

In efforts of standardization, DER equipment requires to have either an IEEE 2030.5 (Smart Energy Profile 2.0 (SEP2), IEEE 1815 (DNP3), or SunSpec Modbus communication interface in a revision to the US interconnection and interoperability standard, IEEE Std. 1547 (i.e., IEEE 1547-2018 [8]). Moreover, the California Public Utility Commission (CPUC) Electric Rule 21 [10] defines IEEE 2030.5 as the default application network protocol for Investor Owned Utilities (IOU) communications to DER [11], effective in early 2019. It is anticipated that the adoption of IEEE 2030.5 for DER will soon be expanded to other states in U.S. and nations due to the advanced features such as internet protocol (IP)-based interoperability and security mechanism for securely exchanging application messages via internet among communication protocols.

With an awareness of special attention to IEEE 2030.5, a few researchers have recently adopted the protocol as a standard of smart grids. A network protocol compliant with IEEE 2030.5 standard is applied for private message exchange between a transactive agent and a home energy management system for transactive demand response for residential customers [12]. In [13], the authors proposed a two-way smart grid communication system compliant with IEEE 2030.5 standard between a transformer agent attached to a neighborhood's electric transformer and customer agents attached to each house. Sandia National lab assessed network-based defense techniques for DER in a virtualized co-simulation environment where SunSpec-compliant PV inverters are deployed as virtual machines and interconnected to simulated communication network equipment and a local DER management system (DERMS) monitors and controls the PV inverters [8]. However, the testbed does not fully investigate and implement IEEE 2030.5 standard for DER systems. Therefore, it is necessary to design a DER system testbed using a network protocol compliant with IEEE 2030.5 standard.

This paper proposes a real-time hardware-in-the-loop (HIL) DER system testbed using IEEE 2030.5 standard. The proposed real-time DER co-simulation testbed consists of a DER physical system simulation using a real-time simulator and a cyber system simulation including DER gateways and a DER management system (DERMS) cloud server. The proposed testbed provides a comprehensive real-time cyber system modeling and HIL capability that captures the cyber-physical impacts of the DER using the IEEE 2030.5 profile. As a result, researchers can analyze the complex interactions in a cyber-physical environment, which is required for studying on cyber-physical DER systems such as optimizing DERMS and defending cyber-attacks. Experimental studies are conducted to validate the feasibility of the proposed testbed for DER systems.

II. DER NETWORK USING IEEE 2030.5 STANDARD

IEEE 2030.5 standard defines an application protocol which provides an interface between the smart grid and users via internet and enables to manage the end user energy environment such as demand response, load control, price communication [14]. 2030.5 was previously named the SEP and based on Zigbee Alliance as a metering communication solution for building energy devices. In 2013, SEP2 was originally developed after adopted and ratified by IEEE (i.e.,
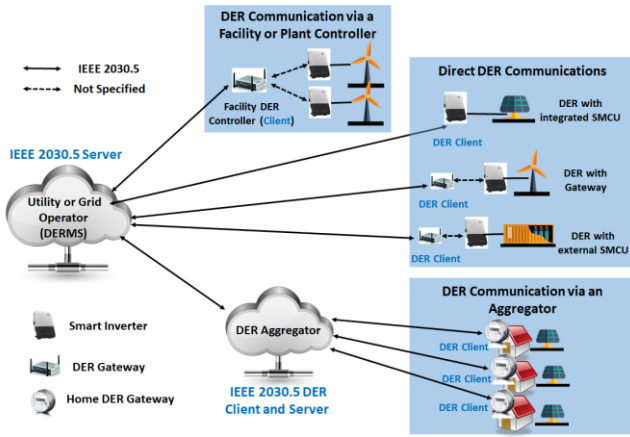
Fig. 1. Utility-to-DER communication architecture using IEEE 2030.5.

IEEE 2030.5-2013). In 2016, CPUC chose this protocol as the default protocol for Rule 21. The revision, IEEE 2030.5-2018, provides an expanded feature set that supports all controls in IEEE 1547-2018.

Fig. 1 shows examples of utility-to-DER communication architecture using IEEE 2030.5 where the DER is composed of a communication module and the power converter. IEEE 2030.5 applies to communications between the utility and DER systems through connections via DER facility controller, or an aggregator or direct connections [15]. In direct DER communications either the smart inverter control unit (SMCU) or a separate gateway/control unit will be the IEEE 2030.5 client. The DER aggregator manages small DER as an IEEE 2030.5 server and communicates with DERMS as a client.

Technical components of IEEE 2030.5-2018 mapping to OSI layer include: 1) IP-based network mixing various link layer technologies (i.e., Wi-Fi, ZigBee) to promote interoperability; 2) transport layer security (TLS) v1.2 with a strong cipher suite (e.g., TLS_ECDHE_ECDSA_WITH_AES_128_CCM_8 unless otherwise indicated by utility interconnection obligations) for secure communication including the encryption,
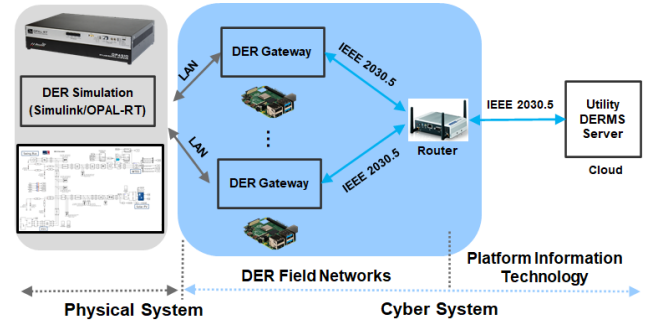

Fig. 2. A diagram of the proposed HIL DERMS testbed using IEEE 2030.5 standard.

authentication, and key management; 3) representation state transfer (REST) HTTP architecture over TCP/IP for a client-server interaction; 4) extensible markup language (XML) schema to describe resources; 5) multicase DNS (mDNS) for host discovery on a local area network (LAN) and DNS-SD for resource discovery (standard DNS for host discovery is acceptable as well); and 6) providing application profile sources elements to direct support for DER controls defined in IEEE 1547-2018 (or other existing standards such as IEC 61968 and IEC 61850). Clients and servers perform mutual authentication using certificates (i.e., X.509 v3) during handshake through verification with the Root-CA. RESTful protocols allow HTTP actions. Common Smart Inverter Profile (CSIP) defines the operation of IEEE 2030.5 in the California Rule 21 use case. For example, POST (create) and DELETE (remove) can be used to create or remove DER end-devices or DER controllers.

III. PROPOSED REAL-TIME HIL DER TESTBED USING IEEE 2030.5-2018

Fig. 2 shows an overview of the real-time HIL DER testbed using IEEE 2030.5-2018 standard. This testbed including 1) a real-time DER physical system simulator using a grid simulator and 2) a real-time cyber system testbed consists of DER gateways and a DERMS cloud server.
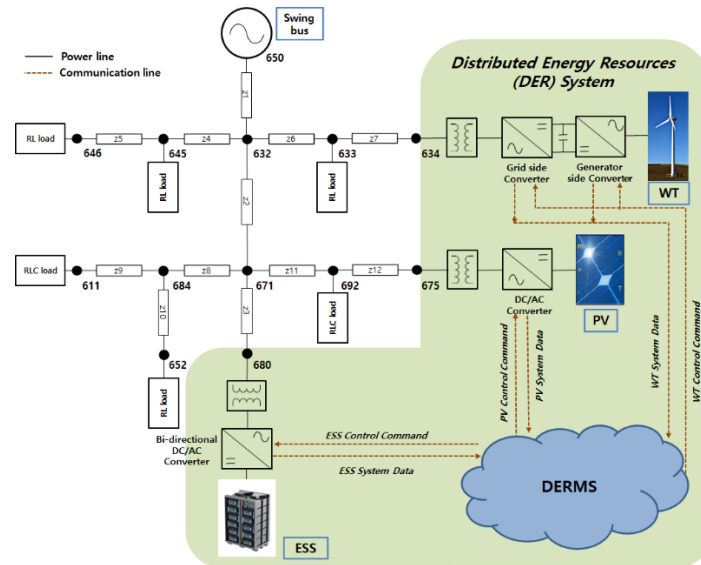

Fig. 3. A DER system in IEEE 13 node test feeder circuit, monitored and controlled by a DERMS.

A. DER System Modeling and Grid Simulation

Fig. 3 illustrates a DER system in IEEE 13 Node Test Feeder circuit where the DER system consists of multiple smart inverters, a swing bus, a wind turbine (WT), a Photovoltaic (PV), an energy storage system (ESS) and loads. The system bus frequency is 60Hz and the nominal voltage is 4.16kV. Smart inverters of WT and PV perform maximum power point tracking (MPPT) control. The WT of the 634 bus is applied with the permanent magnet synchronous generator (PMSG) model and the rated power is 2.2 MVA. The PV is located on bus 675 and the rated output is 1MW. The ESS capacity of bus 680 is 1 MWh and a lithium-ion battery model is used. Except for the bus where the generators are connected, the resistive, inductive, and capacitive loads are evenly connected to the other buses, where the real power demand of the distribution system is 3.5 MW; the reactive power demand of inductive loads is 2.102 MVAR; and the reactive power demand of capacitive loads is 0.7 MVAR. The impedance values between the buses are chosen based on the IEEE 13 bus system. The DERM system model is implemented in MATLAB/Simulink.
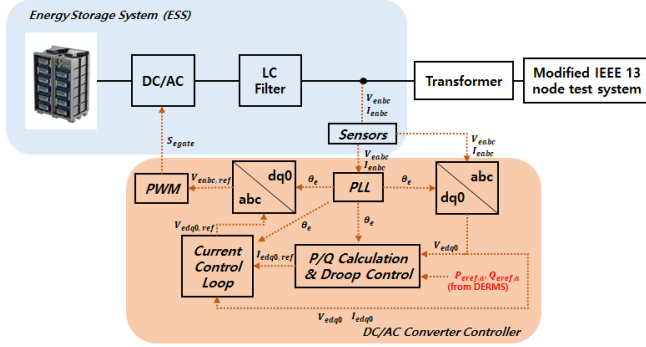

Fig. 4. ESS control model in IEEE 13 node test feeder circuit.

DERMS is implemented in a cloud server monitors the DER system data and sends control commands to the DER devices as described in CSIP. A real-time power grid simulator (e.g., OPAL RT's OP4510) simulates the DER system modeled in MATLAB/Simulink.

Due to the page limit, this paper only provides the ESS converter control. Fig. 4 shows the ESS converter control model in IEEE 13 node test feeder circuit where the converter controller receives the control command such as active power reference ($P_{eref,a}$) and reactive power reference ($Q_{eref,a}$) from the aggregator. A droop control is applied for primary control of the controller. Combination of active/reactive (P/Q) calculation and droop control determines $I_{edq0,ref}$ (= $I_{ed,ref}$ and $I_{eq,ref}$) which can be expressed as follows:

$$I_{ed,ref} = \frac{2}{3}\frac{P_{eref}}{V_{ed}} \tag{1}$$

$$I_{eq,ref} = -\frac{2}{3}\frac{Q_{eref}}{V_{ed}} \tag{2}$$

where P_{eref} and Q_{eref} are the active and reactive power references, respectively; V_{ed} is the measured line voltage. Through the P/Q calculation and droop control, P_{eref} and Q_{eref} are computed as follows:
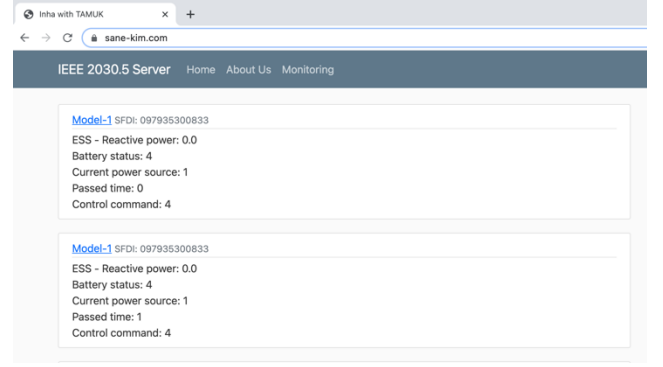

Fig. 5. DERMS cloud server web page.

$$P_{eref} = P_{eref,a} + \Delta P_{edroop} \tag{3}$$

$$Q_{eref} = Q_{eref,a} + \Delta Q_{edroop} \tag{4}$$

$$\Delta P_{edroop} = -\frac{f - f_0}{K_{eP}} \tag{5}$$

$$\Delta Q_{edroop} = -\frac{V - V_0}{K_{eQ}} \tag{6}$$

where ΔP_{edroop} and ΔQ_{edroop} denote variations of P and Q, respectively; f_0 and V_0 are nominal frequency and voltage of the system; f and V are measured frequency and voltage, respectively; and K_{eP} and K_{eQ} are droop coefficients. The output of the inner current control loop is modeled as:

$$V_{ed,ref} = V_{ed} + k_{pi}(I_{ed,ref} - I_{ed}) + \frac{k_{ii}(I_{ed,ref} - I_{ed})}{s} - \omega L_f I_{eq} \tag{7}$$

$$V_{eq,ref} = V_{eq} + k_{pi}(I_{eq,ref} - I_{eq}) + \frac{k_{ii}(I_{eq,ref} - I_{eq})}{s} + \omega L_f I_{ed} \tag{8}$$

where k_{pi} and k_{ii} are parameters of the proportional integral (PI) for the inner current loop; ω is an angular frequency (= $2\pi f$); and L_f is the inductance value of the LC filter.

B. Cyber System Simulation using IEEE 2030.5-2018

A cyber system testbed using IEEE 2030.5-2018 standard consists of DER Gateways (i.e., IEEE 2030.5 client), a router, and a DERMS cloud server (i.e., IEEE 2030.5 server). DER gateways in network layers are implemented by using internet of things (IoT) devices. Each gateway is connected to each component (i.e., WT, PV, ESS) of DER devices simulated by the real-time simulator. The DER client in the DER Gateway receives the DER system data and sends them to the cloud server. Although IEEE 2030.5-2018 standard recommends TLS v1.2 for secure communication. Latest TLS v1.3 also can be used once the cipher suite of TLS v1.3 meets all of the security features of IEEE 2030.5-2018. These cryptographic protocols are designed and implemented using OpenSSL. The Root-CA public key can be provided from third-party CA. It used to validate the certificate chains of communicating devices as part of the TLS handshake process.

Fig. 5. Shows the custom-built DERMS cloud server web page. DERMS server is implemented on a virtual private server. The server runs on Ubuntu 18.04 and uses Apache2 HTTP server project to host the server. Python 3.6.9 and
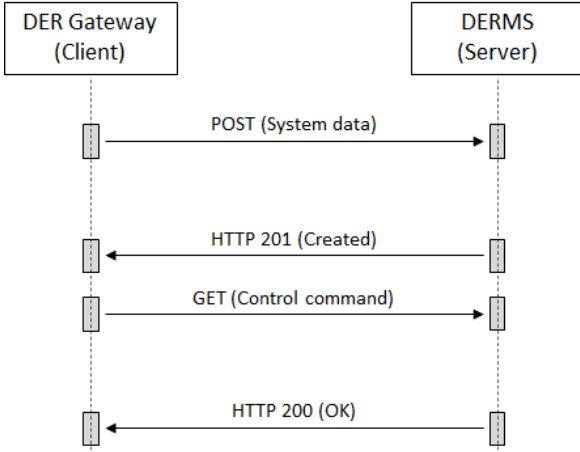
Fig. 6. An example of communication hierarchy using IEEE 2030.5 between DER Gateway and DERMS.

Django REST Framework are used to meet the technical components of IEEE 2030.5-2018 standard as mentioned in section II. In server, real-time DER system data such as reactive power or power factor are stored in local SQLite3 database. Such data are linked with identification data like sfdi (Short-form device identifier). These data are visualized in server as a graph in real time using Python library named pyplot from matplotlib.

C. DER Operation

The IEEE 2030.5 DER clients and the DERMS server perform CSIP operations once the TLS network is established. Server sends control commands to the DER clients such as autonomous function (e.g., vol-var, volt-watt, and freq-watt), immediate control (e.g., active power curtailment, fixed reactive power, and fixed power factor), and protection setting (e.g., high/low voltage ride-through and high/low frequency ride-through). DER clients send system information to the DERMS server such as DER nameplate ratings and settings, DER alarms and status, and DER measurements (e.g., active power, reactive power, voltage, current, power factor, and frequency). Fig. 6 describes an example of IEEE 2030.5 messaging sequence via RESTful commands for XML files when DER Gateway sends DER system data to the DERMS and receives control commands from the DERMS.
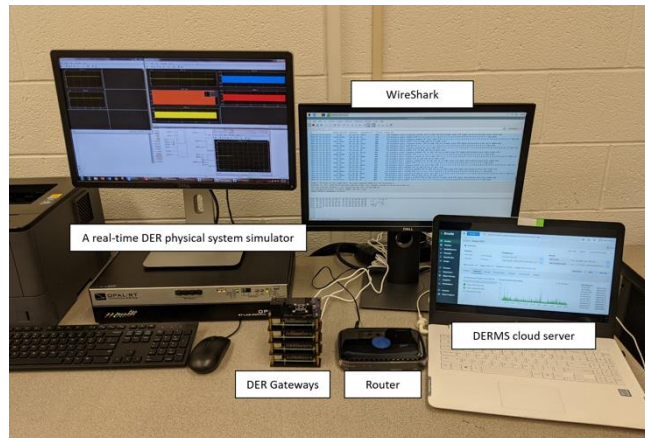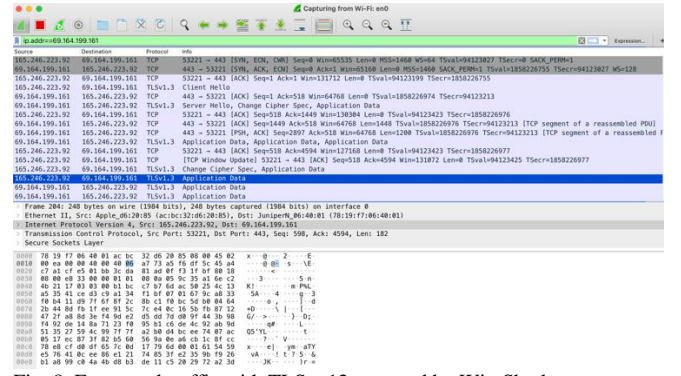

Fig. 7. Experimental setup

Fig. 8. Encrypted traffic with TLS v.13 captured by WireShark.

IV. VALIDATION

Fig. 7 shows the experimental setup to perform experiments to validate the proposed testbed which is described in Section III. To build a real-time DER physical system simulator and gateway OPAL-RT's OP4510 and Raspberry pi 4B are used. A DERMS cloud server is built in cloud provided by Linode [16]. The Root-CA public key is provided by Let's Encrypt [17]. Three test cases are performed: 1) TLS encryption and its performance using Wireshark to monitor in-transit DER network data; 2) real-time DER system data monitoring by DERMS server; 3) and impact of control command provided by DERMS.

DER Gateways (i.e., IP: 165.246.223.92) and DERMS cloud server (i.e., IP: 69.164.199.161) are connected. Fig. 8 shows that the screenshot of the encrypted exchanging data between them by TLS 1.3 in WireShark. We can see all the data is encrypted and just showed as Application Data. Also, it is expected that TLS v1.3 provides fast processing time than TLS v1.2 since the number of round trips has been reduced in TLS v1.3. Fig. 9 shows real-time active power data from PV, WT, ESS with one second sampling rate via DER gateways. It is observed that the server can track real-time DER system data. Fig. 10(a) illustrates reactive power change in ESS shown in the real-time simulator due to a control command provided by DERMS and Fig. 10(b) shows the reactive power data received in DERMS. The control command changing reactive power of ESS from 0 VAR to 0.5 MVAR is received at 5 second, and then the controller of ESS changed the reactive power. The ESS operation change is available in the next sampling period (i.e., one second) in DERMS. Therefore, the proposed testbed can simulate both cyber events and impact of dynamics of DER system using the realistic IEEE 2030.5 standard.

V. CONCLUSION

This paper proposes a real-time hardware-in-the-loop (HIL) DER system testbed using IEEE 2030.5 standard. The proposed testbed provides a hardware-in-the-loop (HIL) simulation for DER using DER system simulator, gateways and DERMS cloud server. The proposed testbed will be used to analyze the complex interactions in a cyber-physical environment with IEEE 2030.5 for studying on cyber-physical DER systems such as optimizing DERMS and defending cyber cyber-attacks. Future works include detailed network performance analysis, adding more optimal control and security functions in DERMS.
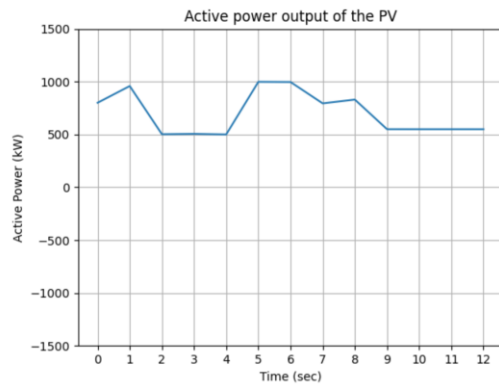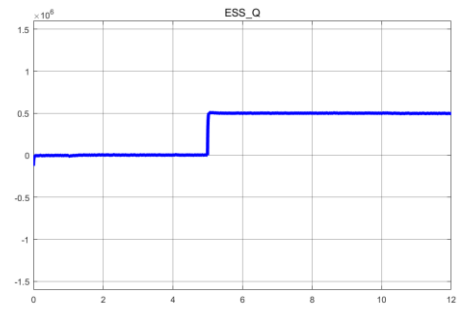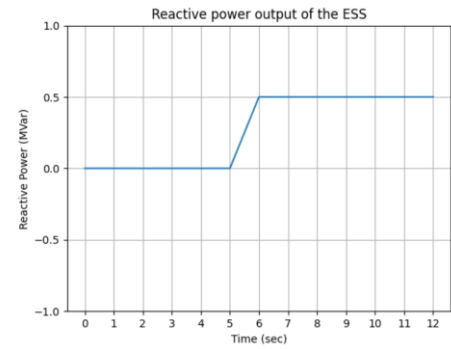
(a)
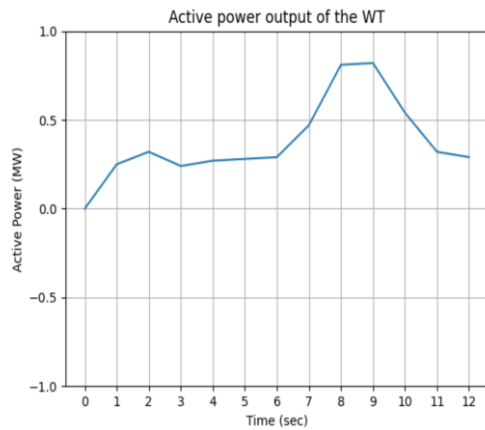
(b)
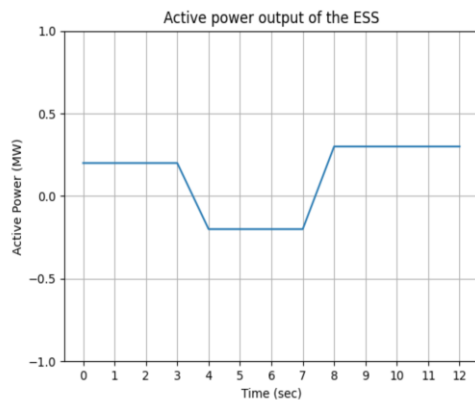
(c)

Fig. 9. Real-time active power data monitoring in DERMS: (a) PV, (b) WT, and (c) ESS.

(a)

(b)

Fig. 10. ESS Reactive power change command sent by DERMS: (a) reactive power change in OPAL-RT and (b) monitoring data in DERMS.

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