Cloud-based DERMS Test Platform Using Real-time Power System Simulation

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***Abstract*—Effective software development of distributed energy resource management systems (DERMS) requires an adequate test environment to facilitate implementation and testing. As the power system with distributed energy resources (DER) is a complex physical system and access to real-world test environments is limited, it is of interest to use real-time simulation for DERMS development. This paper introduces a cloud-based DERMS test platform using an OPAL-RT simulator for hardware-in-the-loop testing. A phasor-domain model of a modified IEEE 34 node test feeder with DER is implemented within ePHASORsim and interfaced through a Modbus connection to an internet-of-things (IoT) solution of KMC Control. The DERMS by Enbala operates on the Amazon cloud and is interfaced to the IoT cloud over a proprietary API. This paper describes the test setup and provides results of a sanity test of the DERMS. In the sanity test, DERs are controlled to avoid reverse power flow at the substation during high DER generation periods. The real-time hardware-in-the-loop test results have verified the basic functionalities and operations of the cloud-based DERMS control platform.**

***Index Terms*—Distributed energy resource management system, real-time simulation, hardware-in-the-loop, IoT cloud.**

I. Introduction

IN modern electricity grids, generation and control are continuously moving towards the grid edge, close to end-customers. Through the integration of increasing numbers of distributed energy resources (DER) within the distribution system (DS), new grid balancing and reliability challenges have emerged. However, DERs also open opportunities for increased controllability and visibility of the power grid [1].

DERs are physical and virtual assets that are installed across the DS, typically close to loads, either on the primary or secondary side of service transformers behind the meter. Typical DERs are solar and wind plants, storage systems, demand response management systems, electric vehicle chargers, etc. DERs can provide grid services individually or in aggregate and enable new ways of grid control and optimization. In order to leverage the grid services of DER and orchestrate their operation across electricity grids, utilities and the industry develop distributed energy resource management systems (DERMS). A DERMS is a software-based solution to allow a distribution system operator to have real-time visibility and control of the distribution grid and its distributed assets to more effectively manage the operation. By the means of a DERMS it is possible to make use of the DERs and use their capabilities such as active and reactive power control to optimize the DS on a system wide basis. The emerging internet-of-things (IoT) technology is suitable to implement cloud-based DERMS as it is capable of seamlessly interact and optimize assets across the entire power grid, which is a significant advantage over local controllers that are only able to sense and control local data. In addition, cloud-based DERMS solutions offer high scalability, computational power and security.

The deployment of a DERMS is not simple as there are several challenges and constraints to overcome: reliability, security and speed of communication channels, cost and financial constraints, regulatory challenges, customer and investor resistance being some of them [2]. Furthermore, DERMS providers need either real test systems or simulators to develop and test their software solutions. Access to real world test systems is limited and additionally, a DERMS managing a real-world test system needs to be mature. Therefore, it is preferred to test a DERMS in a laboratory environment using power grid simulators to facilitate the development and the quality testing of software controllers.

Power grid simulators can be classified into two categories, offline and real-time simulators (RTS) [3], [4]. For testing of control hardware such as a DERMS, RTS are of particular interest. RTS run models of physical systems in synchronism to the real time and enable hardware-in-the loop (HIL) simulations [3], [4]. In HIL simulations, the RTS emulates inputs and outputs of a physical system and provides these signals to external hardware, i.e. a controller. RTS are powerful tools to develop hardware and software that are interfaced with complex physical systems, for example, the power grid.

With the emerging DER in power grids, simulation studies become more and more complex. As DER are typically connected to the grid through power converters with high switching frequencies, the requirements for RTS are demanding. In order to achieve accurate simulation results, simulation time-steps in electro-magnetic transient (EMT) simulations have to be small (within 20-100 us) [5], which requires high computational resources for large power systems.

To speed up the simulation, research has focused on splitting up the power system model on several processors for parallel computation. However, this is not an easy task, because of the latency between processors. For transmission systems, it is possible to separate the grid model at long lines, because they inherently have a certain propagation time. This is not possible in the distribution system where short lines are prevalent. Therefore, multiple solutions have been introduced to split the distribution grids for parallel computation on multiple processors. The use of stublines (a line with a single time-step

978-1-5386-7703-2/18/$31.00 ©2018 IEEE

propagation) [6] and the state-space-nodal (SSN) method [7] enable parallel computation of distribution systems in EMT domain. A different approach is to run simulations in the phasor-domain for evaluation of large-scale power grids, where accuracy down to the waveform level is not required [8]. The phasor-domain solver ePHASORsim by OPAL-RT enables large-scale dynamic and transient stability analysis studies in real-time. In ePHASORsim the power system model is either defined in OPAL-RT's proprietary Excel spreadsheet form, or alternatively a more common description in CYME, PSS/E [9] or OpenDSS [10] can be imported in ePHASORsim.

Aforementioned tools have been used for several real-time studies. In [11], an active distribution network test system for smart grid, control, protection and dynamic studies is implemented using both EMT and SSN simulations without HIL interface. An EMT HIL simulation was used to demonstrate the integration of relays in the smart grid in [12]. A hybrid EMT and phasor-domain simulation was performed to study islanding detection in micrograds with DER in [13]. ePHASORsim was used to implement a real-time state estimation on the transmission system in phasor-domain in [14]. The distribution grid operation was evaluated when advanced metering infrastructure and EV chargers are connected, using a power HIL simulation in [15].

The contribution of this paper is the demonstration of a test platform on a RTS that is interfaced to a cloud-based DERMS. The proposed test platform facilitates development and testing of DERMS software and provides a power system model with high DER penetration for software testing purposes. The setup uses modern hardware (OPAL-RT simulator and an IoT solution) and allows for remote controlled power generation of DERs using standardized communication channels (i.e. Modbus interface and IoT connection).

GridLab-D [16] offers similar real-time simulation capabilities for testing purposes of DERMS software as used in [17]. However, with GridLab-D it is not possible to test the underlying communication system and how latency may affect the control approach. The novelty of this work lies in the use of standardized communication protocols and IoT technology to emulate a near real-world test scenario.

The rest of this paper is organized as follows. Section II describes the DERMS test platform, Section III provides details of the network and the DER models, Section IV presents test scenarios for a sanity test and simulation results, Section V discusses simulation results and presents future work, and Section VI concludes the paper.

II. Description of the DERMS Test Platform

In this work we employ an OPAL-RT simulator with the phasor-domain power flow tool ePHASORsim [8]. ePHASORsim can solve large power grids with up to 20000 buses at time steps of 10ms. In addition, the OPAL-RT system emulates industry-standard communication protocols such as DNP3, Modbus, IEEE C37.118 etc. This facilitates interfacing power grid models with standard-compliant controllers and allows a close-to-real environment to develop and test DERMS.

Fig. 1 provides an overview of the test environment with the RTS being the key element. A power system model is implemented within the RTS using the power flow tool ePHASORsim. Within the RT Simulator DER units and grid telemetry is interfaced with the power system model at different locations. Data for model initialization and for specific load and solar generation profiles is loaded from external files. An operator can control the RTS using a console computer to run and modify simulations as well as visualize and extract simulation results.

The RTS provides standardized communication interfaces using the Sunspec Modbus over TCP/IP protocol [18]. The Modbus map specified by Sunspec has been implemented within the DER models, to allow the control hardware to interact with the DER models the same way as with physical DER devices.

The control hardware used is a cloud-based IoT solution. In the IoT solution, IoT appliances from the KMC Controls Commander IoT suite are directly interfaced to the DER models over Modbus TCP/IP through a LAN connection. The IoT appliances act as gateways to separate the internet from the vulnerable Modbus protocol in the LAN. They provide data of the power system and DER models from the RTS via secure communication channels to the IoT Cloud. The IoT technology from KMC is a modern solution meeting all the requirements for secure and scalable cloud-based IoT automation and control systems. It simplifies the task of communicating with a variety of different devices in a secure way because of its different drivers (i.e. DNP3, CAN, Modbus etc).

Enbala's DERMS called *Symphony* is implemented within the Amazon Cloud and communicates to the IoT Cloud through a proprietary application program interface (API).

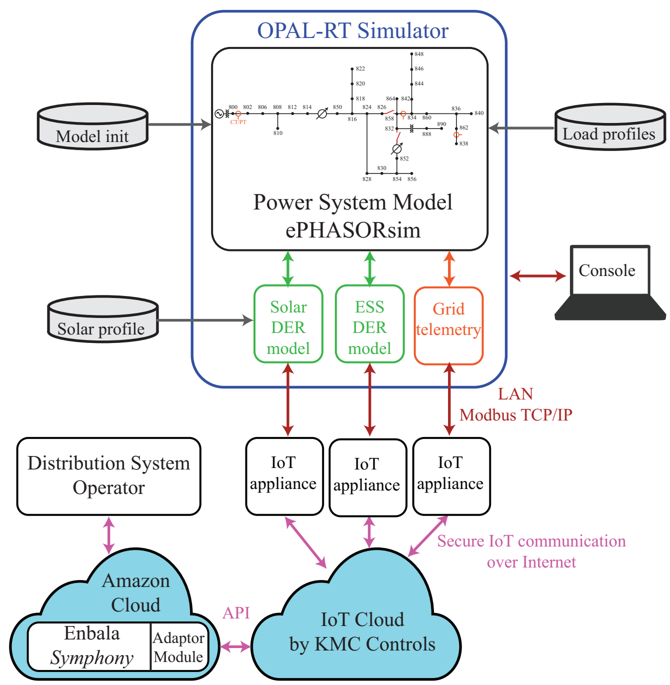

Fig. 1 Overview of cloud-based DERMS test platform

The adaptor module of the DERMS platform includes logic and translation calculations that convert points specific to grid telemetry and DER assets into standardized parameters – for input into the control and optimization module of *Symphony*.

This mapping of points to standardized parameters allows any type or model of grid asset to be connected to the *Symphony* platform. The translations that map the points are built as toolboxes – there are separate toolboxes for different grid assets (e.g. solar inverters, storage systems, capacitors) and toolboxes for different models of devices (e.g. different models/makes of solar inverters). If there are any asset-specific constraints or processes that need to be considered when controlling the asset, the adaptor also allows for custom code for any device.

Once *Symphony* has performed optimization calculations and determined setpoints for each asset, the setpoints are communicated to the adaptor module of each asset and translated into control directives specific to that asset. Often the control of assets is achieved through the manipulation of asset-specific setpoints e.g. rather than overriding the installed logic of a capacitor to alter the switch status, the high and low voltage trip setpoints is adjusted to 'force' the capacitor switch status to change. This ensures safe operation of the asset and allows the asset to operate during a communication outage. The aforementioned setup is a fully closed-loop HIL test platform for a cloud-based DERMS using a modern RTS and state-of-the-art IoT technology for secure and fast communication links.

III. Network and DER Model Description

The power system model (Fig. 2) implemented within the RTS is based on the IEEE 34 node test feeder [19] with several modifications to accommodate the DERMS testing. (1) the system was balanced (single phase drops were modified to 3 phase line sections); (2) a total of 6 DER have been installed on the feeder at the locations of spot loads, whereas 3 energy storage systems (ESS) at buses 830, 844, 890 and 3 solar generation plants at buses 840, 848, 860; (3) 2 switches were implemented between buses 826 and 858 as well as 852 and 832 in order to reconfigure the network model; (4) current and potential transformers have been installed at the sending end of the line between buses 800 to 802 (substation getaway cable), 858 to 834 and 862 to 838 to provide voltage magnitude, current magnitude, real and reactive power telemetry to the DERMS.

To each of the distributed loads, a residential 24h load profile with 1s resolution was added, similarly a commercial load profile was added to the spot loads from real data [20]. A typical generation profile of a clear day with 1 s resolution was added to the solar generation DER from real measurements [21].

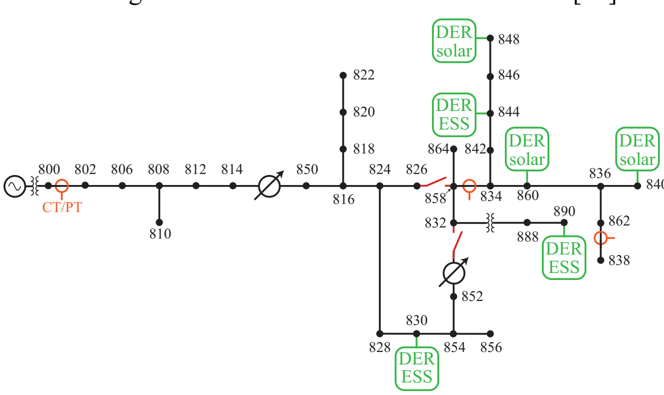

Fig. 2 Power system model implemented within the RTS based on the IEEE 34 node test feeder with a total of 6 DER

A. DER models

Two different types of DER have been modeled within the RTS. Fig. 3a illustrates the model of a solar generation DER. The real power generation (P_{out}) is defined by a normalized solar generation profile, which is multiplied by the maximum power capacity (P_{max}) of the solar DER. The DERMS controls the output power setpoint (P_{set}). The DERMS is capable of curtailing the power output of the DER. However, the power setpoint can only be maintained if there is sufficient solar power available at given time.

The second DER model within the RTS is an ESS (Fig. 3b). Similar to the solar system, the ESS model has a maximum power capacity P_{max}. The output power of the ESS is fully controllable by the DERMS as long as the state of charge (SOC) of the ESS is within 0 and 100%. An integrator tracks the SOC according to equation (1) in percent, where P_{set} is the power setpoint of the ESS and $E_{capacity}$ is the total energy capacity of the ESS. When the ESS is fully charged (SOC=100%) or discharged (SOC=0%), P_{out} drops to 0, as the ESS can no longer supply power when fully discharged or absorb power when fully charged. The SOC can be initialized to a user-defined value at the beginning of the simulation (SOC_{init}).

$$SOC = SOC_{Init} + \frac{\int P_{set} dt}{E_{capacity}} \cdot 100 \quad (1)$$

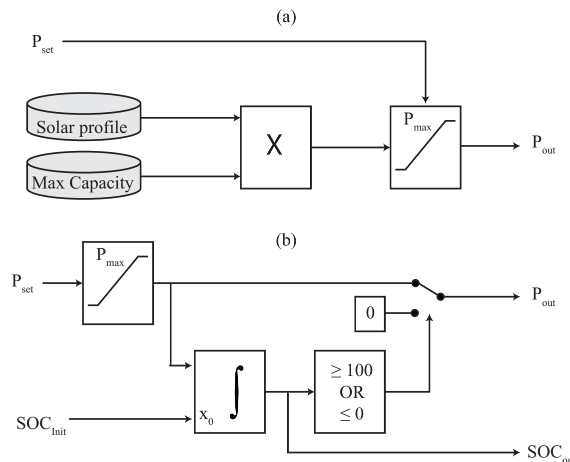

Fig. 3 (a) block diagram of solar DER model
(b) block diagram of ESS DER model

TABLE I. DER Specifications

#	Type	Location	P_{max}	$E_{Capacity}$	SOC_{init}
1	ESS	830	300 kW	1500 kWh	50 %
2	ESS	844	810 kW	2500 kWh	60 %
3	ESS	890	60 kW	200 kWh	50 %
4	Solar	860	300 kW	-	-
5	Solar	840	135 kW	-	-
6	Solar	848	300 kW	-	-

TABLE II. Modbus Register Map According to Sunspec

Address	Name	Type	Units	Description
40067	DA	uint16	-	Modbus device address
40074	AphA	float32	A	Phase A Current
40080	PPVphAB	float32	V	Phase Voltage AB
40092	W	float32	W	AC Power
40134	DERTyp	enum16	-	Type of DER device
40135	WRtg	float32	W	Power output rating
40162	WMax	float32	W	Setting for max power output
40200	ChaState	uint16	%	Current state of charge (SOC)
40098	Var	float32	Var	Q output

Table 1 provides information on the type, power and energy capacity, location and initial SOC of the DER. The DER power ratings represent a 100% penetration case for the IEEE 34 node test feeder in order to create reverse power flow at the substation getaway cable (i.e. total load capacity is equal to total DER power capacity).

Table 2 illustrates the fields of the Sunspec Modbus map that have been integrated within the DER models for interactive observation and control of the DER.

IV. Sanity Test and Simulation Results

In order to verify the operation of the DERMS test platform, sanity tests have been performed. Three different scenarios have been investigated:

1) 24 h scenario with solar generation, without control of DER
2) 24 h scenario with curtailed solar generation to avoid reverse power flow at the substation getaway cable (no control of ESS)
3) 24 h scenario with solar generation and control of ESS to avoid reverse power flow around noon and to reduce the peak demand at the substation getaway cable in the evening

For the scenarios (2) and (3) time-scheduled control commands have been integrated in the DERMS to dispatch the power output of the DERs. The simulation results are shown in Fig. 4 - 6.

In Fig. 4 the base case (test scenario 1) with high solar penetration is presented. Fig. 4a shows the current magnitude at the substation getaway cable (I_{mag_sub}) with a peak current around 7pm. Fig. 4b shows that the high solar power generation of DER 4 – 6 causes significant reverse active power flow at the substation getaway cable around noon, while the substation still supplies positive reactive power to the loads. Fig. 4c shows that there is no participation of the ESS (DER 1 – 3) and Fig. 4d shows the power generation of the solar generation DER 4 – 6.

Fig. 5a illustrates the current magnitude at the substation getaway cable for test scenario 2. The solar generation of DER 4 – 6 has been curtailed by the DERMS around the peak generation hours (Fig. 5d), which results in positive real power flow from the substation throughout the full day (Fig. 5b). There is no participation of the ESS (Fig. 5c).

Fig. 6 illustrates simulation results of test scenario 3 with participation of the ESS (DER 1-3). With a scheduled charge/discharge pattern of the ESS (Fig. 6c), it is possible to reduce the range of the current magnitude at the substation significantly (Fig. 6a) and avoid reverse active power flow (Fig. 6b). The solar generation has not been curtailed (Fig. 6d) in test scenario 3.

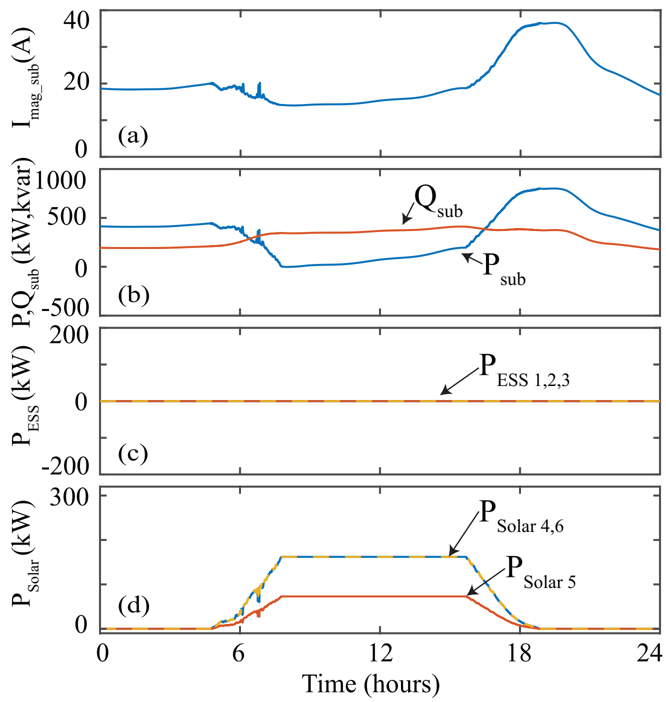

Fig. 5 Simulation results test scenario (2)

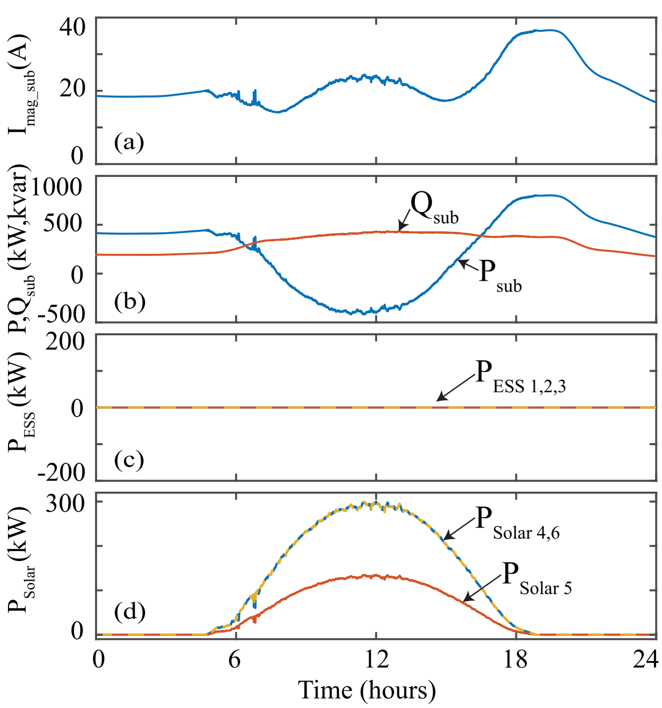

Fig. 4 Simulation results test scenario (1)

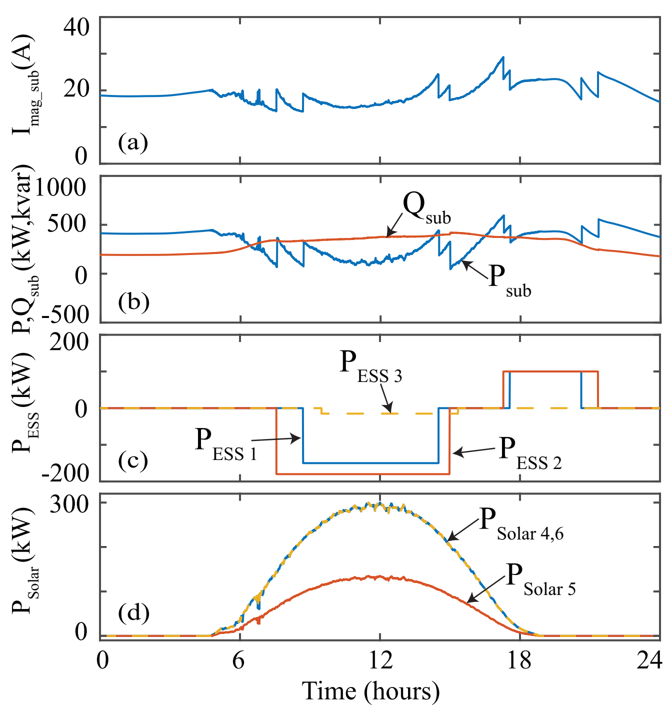

Fig. 6 Simulation results test scenario (3)

V. Discussion and Future Work

The simulation results verify that the cloud-based DERMS was able to dispatch control actions to DER models within a RTS for active power management at the substation getaway cable of a test feeder. Control records go through several interfaces from the DERMS cloud before reaching the DER asset. It was evaluated that the latency from dispatching a control record in the cloud to reaching the DER model is around 2 seconds. According to [22], control intervals for DER should be within 15 seconds in order to mitigate effects of highly variable renewable generation. For active power management, the setup with a centralized DERMS managing a number of distributed assets seems suitable. However, for volt-var optimization with continuous reactive power control of DERs, distributed controllers may have to be installed at DER locations to achieve faster local response of DERs.

The simulation environment additionally enables studies that are difficult to execute in the real-world. With the setup, failures of any equipment can be studied without consequences and cost. Specifically, our future studies will investigate the requirements for communication channels of a DERMS for both active and reactive power management of DERs. With the RTS, weak communication channels can be simulated by introducing artificial latency or total loss of specific connections. This will provide valuable information for future development and design of suitable hardware and control mechanisms for DERMS.

Furthermore, with the use of ePHASORsim, large-scale power grids with transmission and distribution systems at different voltage levels can easily be modeled. With the test platform, it will be possible to study the impact and benefit of a DERMS and the grid services of DERs to the transmission systems. In addition, it is also feasible to introduce service transformers in the power system model and consider residential DERs that are connected to the low voltage side.

VI. Conclusion

A fully closed-loop HIL test platform for a cloud-based DERMS using a modern RTS and state-of-the-art IoT technology with secure and fast communication links was implemented. The test environment enables the DERMS to connect to DER models over standardized interfaces (i.e. Modbus). Sanity tests have shown that the cloud-based DERMS successfully dispatched controls to DER in order to perform active power management in the IEEE 34 node test feeder to mitigate reverse power flow due to high DER generation and reduce peak demand by charging energy storage systems appropriately. The test platform facilitates the development and quality testing of DERMS software by providing a laboratory environment and enables interesting studies for future research.

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