Modbus TCP/IP Based BESS Plant Controller Operations for a Peak Shaving Application

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***Abstract*—Battery energy storage systems (BESS) coupled with vendor plant controller and reliable communication can provide practical peak shaving solutions to the utility grid. This can be achieved by incorporating day-ahead charge/discharge set-point evaluation strategies in the BESS plant controller. This paper implements a simple peak shaving strategy in the real-time hardware-in-the-loop laboratory testbed and open platform (HILLTOP), detailing the integration process for the BESS inverter, plant controller, and conventional Modbus TCP/IP communication protocol. Also, the potential compatibility of the TCP/IP-based BESS plant information and control signals with the IEC 61850 communication standard has been investigated.**

***Index Terms*—BESS, plant controller, control hardware-in-the-loop, Modbus TCP/IP, peak shaving**

I. Introduction

WITH the rising utilization of utility-scale battery energy storage systems (BESS) in the grid, the operation and control strategy of the BESS plant becomes important. Frequent charge and discharge cycles, coupled with inappropriate upper and lower limits of the state of charge (SoC), may significantly diminish BESS lifespan [1]. Proper charge/discharge set-points need to be communicated to the BESS inverter from the BESS plant controller. Many studies have utilized vendor plant controllers for specific power plant control applications. In [2], virtual inertia is incorporated into a BESS plant secondary controller to improve the system stability. Authors in [3] use an SEL real-time automation controller (RTAC) for sending the commands to control and protective relays in an IEEE-33 bus system, whereas the BESS plant's charge/discharge strategy is established through conditioning set-points according to a hierarchical approach. In [4], droop-based voltage control scheme is implemented in a vendor plant controller, so that the PV and BESS plants can participate in Volt-VAr ancillary services. The impact of effective plant-level controls on system stability has also been investigated.

Conventional offline power system simulations do not include any communication network for information and control signal flow between interacting components of a BESS power plant. Integrating a hardware-in-the-loop (HIL) environment enables testing and validation under realistic conditions without the risks associated with direct grid interaction and ensures interoperability between various devices through an industry proven communication protocol, e.g., Modbus TCP/IP and Sunspec Modbus TCP/IP. The HIL testing involves connecting a physical device or controller to a real-time simulator, allowing engineers to evaluate performance under realistic conditions. This allows early identification of flaws, testing under extreme grid conditions, reducing risks and costs, and accelerating the validation process [5]. In this work, a Hardware-In-the-Loop Laboratory Testbed and Open Platform (HILLTOP) [6] is utilized to deploy a simple and effective peak shaving strategy for a BESS power plant. HILLTOP comes with TCP/IP-based communication infrastructure that enables interaction between the BESS plant components, i.e., an EPC Power hardware inverter controller, SEL RTAC plant controller, and the Typhoon HIL simulation environment.

As the electricity demand continues to increase, utilities face challenges in managing time-varying peak load demands, which often result in strain on the grid, potential resource inadequacy, and higher operational costs. The HILLTOP can be utilized to mitigate this problem based on developing a BESS plant control scheme according to the day-ahead load profile. For the real-time peak-shaving operation of the plant model, two straightforward algorithms have been deployed. The first algorithm applies the energy balance concept, considering a day-ahead utility load profile and BESS plant SoC operation limits, to determine the plant charge/discharge power set-points during off-peak/on-peak hours. This is essential for performing peak shaving effectively. The second algorithm incorporates the obtained set-points from the first stage into the

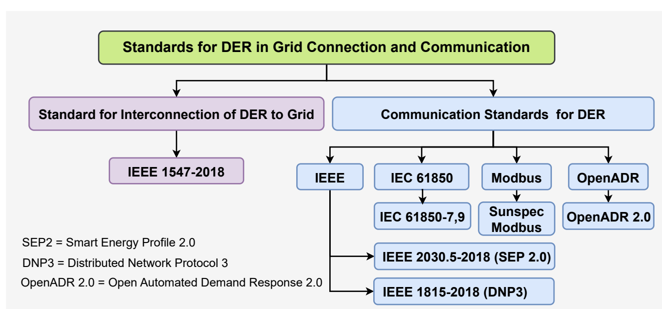

Fig. 1. Most relevant standards for integration and communication of distributed energy resources (DER)

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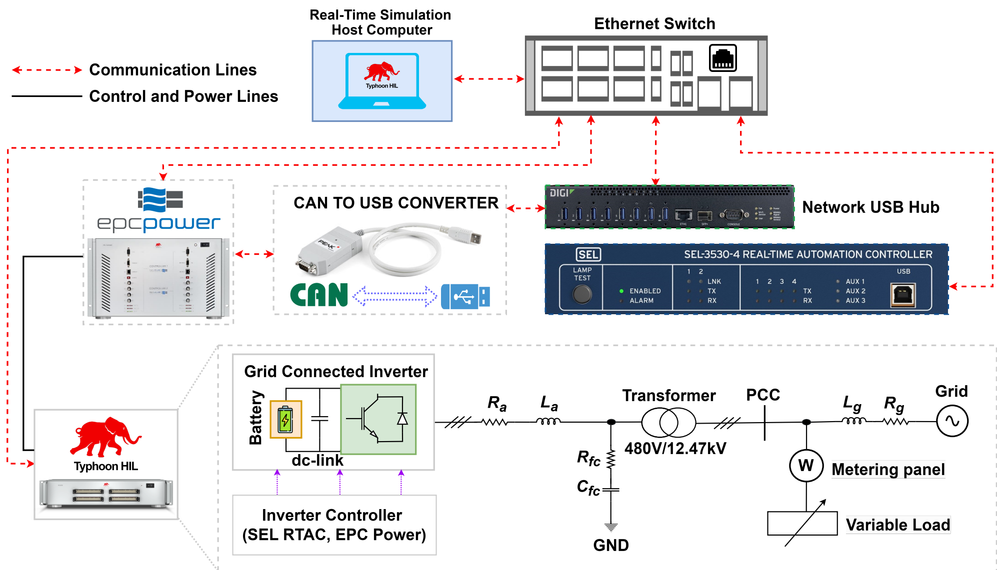

Fig. 2. Conceptual configuration for the Real-Time HIL Testbed using Typhoon HIL-606, SEL RTAC 3530-4, EPC Power Inverter Controller, and Modbus TCP/IP Communication

SEL RTAC plant controller for performing HILLTOP-based peak-shaving simulation while evaluating the seamless integration of various components and communication protocols.

There are several established standards to comply with on grid connection and communication aspects for integrating DER [7], which are shown in Fig. 1. Modbus TCP/IP is used in this research as the communication interface due to its simplicity, reliability, and compatibility with Typhoon HIL, vendor inverter power controllers, and RTAC by ensuring efficient data exchange and control in an embedded energy management environment.

Modbus TCP/IP, which is a widely used technology for industrial devices communication, inherently lacks encryption and authentication mechanisms. This makes it susceptible to various cyber vulnerabilities [8]. Therefore, mapping and checking the compatibility of the system with the more secure IEC 61850 standard communication protocol (which supports encryption and authentication features [9]) is part of this work.

The two main contributions of this work are outlined as:

- The demonstration of a HILLTOP-based solution to ensure realistic and seamless operation through Modbus TCP/IP communication and mapping compatibility with the IEC 61850 standard.
- The detailed implementation of a simple and effective peak shaving approach into the BESS plant controller of HILLTOP for energy balance and power set-points calculations for utility peak shaving and battery charging, along with performance validation in real-time HIL.

The remainder of the paper is organized as follows: Section II provides a detailed description of the system along with the research methodology. Section III presents the results of peak shaving using experimental validation based on case studies around different seasons of the year. Section IV has conclusions and future recommendations.

TABLE I
BESS PLANT POWER CIRCUIT PARAMETERS IN TYPHOON HIL

Description	Parameter	Value	Unit
Battery Capacity	E_{batt}	17	MWh
Nominal Voltage of Battery	$V_{\text{nom-batt}}$	1.00	kV
Capacity at Nominal Voltage	$E_{\text{nom-batt}}$	93.50	%
SoC Limit of the Battery	SoC_{limit}	10 – 97	%
Inverter Capacity	S_{inv}	9.125	MVA
Nominal Voltage of Inverter	$V_{\text{nom-inv}}$	0.480	kV
Switching Frequency	f_s	2.50	kHz
Nominal Frequency	f_{nom}	60	Hz
Nominal Load	$S_{\text{load-nom}}$	27	MVA

II. System Description

The real-time HILLTOP-based platform utilized the following key components and provided a scalable model for future enhancements in grid-tied BESS applications, allowing for increased integration of renewable energy sources. The complete block diagram of the overall system is shown in Fig. 2. It represents a real-time HIL testing setup involving a combination of Typhoon HIL 606 [10], SEL RTAC 3530-4 [11], an EPC Power inverter controller (blue card) [12], and a Modbus TCP/IP communication to facilitate a grid-connected inverter for BESS to perform peak shaving. Table I shows the parameters of the BESS inverter, and filtering components used in the schematic of the Typhoon HIL control center.

Real-Time Simulator: The Typhoon HIL device hosts the primary simulation environment, enabling the testing of the BESS plant's cyber-physical framework under various grid conditions. Typhoon HIL is capable of high-fidelity simulations for grid modeling applications and supports most communication protocols commonly used in power systems.

Real-Time Automation Controller (RTAC): The RTAC controller is the central real-time control unit, interfacing directly with the Typhoon HIL and EPC Power inverter controllers. The SEL RTAC 3530-4 offers rapid processing capabilities that allow it to manage the flow of power set-points between the simulated grid, the BESS plant, and other control elements that enable real-time adjustments to the BESS output based on the simulated grid's status. Furthermore, the SEL RTAC natively supports a wide variety of communication protocols.

Commercial-off-the-Shelf Inverter Power Controller: In a grid-tied system, the role of the inverter is important as it is used to convert the stored energy in the BESS plant into AC power that can be fed back into the grid. The EPC Power inverter controller device is used to control a vendor provided and validated inverter model in Typhoon HIL to ensure the conversion is both efficient and responsive to changes based on the BESS plant control commands from RTAC, thus supporting rapid adjustments during peak load periods. The EPC Power inverter controllers support communications and controls over SunSpec Modbus and CAN bus.

BESS Plant Control Strategies: The plant control strategy is designed to provide an understanding of the system dynamics by integrating multiple components for real-time simulation, testing, and control. A host computer runs simulation models and interfaces with other devices in the setup, serving as the core of the simulation environment. The Typhoon HIL is employed for the safe testing of the inverter controllers and simulated grid models, emulating grid conditions and loads to evaluate plant control strategies in real-time. The SEL RTAC 3530-4 controller used the calculated set-points from the developed algorithm for battery charging/discharging. Then, the EPC Power inverter controller facilitated power dispatch based on those set-points, allowing energy dispatch from the BESS plant to the grid. In addition, a metering panel measures the voltage and current in the system, ensuring accurate monitoring and control of electrical parameters essential to overall plant control and operation. The BESS plant energy management is described within algorithms 1, and 2, respectively. The algorithm 1 solves the energy balance equations based on the day-ahead load profile and determines appropriate set-points, whereas algorithm 2 utilizes these set-points to charge and discharge the BESS plant to fill the valley and shave the peak load demands effectively.

Configuring Modbus TCP/IP Communication: For reliable data exchange between the different components, the testbed platform utilizes the Modbus TCP/IP communication protocol, commonly used in industrial and power system applications. The overall BESS plant communication process involved different components such as Typhoon HIL Control Center (Schematic and HIL SCADA), HIL 606 device, SEL RTAC 3530-4, EPC Power inverter controller. All of them are connected via the Modbus TCP communication protocol to transmit and receive information, power set-point commands, and other associated parameters. A CAN to USB converter and USB switch enable cross-device communication, while an ethernet switch ensures network connectivity between the host computer, SEL RTAC, and other components [6]. The host computer sends commands to the Typhoon HIL, and RTAC, configured as a Modbus master, polls information from the components for real-time measurements. The control strategy of the EPC Power inverter controller is guided by the RTAC's commands, aligning the power flow based on load demand.

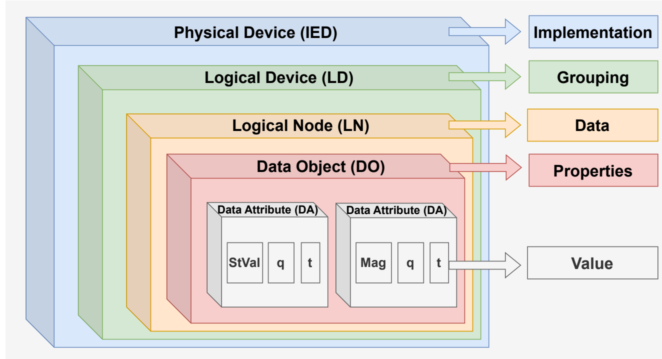

Fig. 3. IEC 61850 data model hierarchy of physical devices (IED), logical devices (LD), logical nodes (LN), data objects (DO), and data attributes (DA)

Mapping Compatibility of BESS Plant with IEC 61850 Standard: IEC 61850 is an important standard used in substation automation systems (SAS), enabling efficient monitoring, control, and protection of electrical grids. It ensures communication between Intelligent Electronic Devices (IEDs) for real-time operation. This standard is a cornerstone for the integration and operation of BESS in modern power grids. Its importance lies in its ability to standardize communication protocols, ensuring seamless interaction between different components such as inverters, controllers, and other devices, regardless of manufacturer [13].

IEC/TR 61850-90-7 is a standard that outlines the functions of DERs such as BESS. For the integration of BESS, information models based on IEC 61850-7-420 are addressed in the standard document IEC/TR 61850-90-8 [14]. The information model hierarchy of the IEC 61850 standard can be categorized into five types [15] such as physical devices (IED), logical devices (LD), logical nodes (LN), data objects (DO), and data attributes (DA), as shown in Fig. 3. As in [16], the logical nodes and IED configurations of the BESS plant are shown in Table II and Fig. 4, respectively. The logical nodes and their functions are checked and compared with the current BESS plant. The unavailable information is marked as gray-colored text. The IEDs available in the plant are used for measurement, control, and protection. The measurement IEDs receive voltage and current data from the Potential Transformer (PT) and Current Transformer (CT) to monitor the system. Information from IEDs helps to manage the charging and discharging of the battery, controls the power flow through the switch, and ensures system protection with functions such as overcurrent and overvoltage protection. Communication with other devices and systems is facilitated through various communication channels, allowing the control of the BESS plant.

The IEC 61850 standard also supports generic object-oriented substation event (GOOSE) messaging and sampled values (SV), which provide high-speed and reliable communication. These features are important for substation automation,

TABLE II
LIST OF LOGICAL NODE CLASSES RELATED TO BESS PLANT ACCORDING TO IEC 61850 STANDARD AND COMPARISON WITH THE BESS PLANT

LN Group	Name	Description	Information from the BESS Plant
Power System Equipment	ZINV	Inverter	Inverter (Typhoon HIL) and Inverter controller (EPC Power)
	ZBAT	Battery Systems	Battery (Typhoon HIL)
	ZBTC	Battery Charger	Bidirectional inverter (Typhoon HIL)
	ZRTC	Rectifier	—
Transformer	TCTR	Current Transformer	Current measurement (Software device)
	TVTR	Voltage Transformer	Voltage measurement (Software device)
Metering and Measurement	MMXU	Measurement	Three-phase meter (Typhoon HIL)
	MMET	Provides meteorological information	—
	MPRS	Pressure Measurement	—
Switchgear	XCBR	Circuit Breakers	Three-phase single-throw contactor (Typhoon HIL)
	CSWI	Switch Controller	Function block (SEL RTAC 3530-4)
Decentralized Energy Resources	DOPM	Mode at Electrical Connection Point (ECP)	Grid Following Mode (EPC Power)
	DOPA	DER operational authority at ECP	Distribution System Operator–DSO (Typhoon HIL)
	DPST	Provides status information at the ECP	Status in the BESS Connection Point (Typhoon HIL)
	DCCT	Economic dispatch parameters	Associated with BESS for economic operation (Typhoon HIL)
	DRCT	DER controller characteristics	Battery storage control based on Algorithm 1 (Typhoon HIL)
	DSCH	Provides DER energy schedule	Energy dispatch schedule based on Algorithm 2 (Typhoon HIL)
	DRCS	Control status of DER	Active, Idle, and Fault mode (Typhoon HIL)
	DRCC	Supervisory control of DER	Plant Controller (SEL RTAC 3530.4)
	DRAT	Provides generator ratings	Rating of BESS Plant (Typhoon HIL)
	DCST	Provide Operating Cost of Generator	Charged BESS at off-peak Tariff rate (From Utility Tariff)
	DGEN	State of DER Generator	Operational State of BESS (EPC Power and Typhoon HIL)
Protection	PTOC	Time Over Current	DC and AC over-current (EPC Power, Typhoon HIL)
	PTUV	Time Under Voltage	DC and AC under-voltage (EPC Power, Typhoon HIL)
	PIOC	Instantaneous Over Current	Instantaneous Overcurrent – OC50 (EPC Power, Typhoon HIL)
	PTOV	Time Over Voltage	DC and AC over-voltage (EPC Power, Typhoon HIL)
	PHIZ	Thermal Overload	Overtemp protection (EPC Power)

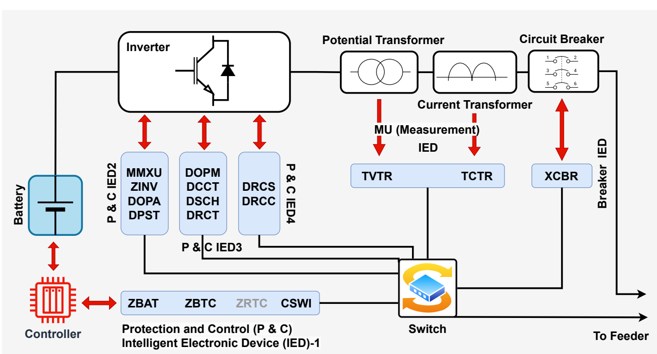

Fig. 4. An IED Configuration for the BESS plant according to IEC 61850 standard for protection, control, and measurement

which requires fast data exchange between the simulation platforms for real-time decision-making. IEC 61850 also allows scalability for future grid expansions or modifications, which is useful in BESS-based peak shaving, where systems may need to adapt to varying grid loads.

Determining the Set-points and Algorithms for Utility's Peak Load Shaving: The algorithm is written based on energy balance calculations to find the appropriate battery charging and discharging set-points for the peak shaving of the utility demand, which is written in Python code, and its pseudo-code is shown in algorithm 1. To determine the appropriate set-points for battery charging and discharging for shaving peak load demand, the following Eq. 1 of energy balance is considered along with constraints in Eqs. 2 and 3, respectively:

$$\sum_{t=0}^{T=24} |P_{\text{set-point}} - P_{\text{load},t}| \cdot \Delta t = E_{\text{batt}} \tag{1}$$

where, $P_{\text{set-point}} = x\% \times S_{\text{base}} \times PF$; variable x is the unknown set-point to be calculated by solving Eq. 1, S_{base} is the maximum load in MVA, PF is the power factor, $P_{\text{load},t}$ is the day-ahead load profile corresponding to a time interval of $\Delta t = 30$ min.

The charging set-point of the battery during off-peak hours ($P^{\text{charging}}_{\text{set-point}}$) is subject to the following constraints:

$$P^{\text{off-peak}}_{\text{load},t} \leq P^{\text{charging}}_{\text{set-point}} \quad \text{and} \quad P^{\text{charging}}_{\text{set-point}} \leq (P^{\max}_{\text{load}})_{\text{off-peak}} \tag{2}$$

The discharging set-point of the battery for utility peak shaving ($P^{\text{utility}}_{\text{set-point}}$) during peak is subject to the following constraints:

$$P^{\text{utility}}_{\text{set-point}} < (P^{\max}_{\text{load}})_{\text{on-peak}} \quad \text{and} \quad P^{\text{utility}}_{\text{set-point}} > (P^{\min}_{\text{load}})_{\text{on-peak}} \tag{3}$$

where, $P^{\text{off-peak}}_{\text{load},t}$ is the off-peak load at time t with granularity of 30 min interval, $(P^{\max}_{\text{load}})_{\text{off-peak}}$ is the maximum load demand at off-peak hours, $(P^{\max}_{\text{load}})_{\text{on-peak}}$ is the highest load demand during peak hours, and $(P^{\min}_{\text{load}})_{\text{on-peak}}$ is minimum demand at

Algorithm 1 Battery Energy Management Algorithm

Initialize: $SoC_{\text{init}}, SoC_{\text{target}}, E_{\text{batt}}, S_{\text{base}}, PF$
Load Data Initialization
Conversion of normalized load data into actual value
Calculation of the energy required to charge battery:
Required Energy: $E_{\text{batt}} \leftarrow (SoC_{\text{target}} - SoC_{\text{init}}) \times E_{\text{batt}}$
Function to calculate the set-points:
function calculate_power_set_point(x)
    return $0.01x \times S_{\text{base}} \times PF$
Determine utility peak shaving set-point in peak hours:
function calculate_lhs(x)
    Solve Eq. 1 with constraints in Eq. 3
    return Energy from left hand side (lhs) of Eq. 1 (E_{batt})
for $x \in$ range(lower_limit, upper_limit) **do**
    lhs_value $\leftarrow$ calculate_lhs(x)
    if $|$lhs_value $- E_{\text{batt}}| <$ min_diff **then**
        closest_x_value $\leftarrow x$
        min_diff $\leftarrow |$lhs_value $- E_{\text{batt}}|$
    end if
end for
Similarly, determine charging set-point at off-peak hours
Return Utility Peak Shaving & Batt. Charging set-point

peak hours. Eq. 1 represents the energy balance equations for the system with the BESS plant and grid. The summation condition is the absolute sum of difference between power set-points, and time-varying day-ahead load demand corresponding to constraints in Eqs. 2 and 3 during off-peak and peak hours, respectively. At off-peak hour operation, the total load demand with BESS plant charging power should not exceed the highest load demand, while during peak hours, load demand is minimized by supplying power from the BESS plant and hence should not exceed the utility peak shaving set-points. After solving Eq. 1, the set point can be used to control the charging rate of the battery subject to the constraint in Eq. 2; that is, when the load is equal to $x\%$ or less, the system will charge the battery. By solving Eq. 1 with subject to the constraint in Eq. 3, the set-point is used to discharge the BESS plant and shave the load during peak hours of operation.

The second algorithm is used to reduce the maximum load demand using the BESS plant and is illustrated as the pseudo-code in algorithm 2. It is also utilized by using Python program in the macro widget of the Typhoon HIL SCADA panel and the structured text program in SEL RTAC for peak shaving. The power set-points for utility peak shaving and BESS plant charging are both determined based on the solution of algorithm 1. Those set-points are used in algorithm 2 through the SEL RTAC controller, EPC Power inverter controller, and Typhoon HIL SCADA for peak shaving operation.

III. Results and Discussion

This section presents simulation results demonstrating the effectiveness of implementing the two proposed algorithms for peak load shaving. The case study uses a demand profile representative of the worst days for winter and summer. The

Algorithm 2 BESS Plant Control Algorithm for Peak Shaving

Initialize the load profile and update iteration every min
Update load profile every 30 minutes for 24 hours
Set load input (Load.P, Load.Q) and read battery SOC
Utility and charging set-points from Algorithm 1
if SoC $<$ SoC_{min} OR SoC $>$ SoC_{max} **then**
    Turn off battery
else
    if $P_{\text{Valley\_point}} \leq P_{\text{Load}} \leq P_{\text{Charging\_point}}$ **then**
        Turn on the battery for charging
    else
        Turn off battery
    end if
    if $\text{SoC}_{\text{min}} \leq \text{SoC} \leq \text{SoC}_{\text{max}}$ **then**
        if $P_{\text{Utility\_set\_point}} \leq P_{\text{Load}} \leq P_{\text{Load,max}}$ **then**
            Turn on the battery for discharging
        end if
    end if
end if

discussion is added based on the outcomes, and the overall findings are summarized.

Fig. 5 shows results during a typical cold day in winter. The BESS plant supplies power to the grid at peak hours (3 am - 10 am) and charges from the grid during off-peak hours (1 pm - 8 pm). The BESS plant supplies 12.05 MWh to shave the system peak load demand. The load profile in summer is different compared to winter. Fig. 6 shows that the BESS plant is initially charged from the grid during off-peak hours (2 am - 10 am), and supplies 11.04 MWh to the grid during peak hours (2 pm - 9 pm) reducing peak load levels.

Table III presents the results of the HIL simulation to

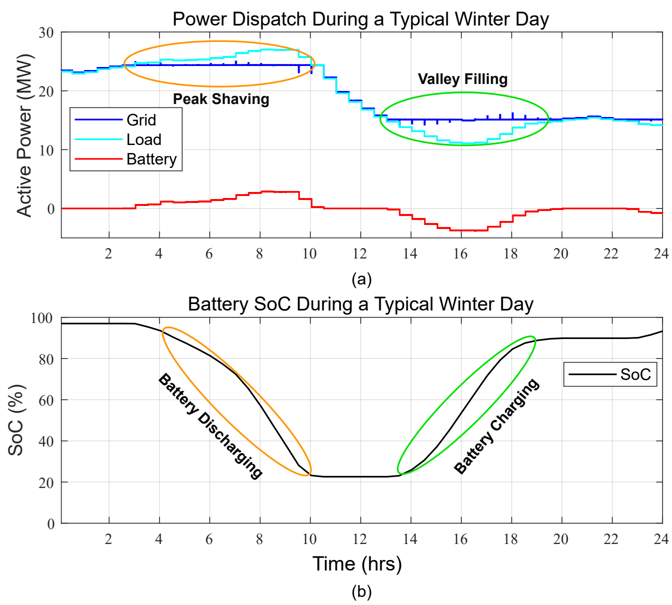

Fig. 5. Active power dispatch during a clear sky day in Winter: (a) P_{grid}, P_{BESS}, and P_{load}, (b) BESS SoC

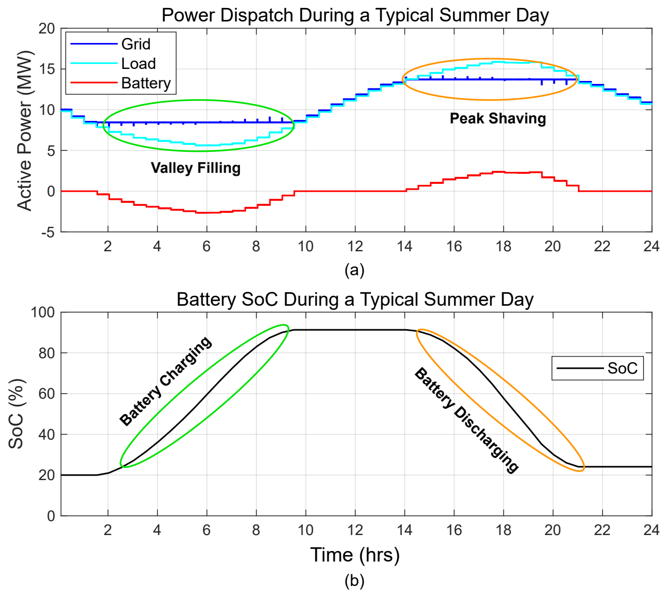

Fig. 6. Active power dispatch during a clear sky day in Summer: (a) P_{grid}, P_{BESS}, and P_{load}, (b) BESS SoC

TABLE III
BESS PLANT PEAK-SHAVING ECONOMIC EVALUATION FOR HILLTOP IN A SELECTED DATE FOR TWO DIFFERENT SEASONS

Season	Peak Shaving Performance Using BESS Plant		
	Energy Supplied [MWh]	**Peak Demand Reduced [%]**	**Amount Saved [$]**
Winter	12.05	7.42	124.77
Summer	11.04	10.98	196.81

monitor the effectiveness of the BESS plant controller at peak shaving tasks through different seasons of the year. The performance parameters are energy supplied by the BESS plant during peak hours in MWh, the percentage of peak demand reduced due to integrating the BESS plant, and the amount of dollar savings due to the peak shaving in a 24-hours period in two different seasons. The result shows that the BESS plant is charged during the off-peak hours to fill the valley and is discharged during the peak hours to shave the peak load demand. This effort reduced the maximum load demand by 10.98% on a summer day and 7.42% on a winter day. Although the energy supplied per day by the BESS in summer is less than that in winter, the estimated utility savings are more due to different seasonal tariff rates during the peak and off-peak hours. Overall, the BESS plant effectively reduced peak demand through all seasons, with highest financial savings on a summer day due to the varying tariff rates.

IV. CONCLUSION

This study presents a BESS plant controller design by utilizing HILLTOP to evaluate the performance of a BESS plant in a utility peak shaving mode. The HILLTOP integrated a Typhoon HIL device for simulating grid conditions, a SEL RTAC as the plant controller, and an EPC Power hardware inverter controller, all communicating via Modbus TCP/IP protocol. The mapping of the current BESS plant communication with the IEC 61850 standard suggests compatibility between the two. This setup facilitated validating the BESS plant peak-shaving control strategy under different operating scenarios, including peak demand periods characteristic of different seasons. A seamless communication between all associated devices for real-time data/information transmission and receiving, along with power signals/set-points is demonstrated. Results demonstrated the effectiveness of the BESS in reducing peak load, highlighting the capability of the real-time HIL testbed to simulate realistic grid conditions and evaluate BESS performance. The results show a reduction of peak load demand of 7.42% and 10.98% in the winter and summer seasons, respectively. In future work, the implementation of the IEC 61850 standard will be addressed in HILLTOP.

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