Power Hardware-in-Loop Simulation of Grid-connected Battery Systems with Reactive Power Control Capability

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***Abstract*—This paper provides a detailed description of developing a power hardware-in-loop (P-HIL) testbed for the simulation and testing of grid-connected battery systems. The test allows not only analyzing the impact of operating grid-tied batteries on the power grid, but also analyzing less addressed battery operational issues, such as temperature, balance, age, and premature capacity loss, as well as the four quadrant energy storage inverter operation. The testbed architecture, hardware components, software systems, communications, and computer controls are explained. P-HIL model validation is provided for both static and dynamic test cases. The applications and benefits of the developed testbed are investigated to study battery characteristics during charge and discharge cycles, individual cell characteristics and cell imbalance, and impact on the power grid.**

***Keywords*: Testbed, power hardware-in-loop simulation, battery energy storage, active power control, reactive power control, grid-tied operation management, dynamic response.**

I. INTRODUCTION

The analysis of distribution system operation with the presence of distributed energy resources (DERs), often suffers from the lack of accurate models with enough details for such resources. The accurate modeling of battery energy storage systems is particularly challenging, as their response is dependent on the inverter characteristics and the controls applied, as well as to the battery cells and their dynamics.

To overcome this shortcoming, the power hardware-in-loop (P-HIL) modeling approach is often utilized by constructing a hardware-software simulation testbed that includes one or more power elements embedded to the numerical models through actual physical prototype or true-scale hardware.

P-HIL modeling and analysis have already been utilized for addressing a range of issues across the distribution grids. For example, in [1], [2], real time simulations are used to study and validate control systems for microgrids. Other studies focus on the power hardware, such as in [3]. In [4], a solar inverter is interfaced with a real time distribution grid simulator to study the characteristics and impacts of distributed PV systems. In [5], a wind turbine is tested in a P-HIL simulation.

P-HIL modeling of grid-connected battery energy storage systems allows us to accurately analyze and capture several features that would be very difficult to see with numerical modeling. However, the battery P-HIL test systems that are developed so far have focused mainly on the electric vehicle (EV) applications [6], [7]. In an EV, the battery is tightly regulated and controlled since it must provide high performance and power density to be useful in a vehicle. In contrast, in this paper, we focus on developing P-HIL modeling tools and analysis of larger grid-connected stationary battery storage systems, which are more flexible and have the potential to be used longer. In [8], an energy storage system is tested in an P-HIL simulator, to implement active power control, i.e., charge and discharge scheduling, to help regulate voltage in a distribution grid with high PV penetration. However, in [8] the focus is not on the battery operational issues such as temperature, balance, age, and premature capacity loss, or on four quadrant energy storage inverter operation.

Fig. 1. The power hardware in loop (P-HIL) testbed for the grid-connected battery storage system using RTDS Simulator and lab-scale battery cells.

The P-HIL testbed that we developed in this paper, shown in Fig. 1, realizes a battery system with both active and reactive power capability and provides several key advantages for testing and analysis. In particular, it enables the tracking of various operational issues of the battery cells, such as:

- The effects of charge and discharge cycling on battery cells, battery packs, and on the entire system.
- The interactions of the battery management system with the cells and inverter and related operational issues.
- The effects of reactive support on the inverter and battery such as ripple current, temperature, operating voltage, etc.

II. TEST SETUP

A. Testbed Overview

We aim to develop a P-HIL simulation testbed, that allows *dynamic modeling* of a grid-tied four-quadrant battery system, i.e., a battery-inverter system with both active and reactive power control capability, which operates connected to a distribution feeder. Our test setup has four main components:

- The distribution feeder and the related elements;
- A four-quadrant inverter serving as the interface between the battery storage system on the DC side and the distribution grid on the AC side;

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- A battery pack consisting of multiple battery cells, a battery management system (BMS), and accessories;
- A manager computing unit with optimization software, for optimizing battery system operation.

These four components are then connected to a real-time power system simulation such as RTDS [9] or Opal-RT [10]. In this work, we use RTDS for distribution feeder simulation.

A key challenge to establishing a complete P-HIL testbed set-up is the effective interconnection of the hardware components and the simulation environment so that the testbed allows for flexible operation and control strategies as well as accurate results [3]. Of course, the RTDS simulation environment alone provides certain capabilities in developing and connecting all the four aforementioned components. However, it does not lead to the flexibility nor the accuracy desired, which, in fact, is the basic motivation to develop a P-HIL setup.

The block diagram of the proposed P-HIL testbed is shown in Fig. 2. The general operating principle involves duplicating a bus in the software system inside the RTDS as well as in the hardware system outside the RTDS in form of an amplifier and physical battery system components. At the inverter's DC bus, the voltage is measured and sent to the RTDS through the Analog Input (AI) card. Conversely, the simulated current signal in the RTDS is sent out through the Analog Output (AO) to an amplifier and is drawn from the battery pack, closing the simulation loop. The detailed description of the hardware components in this testbed is provided in Section II.B.

The proposed configuration allows us to utilize the physical battery-cells and BMS, where the modeling is most challenging and the existing models lack accuracy the most. Yet, our test setup leverages the well-developed RTDS switching and control models. This helps by simplifying the integration with the computing unit for advanced management and control. Therefore, while our testbed produces accurate characteristics of the grid-tied battery system, it also enables the effective implementation using the commodity hardware equipment.

B. Hardware Components and Communications

Our testbed consists of several hardware elements:

1) An RTDS Simulator with the AO and AI cards;
2) A Power Amplifier;
3) A Li-ion Battery Pack;
4) A Battery Management System
5) A Computer System for Control and Monitoring

There are also multiple communications interfaces that need to be established between these hardware elements, see the dotted red lines in Fig. 2. The RTDS is interfaced through its AI/AO cards and with the use of an external amplifier. The RTDS is also interfaced with the BMS via several channels of the AI/AO cards. The BMS is interfaced with the computer through a serial USB adapter. The RTDS and the computer are interfaced with an Ethernet network connection.

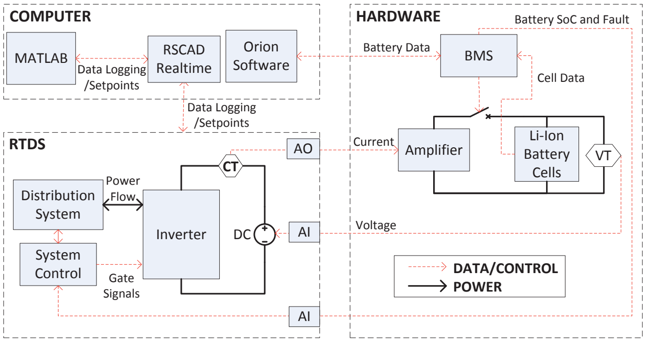

Fig. 2. The block diagram of the implemented P-HIL simulation testbed.

1) The RTDS and AI/AO Cards: The RTDS simulation environment contains all the dynamic power system models; its software details are described in Section II-C. The simulation model includes the inverter power electronics components and their controls. The inverter's DC side is connected to a virtual DC bus which is simulated by the external hardware. To establish the virtual DC bus, the voltage signal that is received from the AI, is scaled up to set the bus voltage. The current drawn from the same bus, is also scaled and sent to the AO.

2) Power Amplifier: The analogue signals at the AI/AO terminals are in the ± 10 Volts range. We use a power amplifier to scale up these small signals and produce the voltage and current of the *physical* DC bus. A 7224 AE Techron amplifier is used in this work [11]. This device is capable of delivering 1 kW of continuous, and up to 5 kW of pulsed power in both directions, i.e., operating as a *source* or *sink*. It also can produce a wide range of frequencies up to $300kHz$. This is an important factor because normally both current and voltage at the DC bus have ripples, that depending on the design of the system, can include different ripple frequencies. The ripple effects in our testbed can be induced by either the battery cells or the inverter model in RTDS. Note that, the voltage of the DC bus is set by the battery pack, whereas, the current is induced by the inverter, which is produced at the RTDS AO.

3) Li-ion Battery Pack: We use 12 Lithium Iron Phosphate battery cells each at 40 Ah, and 3.3 V nominal voltage [12]. The cells are connected in series forming a 40 Ah, $39.6V$ battery array. The battery can charge/discharge at currents as high as $\pm$ 10 C rate, but is limited in our test to 1 C for safety and to extend lifetime. The battery may operate at the State of Charge (SoC) levels between 10% and 90% of the maximum SoC. If the battery cells are charged/ discharged at the SoC levels beyond this range or at current rates higher than their limit, they may be damaged. Therefore, a BMS is needed for monitoring the battery cells during their operation.

4) Battery Management System: The BMS monitors the Li-ion battery cells in order to protect them and prevent operation conditions that are against their recommended guidelines. The BMS gathers various measurements from each battery cell and also estimates the battery SoC. If any measured values violates the tolerable limits of the battery cells, the BMS can disconnect the whole battery from the charger. It will also disconnect the charger if the BMS suffers a fatal error. Finally, the BMS also performs the balancing of the cells.

We use an Orion BMS [13]. This is an advanced BMS that is used even for larger utility scale battery packs. In this testbed, we log and report the following measurements from the BMS:

- Cell voltages (cells 1-12)
- Pack voltage
- Pack current
- Pack temperature (locations 1-3)
- Ambient temperature
- Pack charge current limit
- Pack discharge current limit
- Reason for charge/discharge current limits

During the charging, if any cell reaches $3.65V$, then the BMS charger safety relay will open, disconnecting the charger.

The BMS is equipped with a balancing circuit. This circuit is able to draw $0.2A$ from a single cell at any time to slow down the charging for that cell, allowing the other cells to charge more fully. The BMS starts balancing if any one cell is above $3.25V$ (not to pull an already low cell down lower) and the highest and lowest cells are at least 0.01 volts apart (no need to balance a fully balanced pack). It will never balance a cell to below $3.2V$. Since the $0.2A$ is passive balancing, the energy is wasted and expelled through a heatsink on the BMS. If the internal temperature is too great, it will stop balancing and allow the heatsink to remove some of the heat in the BMS.

The BMS has a communication interface with both the inverter, through the RTDS, and the computer system. The connection with the inverter is to send an error/halt message if needed, and to communicate the SoC from the battery to the inverter. The communication of the BMS with the computer system is to transfer the measurement data.

5) The Computer System: It is a standard 64 bit Windows 7 computer with a 3.4Ghz Intel i7 processor and 8GB of RAM. It runs 3 important pieces of software during testing:

- MATLAB
- RSCAD Realtime
- Orion BMS Software

Each software communications with some test bed components. MATLAB communicates using TCP/IP to interface with the RSCAD. RSCAD also uses TCP/IP, communicating with the RTDS hardware. The Orion software communicates with the BMS using a CAN (Controller Area Network) interface.

C. Software Elements and Computer Controls

The proposed testbed includes multiple software tools and models for the monitoring and control of the grid-tied battery system in the distribution feeder. Particularly, the following software tools and models are utilized/ developed:

1) Distribution Feeder Dynamic Model: The power distribution grid that is currently being simulated is a modified version of the IEEE 13 bus network. It is simulated inside RTDS for PQ loads, sources, and distribution lines.

2) Solar PV System Dynamic Model: The PV model is implemented inside the RTDS. It includes a power source, a breaker, and a controllable load. Using these components in tandem allowed for arbitrary four-quadrant power control at the terminals. The goal is to allow four-quadrant operation for the sake of more flexibility in simulated scenarios. This model operates in the large timestep simulation ($50\mu s$ steps) as opposed to the small timestep ($2.5\mu s$).

3) Battery System Inverter, Power Switching Circuit Model: The inverter model is a standard three-phase bidirectional inverter topology [14]. It is simulated in the small timestep environment ($2.5\mu s$ steps). On the DC side of the inverter, the virtual bus is formed. It consists of a controllable DC voltage source that is controlled by the real measured battery voltage. The current from this source is measured and used as the control signal to the external amplifier hardware.

4) Battery System Inverter, Control System Model: This is the control system implemented in the RTDS to control the virtual inverter. The voltage and current are measured from the distribution system and the setpoint is from MATLAB. The duty cycles go to the inverter to generate the signals that are sent out to the amplifier. The amplifier current then has an effect on voltage of the hardware DC bus (closing the whole loop). This is a standard inverter control scheme [15], [16].

5) Software for BMS management: The Orion BMS software has two purposes: loading the BMS with the initial configuration, and data-logging BMS variables during operation. The initial configuration includes number of cells (12), current limit (40A), cell capacity (40Ah), balance settings (outlined in section II-B4), cell voltage limits (2.9-3.55V), and safety relay settings to turn off the charger if a cell hits the maximum voltage, or if the current goes 30% above the 40A limit.

6) Operation Management Tools: MATLAB and CVX manage the battery system charge and discharge schedule. A MATLAB program receives the real-time data from the RTDS simulation over a TCP/IP connection. MATLAB can run a power flow model with the above inputs to estimate the impact that a potential schedule would have on the entire distribution system. It can then send the optimal battery schedule commands to the RTDS through the same TCP/IP connection. The computer/MATLAB portion of the testbed constantly polls and logs the data from the RTDS. It can store any value available to the RTDS, included in this set are:

- Voltage at each node
- Power/load at each node
- Power at source
- Loss on transmission lines
- Battery active power
- Battery reactive power
- Battery SoC
- Solar power

The above logging process can happen on a $\leq 10s$ timescale. If a specific time of interest is known, the system can also record data down to a $50\mu s$ level for a limited time.

III. P-HIL MODEL VERIFICATION

As a preliminary step, in this section, we verify the testbed results by performing several simulations which may be replicated by using other available simulation tools. Specifically, we implement a modified IEEE 13 bus distribution network [17] by using (i) a traditional power flow simulation tool, and (ii) a purely-simulated transient modeling in RSCAD. Power flow simulations may be performed using various numerical methods and tools, c.f. [18], [19]. Here, we employ a second

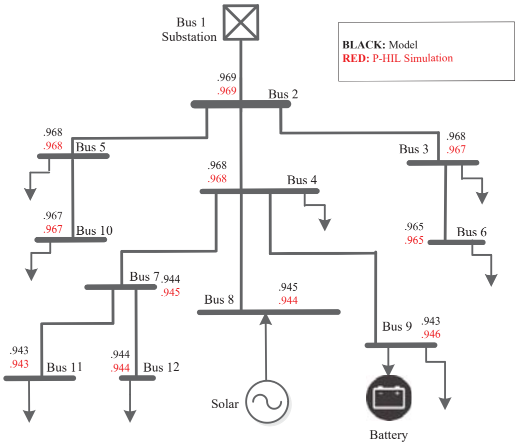

Fig. 3. Comparison of RTDS and HIL node voltages for model validation.

order conic programming (SOCP) model that has been utilized in other recent studies, c.f. [20]. A detailed description of this optimal power flow model is given in [21]. The purely-simulated transient modeling in RSCAD is done similarly to the P-HIL testbed; however, the DC side of the inverter model is directly connected to a battery model available in RSCAD.

The IEEE 13 bus distribution test system, is modified by adding a solar PV system at bus 8, and a battery storage at bus 9, see Fig. 3. We then close all breakers and remove any shunt capacitors. Finally, it is assumed that the feeder is symmetric and the loading is balanced. For the test case shown in Fig. 3 the battery charges at 150kw while the solar is idle.

A. Static Results: Steady Charging

Fig. 3 shows the voltage magnitude during steady state operation of the batteries, that are achieved by the P-HIL testbed (the upper value in black) as well as by conducting static power flow analysis (the lower value in red). It can be seen that the steady state values match up almost perfectly, with less than $0.003 p.u.$ error at the battery node, and less than $0.001 p.u.$ error at other nodes. Thus, we can be confident that the P-HIL and pure simulation results will be comparable, and that both will agree with the standard power flow results, while also providing additional results from the hardware components that cannot be obtained in pure simulation.

B. Dynamic Results: Setpoint Change

The standard power flow model does not capture the dynamic response of the system. For example, during a setpoint change, the power flow model will result in a instant step response. However, in reality, it will take some time for the command to be sent to the bidirectional inverter and for the control system at the inverter to react to the command. Accordingly, there will often exist some delay, overshoot, and settling transients caused by the hardware that is not seen in static simulations. Therefore, we perform a case study to compare and verify the dynamic response of the P-HIL testbed with that of a purely-simulated transient model in RSCAD. In this case study, the setpoint of the idle battery system is changed to charge at $0.2 MW$. The response of the battery system at the point of common coupling are obtained using the P-HIL testbed and purely-simulated transient model.

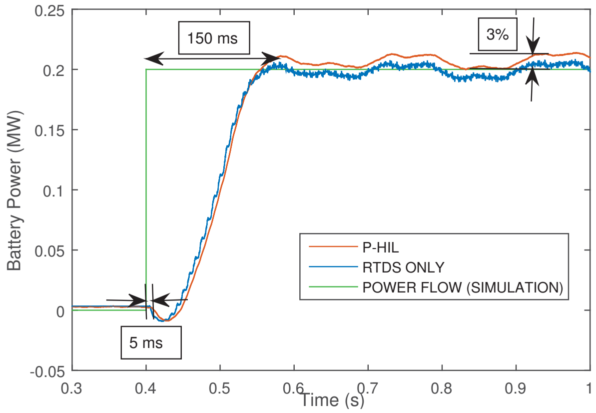

Fig. 4. Step response of battery system with load flow, simulated battery, and real battery. Power is measured at the point of common coupling.

The results are shown in Fig. 4. We can see that the P-HIL testbed results agree very closely to those of the purely-simulated model. Accordingly, we can conclude that the testbed, and particularly the physical components and the communications are setup and calibrated accurately.

IV. P-HIL TESTBED APPLICATIONS AND BENEFITS

A P-HIL testbed enables the study of several practical aspects of battery system operation in the distribution systems that *otherwise would be difficult* to achieve with the existing tools. For example, the second and sub-second characteristics of a physical battery system, and the inverter induced voltage and current distortions and their impact on the distribution feeder operation is not captured in most modeling tools. Although some models, including those incorporated in our testbed, provide very accurate reproducing of a real-world inverter, often they impose difficulties in the implementation and testing of advanced and flexible control and management algorithms. As another example, the proposed P-HIL testbed enables the study of the communication errors and data disruptions between different components of a real battery system. Our testbed communication structure follows very closely that of a real-world battery system setup with all the essential components. Therefore, faulty operation or communication errors and delays, can readily be explored in other models.

More importantly, our P-HIL testbed also provides measurements and enables studies that *otherwise would not be possible* to achieve with the existing purely-simulated tools. Particularly, the testbed provides measurements on:

- Accurate *non-linear* voltage characteristics of the battery pack during charge and discharge operations;
- Accurate voltage characteristics of the *individual* cells;
- Battery cell temperature and ambient temperature;
- Errors in SoC estimation and their impacts;
- The balancing current that is drawn from each individual cell by the BMS during charging.

These measurements that are uniquely obtained from a physical battery system, enable a multitude of valuable applications. For example, monitoring cell and ambient temperature during the battery system operation allows us to examine how the different charging/discharging schedules affect the battery temperature and/or to see how external temperature affects the battery performance [22]. Here, we focus on the voltage measurements at the battery terminals during the operation. There are several key features and applications for these measurements that we address in the rest of this section.

A. *Battery Characteristics during a Cycle*

The battery voltage characteristics during a charge/discharge cycle is inaccurate in most available models. Note that, batteries response greatly vary at different temperatures, different charging/discharging currents, and at different stages of the cycle. In most numerical models, the characteristics of batteries are normally recreated by assuming a fixed capacity for the cells, and assuming the energy stored in the cells are known. However, the battery capacity may vary depending how it is charged/discharged and by aging of the cells.

Fig. 5 shows the battery terminals' voltages during a full charge obtained from both physical measurements as well as purely-simulated models. Note that, in this study we used the same nominal parameters of the physical battery pack in the model-based simulation, i.e., 12 cells in series. Also, both physical and simulated battery systems were charged at slightly less than $1/10C$ for about 8.5 hours, left idle for 30 minutes, and again charged for 2 hours. We can make several observations from this figure, as we explain in detail next.

First, the battery characteristics recreated by the numerical model does not adequately represent the true behaviors of a physical battery. We can see that the non-linear characteristics of the actual battery is particularly different when they are reaching to their fully charged, i.e. above 90% SoC.

Having an accurate assessment of the battery voltage during a charge/discharge cycle is essential for a credible estimation of the battery SoC, hence, more effective operation. For example, the BMS often continuously reports the battery pack's SoC during the cycle. These are but an estimation of the battery SoC. Such estimations are made based on the voltage-SoC curves for a specific battery that are provided by the manufacturer. The deployed battery in practice, however, may have different characteristics. As a result, it can happen in practice, that the BMS makes considerable errors in SoC estimations; which can cause major impact on the performance of the grid-tied battery system, c.f. [23]. One option is to use battery measurements to calibrate the estimation of the SoC.

The batteries' capacity and other characteristics, change during their lifetime. As the battery cells are used, they will begin to age, reducing their capacity, and thus, the overall pack capacity. Being able to see how battery operation affects the capacity loss of the cells and pack allows for development of better models. It can also be used to estimate the amount of time the battery could be used in a particular application.

Finally, in Fig. 5, we also see the characteristics of individual cells that are in series. In practice, different cells do not have the same voltage response during the charge cycle. Their responses largely vary. This feature is often entirely ignored in typical grid-tied battery models and simulations; yet, it greatly affects the operation of battery systems and can be understood by noting that the cells in the pack are not identical.

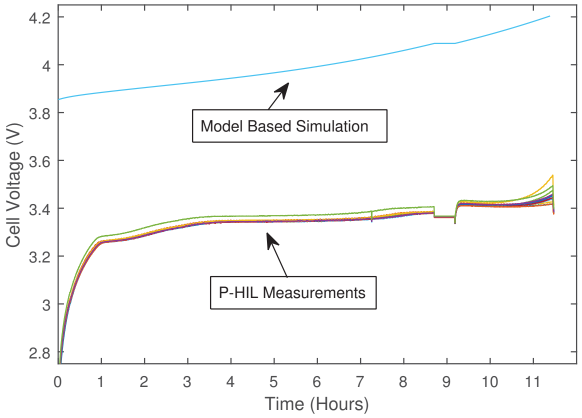

Fig. 5. Comparison of physical measurements and model-based simulation of voltage of individual cells.

B. *Individual Cell Characteristics*

In practice, the cells in a battery pack have different capacities and characteristics. Therefore, a battery pack is often not perfectly balanced, and will become less and less balanced as it is used and ages. This is in contrast to most models where the pack is assumed to be balanced and the effects of out of balance cells are ignored. An out of balance pack may impact operation in various ways; the SoC could jump (when a cell fills or empties too early), the capacity will be less than expected, or in the worst case, the battery will "lock up" because one cell is totally charged or totally discharged.

The results of a full discharge and charge cycle for each individual cell within the battery pack are shown in Fig. 6. Here, during the discharge cycle in Fig. 6(a), the battery has the highest voltage at the beginning of the cycle. The battery is discharged until completely depleted and the discharge is stopped by the BMS. The voltage trajectory of each cell during the discharge are shown. Note that, the cell voltages generally correlate with their SoC; as the battery is discharged, the cell voltages, and their SoC, go down. The discharge is stopped, when one cell dips below the minimum allowed voltage. Similarly, during the charging cycle in Fig. 6(b), the cells start at the lowest voltage and rise up until the battery is fully charged. The battery pack is considered fully charged when one of the cells reaches the maximum allowed voltage.

We note in Fig. 6 that not all cells reach the upper and lower voltage limits during the charge and discharge cycles. In fact, only a few reach the fully discharged or fully charged state. For the cells that do not reach it, some of their available capacity is not used, meaning that they are not operating efficiently. This can be due to particular cells having less capacity, or the pack being imbalanced. As noted in Section II-B4, the BMS performs a cell balancing function during the charge cycle of the battery. However, this function can mitigate only small levels of imbalance between the cells.

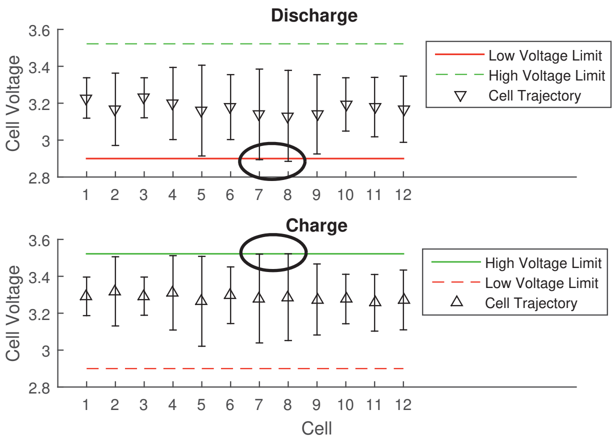

Fig. 6. The measured cell voltages in comparison with the maximum cell voltage limit (green solid and dashed lines) and the minimum cell voltage limit (red solid and dashed lines) during: (a) charge; (b) discharge.

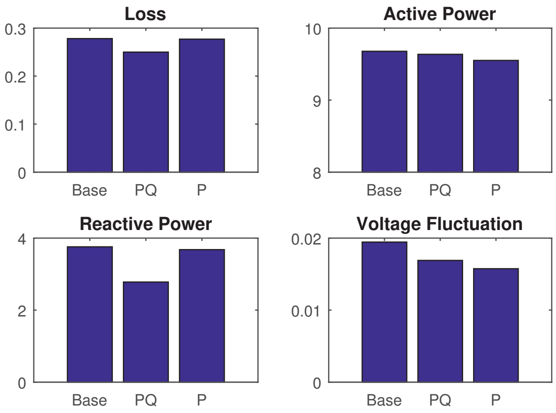

Fig. 7. The results obtained from the developed P-HIL simulation testbed on comparing the impact of different battery operation cases, as described in the text, on the distribution grid. All numbers are given in per unit.

C. Impact on Distribution Grid

As a preliminary test case for the P-HIL grid-tied battery test system that is developed in this paper, in this section, we explore the impact that a battery with PQ support could have on the distribution grid. We use a six hour operation period and run the testbed with both active only and combined active/reactive power support. The grid voltage, loss, active power, and reactive power are measured. The baseline is the case without using the batteries. The results are shown in Fig. 7. We can see that the battery has a positive impact on the grid, reducing loss, voltage fluctuations, and both active and reactive power drawn from the substation. This is just a simple example for the various use cases of the developed P-HIL testbed. In the future, the decision making in choosing the PQ set points can be done via more complex algorithms and the use of optimization, control theory, machine learning, etc.

V. CONCLUSIONS

A P-HIL testbed is designed and successfully tested to enable accurate modeling and testing of grid-connected battery energy storage systems in power system applications. The testbed architecture, hardware components, software systems, communications, and computer controls are explained. Several test cases were discussed. The key advantage of the developed testbed is to allow us to examine the physical battery-cells, battery-packs, and the BMS, where the modeling is most challenging and the existing models lack accuracy the most.

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