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Evaluating Impacts of Battery Energy Storage System Functionalities on Distribution Systems Using Power Hardware-in-the-Loop Simulation

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***Abstract*—In this paper, we present results from a power hardware-in-the-loop (PHIL) simulation that was performed to test and demonstrate the impacts of battery energy storage system (BESS) functionalities on a distribution feeder. The PHIL platform includes a simulated distribution grid in a real-time digital simulator (RTDS), AC and DC power amplifiers, and a battery inverter as the device under test. Guidelines on how to set up a PHIL platform to evaluate the impact of grid integrated systems are provided. Accelerated time-series PHIL simulations of peak shaving and volt-watt functionalities were performed using a 540 kVA BESS. These experimental results illustrate how PHIL simulations can be used to evaluate the impact of BESS functionalities on the distribution grid prior to installation in the field.**

Index Terms*—Power hardware-in-the-loop; battery energy storage system; volt-watt; peak shaving.

I. INTRODUCTION

A battery energy storage system (BESS) can provide various grid support services, including voltage regulation, peak shaving, and photovoltaic (PV) smoothing to transmission, distribution, and behind-the-meter users [1]. Therefore, understanding how battery energy storage can provide value to the electric power system is extensively explored and investigated by utilities, regulators, industry, academia, etc. [2]. Prior to the installation of a BESS in the field, proper evaluation must be performed to understand how the BESS can impact the grid. The most popular hardware testing approach is hardware-in-the-loop (HIL) testing which has several benefits, such as repeatability, relatively low cost, and reliable results. Power hardware-in-the-loop (PHIL) combines the advantages of a complete numerical simulation method and actual hardware [3]. Most importantly, PHIL testing allows hardware devices to be evaluated in an environment that emulates various realistic field conditions.

A PHIL simulation framework for testing functionalities of grid-interactive inverter is presented in [4] with the focus on modeling grid dynamics and replicating IEEE 1547.1 conformance test results. A grid interconnection system evaluator using PHIL technique to rapidly evaluate the interconnection standard is developed in [5] and the high-level architecture and test sequencing of the evaluation tool are illustrated. This work applies the framework proposed in [5] and an augmented interface algorithm to improve the stability and accuracy of the PHIL test is developed. Evaluating impacts of BESS functionalities on distribution systems using PHIL simulation is presented in this paper and specific guidelines on how to set up this PHIL platform are provided. This research was encouraged by San Diego Gas and Electric (SDG&E) in light of their need to comply with the California Public Utilities Commission's requirement to meet a target of 165 MW of cost-effective grid storage by year 2020 [6]. We based our evaluation on an SDG&E feeder in which a lithium-ion-based BESS has been installed. The proposed PHIL evaluation platform ensures stable and accurate simulations that yield reliable and trusted results.

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II. OVERVIEW OF THE DISTRIBUTION GRID WITH BESS

The simulated distribution feeder is a reduced-order representation of the full network. The full SDG&E 2,174-node feeder model was reduced to an equivalent 7-bus model using the procedure described in [7][8]. The resulting line impedances calculated for the reduced order model were all the same. The parameters of the positive sequence impedance are series resistance 0.0143 Ω, series inductive reactance 0.0188 Ω, and the shunt capacitive reactance 9.6 kΩ, and the parameters for the zero sequence impedance are: series resistance 0.082 Ω, series inductive reactance 0.02146 Ω, and the shunt capacitive reactance 9.6 kΩ. The distribution feeder was simulated in an RTDS digital real-time simulator with a time step of 50 µs.

A. Description of the Distribution Grid Model in RTDS

The distribution feeder depicted in Fig. 1 shows the configuration of the reduced-order network. It is a 12-kV feeder with a peak load of 7.5 MW. The loads are modeled as dynamic loads. Two capacitor banks, both rated at 1.2 MVar, are used to regulate the voltage. A 1.2-MW PV system is connected at the end of the feeder, and a 1-MW/3-MWh BESS is connected upstream of the PV system.

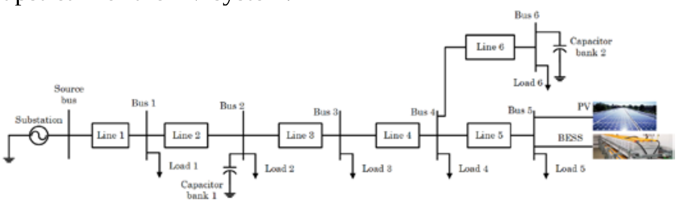

Fig. 1. Overview of the distribution feeder with BESS integration.

The feeder head is modeled as a controllable voltage source with a source impedance of 0.0287 + j 0.458 Ω for positive sequence and 0.0271 + j1.313 Ω for zero sequence. The voltage source is controlled to emulate various voltage profiles for studies.

The loads are modeled as dynamic power sinks, and they are controlled by multiplying a per-unit load profile by a fixed load. The fixed load is set equal to the load at each bus during the annual peak load condition. The load profile is the per-unit (with annual peak load as base) power profile measured at the feeder head. An assumption of a fixed ratio of power between the nodes was made because time-series data were available only at the feeder head and only peak load was provided at all the buses.

The PV system is modeled as a controlled current source. The input to the PV model specifies the output active power of the PV system, and the PV controller regulates the current to match the PV output active power to this input.

The capacitor banks are modeled as capacitive loads. The capacitor bank controllers switch the capacitor banks ON or OFF when the measured bus voltage drops below a minimum voltage or rises above a maximum voltage level. The controllers ensure that minimum on and off times are observed.

B. *Description of the PHIL Model in RTDS*

In this PHIL simulation, augmented ideal transformer PHIL interface method is implemented. Fig. 2 shows the signal level "PHIL model" implemented in RSCAD, the RTDS power system simulation software, and the power level hardware circuit. A controlled-current source is used to emulate the characteristics of the device under test (DUT) within the power system simulation. This "PHIL model" has four blocks: #1 PHIL interfacing compensation, #2 DUT control reference generation, #3 analog input scaling and conditioning, and #4 analog output scaling.

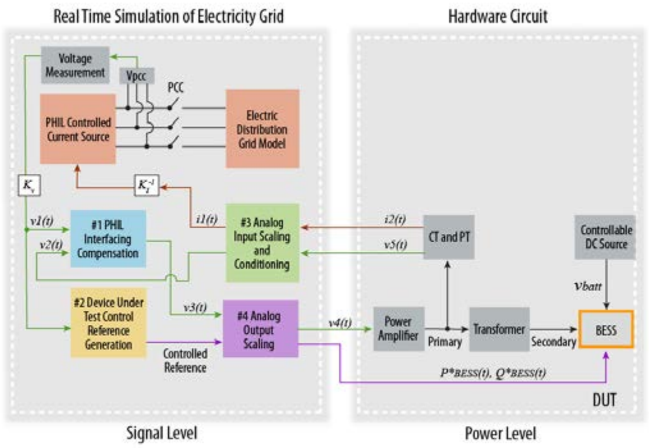

Fig. 2. Schematic diagram of implemented PHIL simulation.

The simulated voltage at the BESS point of common coupling (PCC), ($v_{PCC}(t)$), is scaled by a factor of k_v to a simulated low-voltage signal, *v1(t)*; and the #1 PHIL interfacing compensation block generates an augmented three-phase control reference voltage, *v3(t)*. The #4 analog output scaling block generates a scaled three-phase control reference voltage, *v4(t)*, that is sent to an AC power amplifier (grid simulator) to reconstruct the power level signal and feed the DUT—the BESS—through a transformer. A controllable DC source is connected to the DC terminals of the BESS inverter in place of a battery. The DC voltage (v_{batt}) can be adjusted to simulate changes in the state of charge of the battery.

The output current of the BESS will be measured at the transformer primary side by a current transducer (CT), and this measured current, *i2(t)*, will be sent back to the RTDS through the #3 analog input scaling and conditioning block. This scaled measured current, *i1(t)*, is scaled by a factor of k_I^{-1} to control the current source in RSCAD, thus closing the loop between the power hardware and the simulated test feeder.

In the PHIL mode, this controlled current source injects a current proportional to the measured current at the DUT. It can also be set to a user controllable value when not in the PHIL mode. Note that the voltage at the transformer primary that is measured via a potential transducer (PT), *v5(t),* is scaled in the #3 analog input scaling and conditioning block to *v2(t)* and sent back to the #1 PHIL interface compensation block in the RTDS to improve the stability and accuracy of the PHIL simulation. More details about how this PHIL block is implemented will be discussed in Section III.

III. Development of the PHIL Platform for Testing BESS Functionalities

This section describes the functional and hardware configuration of the PHIL test setup, the test specification, and the development of the test setup.

A. *PHIL Test Setup Functional Description*

PHIL testing is typically used to test power hardware under conditions that cannot (cost-effectively) be generated in an all-hardware test. It works by combining a real-time digital model of the power system (the "virtual" part) with analog-to-digital converters and a controllable voltage source. The controllable source is controlled in real time to follow the voltage at a point in the virtual power system. Test conditions are created in the virtual power system, and the power hardware under test interacts with it as if with a real power system under those test conditions.

We present a test setup that was implemented using a BESS inverter (the power hardware under test), a specified controller for the BESS, and a simulated test feeder. A real-time circuit model of the test feeder was loaded on an RTDS simulator, which solved the circuit model in real time based on time-series profiles for the feeder loads ($P_{L,j}(t)$ for all loads j) and PV generation ($P_{PV,i}(t)$ for all PV systems i).

The BESS inverter implements peak shaving and volt-watt functionalities, and during the PHIL simulation, we observe its effects on the simulated test feeder. The device-level control (current controller, pulse-width modulation) is embedded in the battery inverter, and the system-level controller (control reference generation) is implemented in the RTDS. Based on the scaled AC measurements, the RTDS system-level control will implement real-time controls.

B. *PHIL Test Specifications*

The PHIL test conditions are defined by the voltage conditions at the feeder head and the profiles of all loads and PV generation on the feeder. In addition, real and reactive power references, $P^*_{BESS,Ref}(t)$ and $Q^*_{BESS,Ref}(t)$, representing precalculated reference power inputs for the BESS controller must also be specified based on the particular feeder and test conditions. If the test feeder itself undergoes any changes during the test conditions, then the exact change and its timing must also be specified.

The virtual-to-physical scaling constants k_V and k_I must be specified; these specify the relationship between the virtual BESS PCC bus voltage and current, respectively, in the RTDS feeder model to the physical power hardware in the PHIL setup. These constants should be selected to ensure that the expected range of voltage and current values at the BESS PCC result in physical voltage and current values that are within the capabilities of the power hardware under test and the grid simulator.

Finally, the BESS control mode for the test, its parameters, and the DC voltage of the emulated battery (v_{batt}) must be specified. The control mode and its associated parameters and test procedure are specified in the sections below.

1. Parameters

These data are constant parameters that are to be defined for each PHIL test: the RSCAD model of the test feeder, location of the BESS PCC, and the test time vector *t*. Other parameters that need to be defined are:

- The virtual-to-physical scaling constants, k_V and k_I, for the BESS PCC bus voltage and current
- Specification of any changes to the feeder structure and time at which such change occurs
- Specification of the BESS control functionalities to be used and its parameters
- The DC voltage of the emulated battery.

2. Test vectors

These time series define the particular conditions for the PHIL test:

- Feeder power profile time series ($P_{PV,i}(t)$ for each PV system, i, and $P_{L,j}(t)$ for each load (j)
- Voltage magnitude at the feeder head time series ($V_{src}(t)$). The BESS real and reactive power reference time series ($P^*_{BESS,}(t)$ and $Q^*_{BESS}(t)$), which are precalculated for the particular test conditions. These will be communicated to the test BESS inverter in real time.

C. Development of PHIL Test Setup

This section describes the design and construction of the test setup for the PHIL simulation of a BESS with peak shaving and volt-watt functionalities.

1. PHIL test setup hardware configuration

Table 1 specifies the hardware components that were used to implement the PHIL simulation platform shown in Fig. 2. The 540 kVA BESS is scaled to 1 MW in the RSCAD model.

Table 1. Hardware components in the PHIL platform

Functional Component	Manufacturer And Product	Ratings
Controllable DC source	Anderson AC2000P	0–2,000 VDC, 540 kW
BESS inverter	Schneider Conext Core XC ESS	300 VAC, 540 kVA
BESS transformer	Eaton EE540TQ83020	480-V Delta/ 300-V Wye, 540 kVA
Controllable AC source	Ametek RS270 (x 2)	480 VAC, 540 kVA
Real-time digital simulator	RTDS Technologies	6 PB5 cards, GTAI, GTAO
Current transducer	LEM LF 1010-S (x 6)	1,000 A
Potential transducer	LEM DVL 750 (x 3)	750 V

2. RTDS interface between RSCAD model and hardware

The RTDS interface design is important for PHIL simulation because the RTDS interface is used to combine the virtual simulation and the hardware equipment. This combination introduces time delays and inaccuracies, and appropriate compensation techniques are needed to guarantee stability as well as simulation accuracy. In this platform, the following interfaces between the RTDS and the hardware were implemented:

- Analog signals from PT and CT to RSCAD: This was accomplished by using the Gigabit Transceiver Analogue Input (GTAI) card in the RTDS. The RTDS measurements of voltages and currents were verified, and all measurements and controls were calibrated.
- Analog signals from the RSCAD to the grid simulator: This was accomplished by using the Gigabit Transceiver Analogue Output (GTAO) card in the RTDS. Calibration is also performed for the GTAO channels used.
- The grid simulator's built-in protection is limited under analog control mode, and therefore extensive protection needed to be built into the RSCAD model to protect against voltage magnitude and frequency deviations in the voltage signal applied to the grid simulator. This was especially important in the early phases of the PHIL loop stability analysis because instabilities were encountered, and it allowed the RSCAD model to seamlessly transition to apply a safe voltage and frequency to the grid simulator.
- Active and reactive power commands from RSCAD to the BESS inverter. Initially, we planned to use MODBUS; however, the RTDS did not support MODBUS in real-time mode. So, the power references P^*_{BESS} and Q^*_{BESS} were sent to the inverter through the GTAO. According to the manual of the BESS, the power references are represented by current variables if analog input is used. So the translated current control reference block was implemented on the RTDS. Because the RTDS GTAO card has a voltage output and the Schneider inverter needs a current input, conversion from the current representation to the voltage representation is implemented; however, we encountered grounding issues upon connecting the analog control wires, leading to the necessary installation of isolating voltage-to-current converters.

3. PHIL interface compensation design

We tested the PHIL operation with a simple feeder model using the equivalent impedance at the PCC for the BESS, as determined using the equivalent model in OpenDSS. The PHIL test setup was experimentally determined to exhibit instability for some operating conditions. This instability condition is common in PHIL simulations because of feedback delays, and this necessitates the inclusion of feedback compensation in the PHIL loop [9]. Often a simple low-pass filter applied to the current and voltage feedback is sufficient, but in this case it was not, and it was therefore necessary to complete a detailed three-phase loop stability analysis, as described in [9], to design an appropriate compensator.

This compensation is realized through an augmentation of the voltage reference that is reconstructed by the grid simulator and is implemented in a combination of the #1 PHIL interface compensation block and the #3 analog input scaling and conditioning block in the RTDS, as shown in Fig. 3.

Based on the stability analysis, we discovered that the uncompensated system has both a negative phase margin and gain margin and that the PHIL loop instability is closely related to a resonance at a specific frequency. This was caused by the interaction between the grid simulator's output filter inductance, L_{GS}, and the BESS inverter's output filter capacitance, C_{inv}. To avoid the instability caused by this resonance, a notch filter, G_{comp}, was used in the PHIL interface compensation.

The objective of the PHIL simulation is to assess the effect of the BESS's functionalities that inject active and reactive power into the feeder, so any error introduced in the active and reactive power measurement and reconstructed voltage will result in PHIL simulation errors. To solve this problem, a low-pass filter on the voltage feedback, H_{comp}, is added to create the same phase shift in voltage and in current, which eliminates the errors in active and reactive power.

The grid simulator under analog control does not regulate the voltage at the output terminals—i.e., it does not compensate for the voltage drop across its output filter—so a voltage compensation loop, G_{reg}, was designed and added to the RSCAD model, and its operation was verified. The voltage compensation, G_{comp}, is a feedback control, which is a proportional resonance control implemented in the natural reference frame because the three-phase voltage of the grid simulator is controlled separately.

Combining all the elements to improve the performance and stability of the PHIL platform, a schematic diagram of the PHIL loop with the interface compensator is shown in Fig. 3. The representation of each element of this compensator and its control parameters are listed in Table 2. More details of this interface compensate can be found in [9]. Based on the analytical study of the open-loop transfer function, the compensated PHIL platform has a phase margin of 44.7° and a gain margin of 11.9 dB. This guarantees the stability of the PHIL test setup. And the closed-loop transfer function shows that the gain is approximately 43.5 dB at the fundamental frequency, which ensures a good tracking performance for the grid simulator, thus achieving good accuracy and an authentic evaluation of the BESS functionalities' impacts on the feeder.

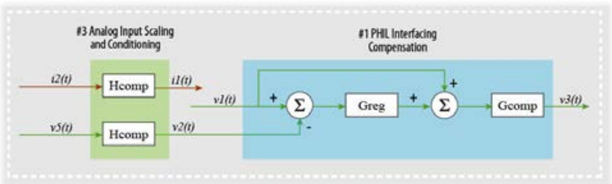

Fig. 3. Schematic diagram of the PHIL loop with the interface compensaton.

Table 2. Elements of PHIL interface compensator

Element	Representation	Control parameters
H_{comp}	$\frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2}$	$\xi = 0.707, \omega_n = 1{,}000$
G_{comp}	$\frac{s^2+\omega_n^2}{(s+\omega_n)^2}$	$\omega_n = \frac{1}{2\pi N_{Txfr}\sqrt{2L_{GS}C_{Inv}}}$
G_{Reg}	$\frac{2K_r\omega_c s}{s^2+2\omega_c s+\omega_0^2}$	$K_r = 150, \omega_c = 2\pi 0.5$, $\omega_0 = 2\pi 60$

IV. Experimental Results

Experimental results were obtained using the PHIL test setup for peak shaving and volt-watt functionalities. See [10] for further explanation of the BESS's peak shaving and volt-watt functionalities. We used two test input data sets—consisting of a per-unit load multiplier profile and a PV output power profile—for a 24-hour period of feeder operation at 15-minute resolution. The first data set was the peak load day, and it was used to evaluate the impact of peak shaving. The second data set was the minimum load day, and it was used to evaluate the impact of the volt-watt functionality. A baseline test case was performed for both data sets in which the BESS is inactive.

For the peak shaving functionality, the capacitors were set the same as in the field, i.e., to switch on at voltages of 0.992 p.u. and off at 1.025 p.u. For the volt-watt functionality, the capacitors are set to switch on and off at 0.98 p.u. and 1.02 p.u. respectively.

A. Peak Shaving Functionality

The peak day load and PV data sets were used, and the BESS was inactive for the baseline test case and it was operated to track a precalculated real power profile for the peak shaving test case. Fig. 4 shows the resulting feeder head power, P_{Src} and Q_{Src} for both test cases; PV system power, P_{PV}; and BESS active power, P_{ESS}.

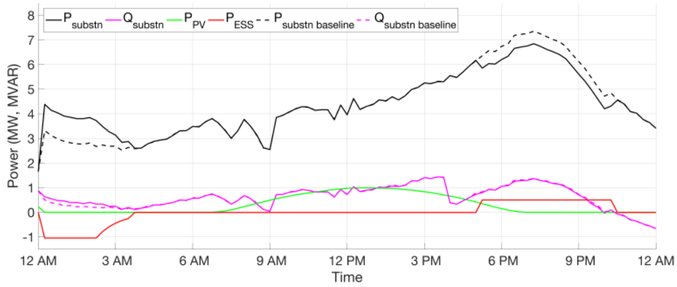

Fig. 4. Feeder power profile results for peak load day with peak shaving.

Observe that in the peak shaving test case the BESS sinks real power (charging the battery) in the early morning near the minimum power and sources power (discharging) in the evening to reduce the peak. As a result, the peak source power is reduced compared to the baseline test case.

In addition, there was only a small difference between the reference BESS real power values and the measured values. Because the BESS inverter regulates real power at the battery DC bus and reactive power at its terminals (whereas the measurements are at the modeled medium-voltage bus), losses across the inverter and transformer appear as an error between the reference and measured profiles. In addition, the loss is highly asymmetric between charging and discharging. When the BESS charges, these losses are significant, as much as 5% of real power and generating nearly 10% of the real power value as reactive loss. Although this effect does not significantly change the voltage profile, it might affect the amount of peak shaving compensation or its duration that the BESS could provide in practice.

B. Volt-Watt Functionality

1. Test Case B1: Minimum Load Day Baseline

In this test case, the minimum day load and PV data set were tested with the BESS inactive. The voltages at all seven buses are shown in Fig. 5. They never rise high enough or drop low enough to activate the capacitors.

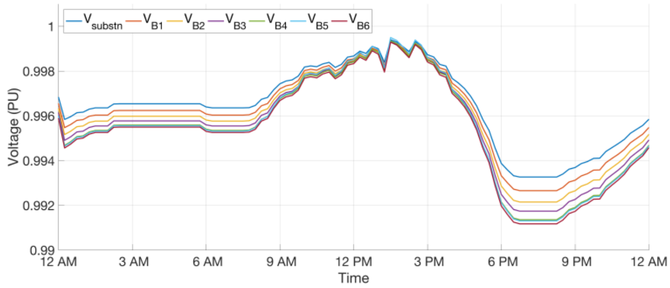

Fig. 5. Feeder voltage results for volt-watt baseline test case.

2. Test Case B2: Minimum Load Day with Volt-watt

In this test case, the minimum day load and PV data sets were used, as for Test Case B1, but with the BESS active and performing volt-watt compensation with no deadband, according to the volt-watt curve shown in Fig. 6.

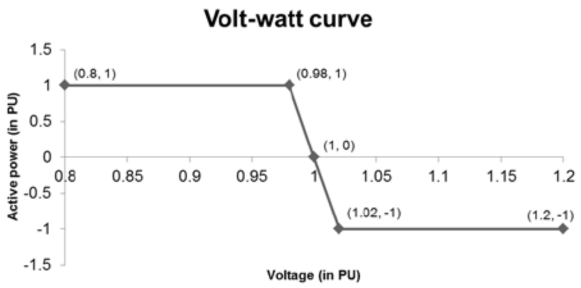

Fig. 6. The volt-watt curve without deadband used for test case B2.

The test results are shown in Fig. 7 and Fig. 8. The BESS provides active power (P_{ESS}, the red trace shown in Fig. 7) to compensate the morning and evening voltage dips. Fig. 8 shows the impact of the volt-watt functionality on the voltage at Bus 5, V_{B5}, where the BESS is located. It can be seen that, despite the fairly steep slope of the volt-watt curve, which transitions from no active injection at 1.0 p.u. voltage to the full capacity of 1.0 MW at 0.98 p.u. voltage, the voltage is increased by only 0.00038 p.u. compared to the baseline in test case B1 (in which no volt-watt was active). The voltage impact is even less at the other buses, therefore neither capacitor bank was activated for the duration of the simulation. For this feeder, the BESS therefore provides voltage support, but it is not of a sufficiently high rating to significantly impact the voltages.

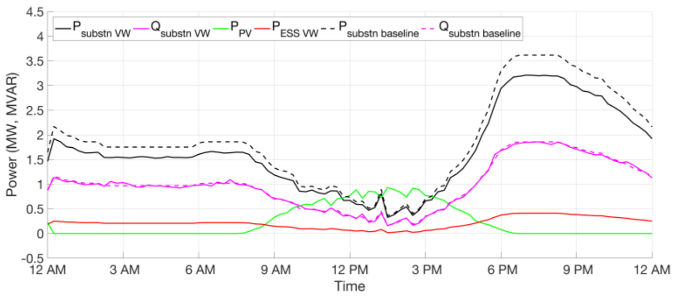

Fig. 7. Feeder power profile results for minimum load day with volt-watt.

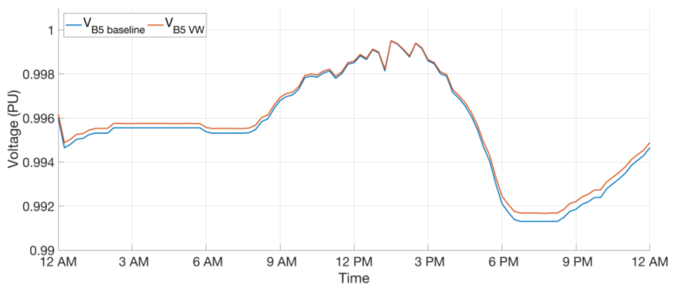

Fig. 8. Comparison of voltage at the BESS PCC with and without volt-watt.

V. Conclusions

This paper presents results from PHIL simulations that evaluated and demonstrated the impact of battery energy storage system functionalities on a distribution feeder. It describes modeling the components in the distribution feeder (e.g., capacitor banks) and the PHIL simulation platform. In particular, the design of the PHIL interface compensation algorithm to ensure stable and accurate evaluation of the DUT is discussed in detail. Moreover, guidelines on how to set up a PHIL platform to evaluate the impact of grid integrated systems are provided.

Two functionalities—peak shaving and volt-watt—are simulated and the experimental results are presented. These results demonstrate how a PHIL simulation platform can provide a valuable evaluation prior to field installation. Information from the PHIL simulations can be used by utility operators to determine how to operate their utility assets most effectively under different scenarios in the field.

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