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Performance Evaluation Testing Protocols to Support Energy Storage Deployment in the Grid

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SUMMARY

Battery Energy Storage Systems (BESS) have been in the spotlight in the last few years to strengthen and stabilize the transmission and distribution grids by offering grid support, reliability and resilience services such as backup power, load management, renewable resource smoothing, and added capacity or regulation applications for supporting energy markets. Because BESS technology development is advancing rapidly and realization of many BESS applications in the field are complex projects, in-depth examination and evaluation of various control, protection, and automation schemes are necessary to fully verify the BESS functions and responses under a multitude of normal and stressed operating conditions.

This paper discusses BESS commissioning and performance testing procedures, testing approaches and data collection methods that are proposed to be executed, most preferably by an independent party, to verify energy storage functions in a controlled environment (laboratory) to the extent possible, and then extensively in the field to ensure the BESS is ready for delivering the required services.

Furthermore, a recent BESS commissioning project is used as a benchmark to discuss various test cases that were performed in the field for performance evaluation and to ensure compliance with design specifications, planning criteria, and operational considerations. The project is a utility scale BESS rated at 2 MW, 4 MWh. The BESS is connected to a distribution systems and is primarily used for reverse flow mitigation from the distribution grid as a result of excess solar production. A secondary use case is for reactive power support.

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KEYWORDS

Battery Energy Storage System (BESS), Key Performance Indices (KPI), Factory Acceptance Testing (FAT), Performance Evaluation, Point of Demarcation (POD), Point of Interconnection (POI), Interconnection tests, Site Acceptance Testing (SAT).

1 INTRODUCTION

Energy storage integration into the grid has been increasing, especially as renewable generation penetration increases. Nowadays Battery Energy Storage Systems (BESS) have been utilized for several use cases. The use cases for the BESS can be classified into four main categories:

- Standalone BESS systems directly connected to the distribution or transmission grid, typically for the provision of ancillary services to the system (frequency regulation, voltage control, …) or energy trading.
- Co-located with a renewable resource, typically for back feeding and renewable smoothing.
- BESS as the dominant source of power supply for delivering power to customers during grid outages in a microgrid and improve system reliability and resiliency.
- Behind the meter BESS when energy is generated (usually from wind, solar, or heat) and stored until it is needed typically at an individual building and "behind the meter".

Commissioning a BESS encompasses establishing and executing a set of plans and procedures to ensure the BESS will fulfill its design objectives. While some of the commissioning plans and tests will validate the BESS's operational performance, additional tests shall be developed to ensure safe and reliable integration of the BESS with the utility system. Comprehensive factory acceptance and commissioning test plans require careful attention to detail and close coordination between the project's engineering, construction, commissioning, and management teams to produce a safe and reliable operating system. Also, commissioning is an excellent means to help familiarize the Operation & Maintenance (O&M) staff with the system, how it operates, and how to respond in an emergency. The recommended performance of BPS-connected BESS and hybrid power plants seeking interconnection to the BPS have been discussed in the NERC reliability guideline [1]. Sandia National Laboratories and PNNL have established a set of "best practices" for characterizing energy storage systems (ESSs) and measuring and reporting their performance. Detailed information on the testing procedures outlined by Sandia and PNNL can be found in [2]. In [3], NREL, in collaboration with the World Bank Energy Sector Management Assistance Program (ESMAP), the Faraday Institute, and the Belgian Energy Research Alliance has summarized international literature and reports as well as testing software and energy storage analysis software.

ESIC Energy Storage Commissioning Guide provides a series of commissioning tests, as outlined in the ESIC Energy Storage Commissioning Guide, which are provided below [4].

- Factory acceptance testing (FAT) performed on critical subsystems such as disconnect devices, inverters, transformers, HVAC, communications interfaces, and control equipment.
- Verification that the BESS was installed correctly per specifications and approved drawings. This includes grounding, proper clearances, safety systems, signage, security equipment, etc. Verification is usually accomplished via the preparation of a turnover package containing all inspection/test results, setpoints, and performance parameters.

•	Verification that the system operates per specifications, including testing functionality of all local and remote communication and control systems, protection, and safety systems.

•	Interconnection tests are required by the utility to obtain a permit to operate per interconnect requirement.

•	Compliance with interconnection-related standards such as Institute of Electrical and Electronics Engineers (IEEE) Standards 1547.

Overall, different stages of the BESS testing has been shown in Figure 1.

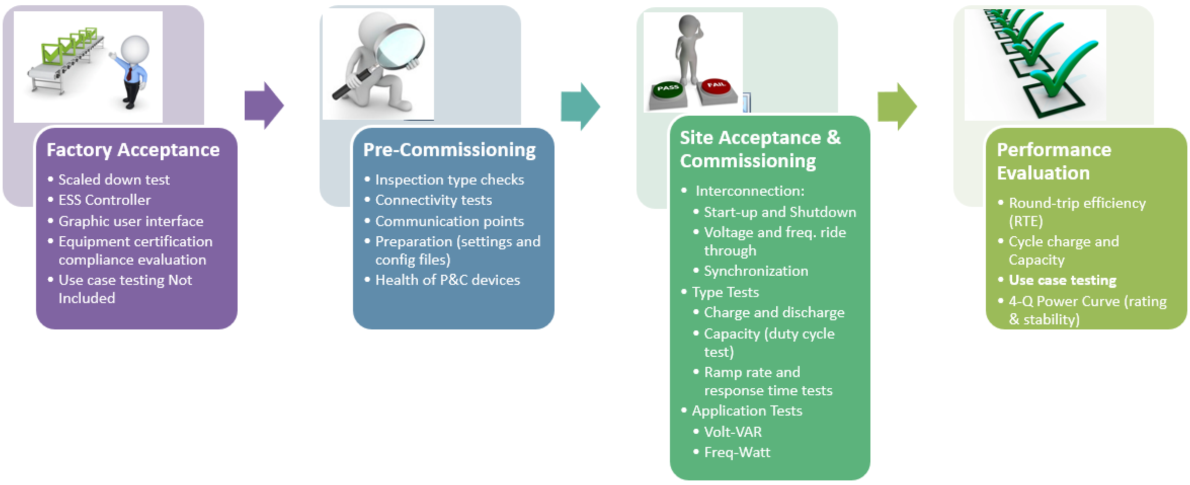

Figure 1. Different stages of the BESS testing

2 OVERVIEW OF THE BESS PERFORMANCE EVALUATION

Comprehensive performance evaluation testing beyond generic tests by the vendor is crucial to ensure the BESS performs as designed and meets the specified performance criteria, discover and correct problems before the system goes “online”, and verify communication interoperability and remote dispatch that are considered proprietary aspects.

Also, as seen in Figure 1, FAT Scope by the vendor is typically very limited nd limited commissioning and SAT are normally performed by the vendors. The performance evaluation process shall be an orderly series of events to demonstrate, measure, and record component and system performance. It is a process that develops and implements a set of tests tailored to a specific design. It should be noted that reference performance evaluation tests establish the baseline initial performance at the beginning of the BESS life and need to be performed at periodic intervals to determine the performance degradation during continuous operation and to assess the state of health of the BESS.

The main test categories that shall be covered during performance evaluation are as follows:

- BESS Specification Verification Testing
- Type Tests
- Application Tests
- Interconnection tests

Depending on the BESS project and its design objective different test cases shall be included as part of each test category (Figure 2).

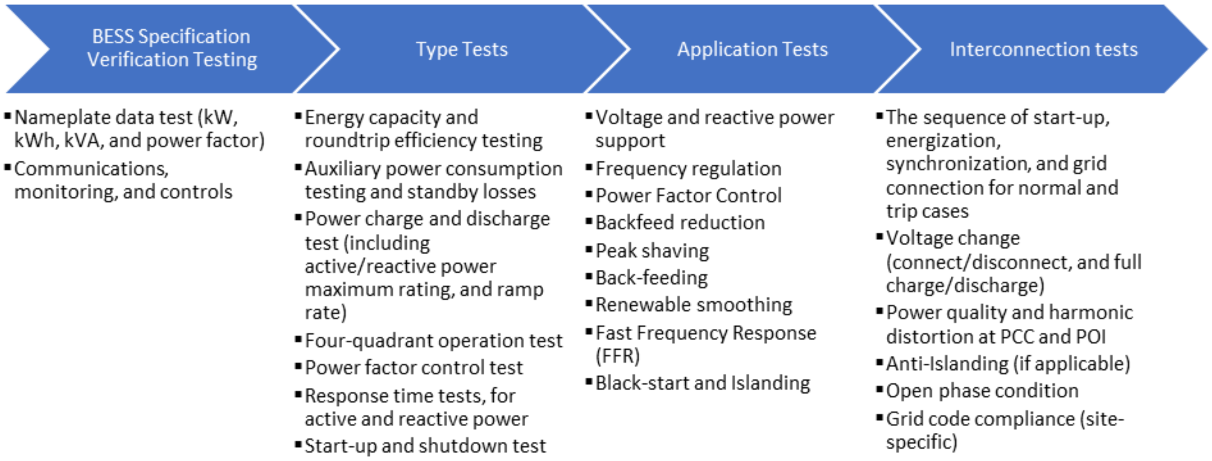

Figure 2. Different test cases for BESS performance evaluation

2.1 DIVISION OF RESPONSIBILITY FOR PERFORMING THE PERFORMANCE EVALUATION TESTING

This section describes the division of responsibility for performing different test categories and test cases as shown in Figure 2. Typically, most of the performance evaluation test cases that are considered in the scope of work for the BESS Vendor/Integrator are focused on the basic BESS performance parameters such as energy efficiency, standby losses, response time/ accuracy, and usable energy at different power rates (category one and two).

Upon completion of the site acceptance testing on basic BESS performance by the BESS vendor/Integrator, the BESS owner shall perform at a minimum interconnection tests and specific applications tests to check out some requirements of grid code compliance including but not limited to synchronization, reactive and voltage control, and power quality and harmonic signature at Point Of Interconnection (POI).

A test plan describing the tests to be completed, procedures, and pass/fail criteria based on the BESS design are needed to make sure the tests are aligned with the performance criteria as specified in the BESS design. The following summarizes the steps to develop a comprehensive test plan, perform the field testing, and test data analysis:

- Come up with the test cases to be performed based on the BESS spec, use cases defined for the project as well as contractual obligations.
- Develop KPIs and their associated metrics that can be used to define and quantify the key performance of the BESS .
- Develop methods for the data collection and data analysis that can be used to determine the metrics of the KPIs .
- Coordinate with the BESS vendor/integrator to review the test plan and incorporate all the comments .
- Perform KPI evaluation and battery usage analysis based on the developed methods.
- Compare the test results with the standards and grid code and prepare the report.

3 CASE STUDY

This section provides various test cases that were performed during performance evaluation testing of a 2 MW/4 MWh BESS plant connecting to a 34.5 kV/230 kV substation. The BESS is designed to operate in parallel with the grid. The primary application of the BESS is to prevent back-feeding from the distribution system into the transmission system. The substation serves a solar farm that experiences back-feeding during the year. The BESS comprises two power blocks with a maximum gross output of 2,574 kVA / 5,364 kWh (BOL[1]). Because of the transformer rating, the real power and reactive output of the plant are limited to 2,000 kW, and 2,500 kvar, respectively. Figure 3 shows a simplified BESS plant diagram with emphasis on the components associated with the tests and measurement locations at 1) the 0.480 kV BESS main bus (POD), and 2) POI at 34.5 kV (low side of the substation transformer).

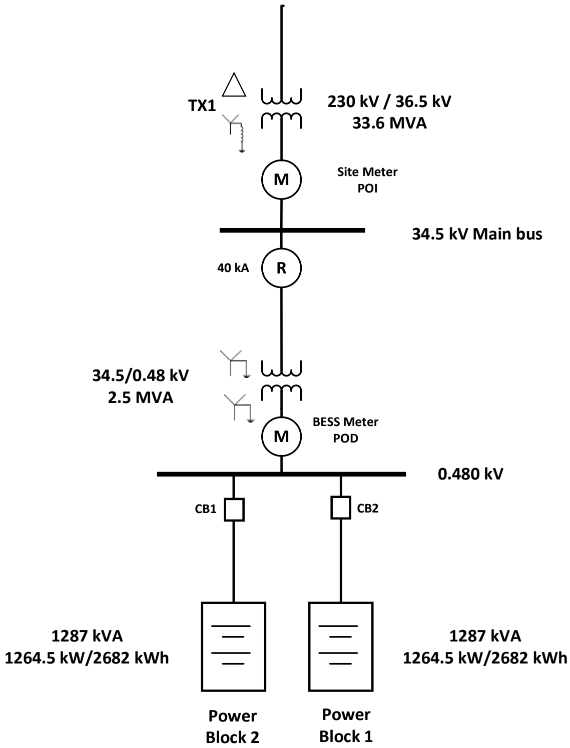

Figure 3 Simplified BESS overview

3.1 TEST METHODS AND TEST PROTOCOLS

This section presents the technical performance evaluation of this BESS facility, based on three test categories (Figure 4). Upon completion of the commissioning test by the BESS vendor, the performance evaluation tests were conducted by preparing the test setup and connecting the BESS tester to the SCADA system. After preliminary communication testing, the performance evaluation testing started by running the first test case from the interconnection test category. The interconnection test was intended to evaluate the operating sequence of the BESS plant and assess any impact on the grid during startup, synchronization with the grid, power dispatch, and shutdown. It also evaluated the BESS capability to disconnect from the grid upon loss of the utility voltage. For the second test category, BESS type tests were intended to assess the general technical capability of the BESS (e.g., maximum real and reactive power, discharge energy capacity, ramp rate performance, ability

[1] Beginning Of Life (BOL)

to track varying charge/discharge commands, …). Upon completion of the BESS type tests, application tests were conducted to examine the performance of the BESS while activated on a certain application such as voltage regulation, back feeding, and State of Charge (SOC) management. To avoid duplication of effort for testing, some of the test cases are performed concurrently to collect associated test results.

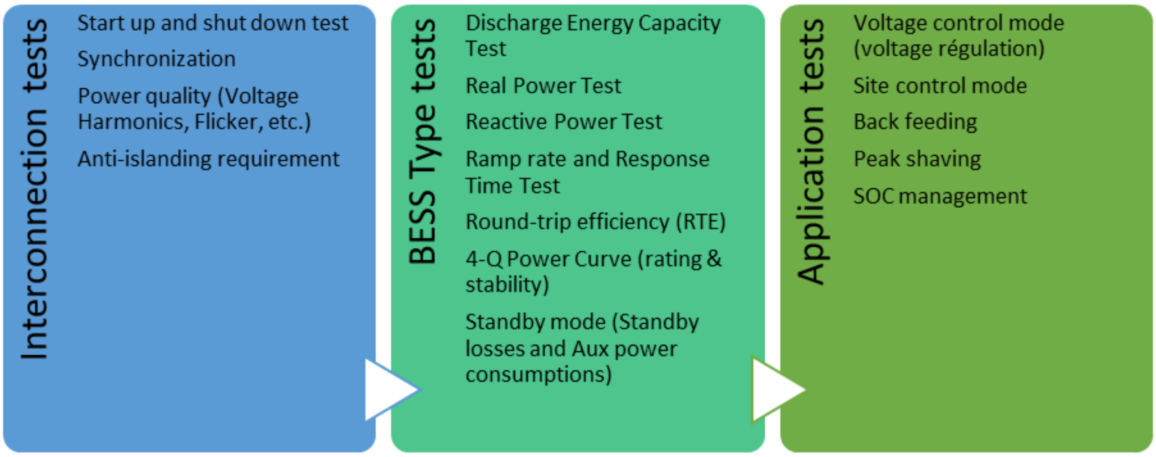

Figure 4 Different test cases performed during performance evaluation testing

3.2 COMPREHENSIVE DATA RECORDING AND DATA ANALYSIS

For comprehensive data recording, data from different sources including SCADA PI historian, BESS EMS, meters at the POI and POD as well as dedicated PQ meters were used during the testing. All measurements of charge/discharge rate, current and voltage at POI and POD, power quality parameters, energy imported/exported, SOC%, and other parameters that must be measured based on the standards, were collected simultaneously at a certain resolution applicable to the function of the BESS application and BESS metrics. All parameters were reported and used for further data analysis and reporting of BESS performance.

3.3 TEST DATA ANALYSIS AND RESULTS

This section summarizes the analysis of the data collected during the testing of the BESS. The test results have been presented for four main test cases:

a. Power Quality test case

The following describes the data analysis approach for the power quality test case:

- Maximum values for each parameter were compared with the acceptable range in IEEE519.
- Maximum and minimum values during each step when the BESS plant reached 98% of the commanded setpoints are investigated separately to evaluate the BESS power quality at certain MW and Mvar output.
- For the parameters which were outside of the acceptable range, the test results were investigated more to make sure external circumstances have not impact the measured values or additional factors needed to be taken into consideration such as when the plant was ramping up/ down.

The following highlighted outcomes summarize the most substantial findings from the power quality test case:

- Different steps during the Power Quality test case are shown in Figure 5. The individual voltage harmonics (%) and voltage THD values at POD (480 V) were within the IEEE 519 standard acceptable ranges (Figure 6). The maximum THD value at POD was 2.50% which is well below the maximum allowed by IEEE 519 standard (Figure 6).
- The data analysis showed the TDD values have remained within the acceptable range during the test but some of the individual current harmonics (%) have not met the acceptable ranges recommended in IEEE519. The maximum TDD value at POD was 2.01% which is well below the maximum allowed by the IEEE 519 standard (Figure 6). Further analysis revealed that except for 4th and 5th current Harmonic (%) other measurements have been recorded when the BESS plant acted as a var resource, or the output of the BESS was ramping up or down. There were specifically four instances of this occurring which caused the current harmonics to spike. Generally, when commanding the BESS with real power there did not seem to be an effect on the current harmonics. It should be noted the maximum measured 4th Current harmonic (%) during different test steps was 1.04% during the injection of +1MW into the grid.
- Test results during the different test steps highlight that an appropriate ramp rate should be considered when operating the BESS, especially in the worst-case scenario (operating the BESS plant at its maximum and minimum var capability).

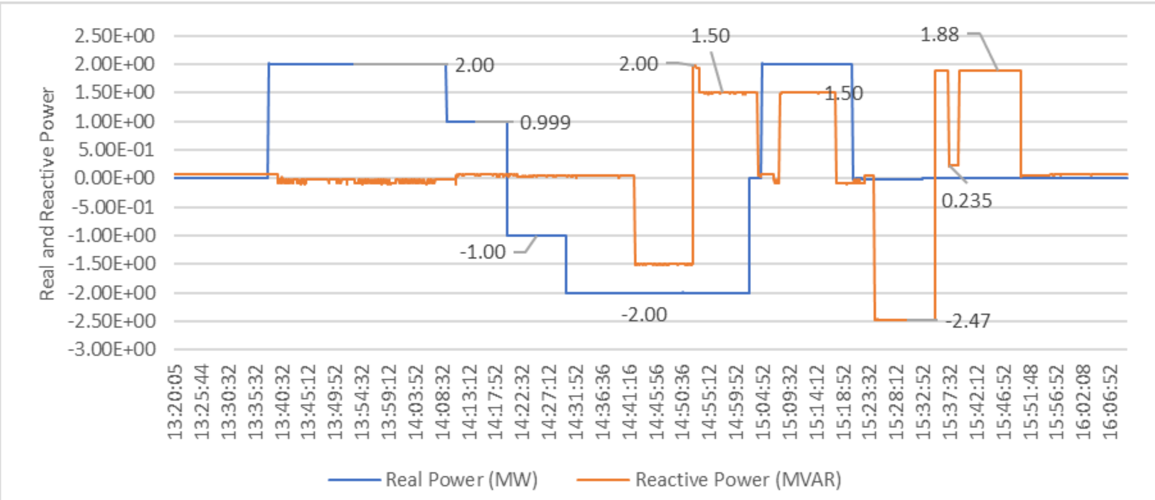

Figure 5 MW and Mvar output of the BESS during the power quality test

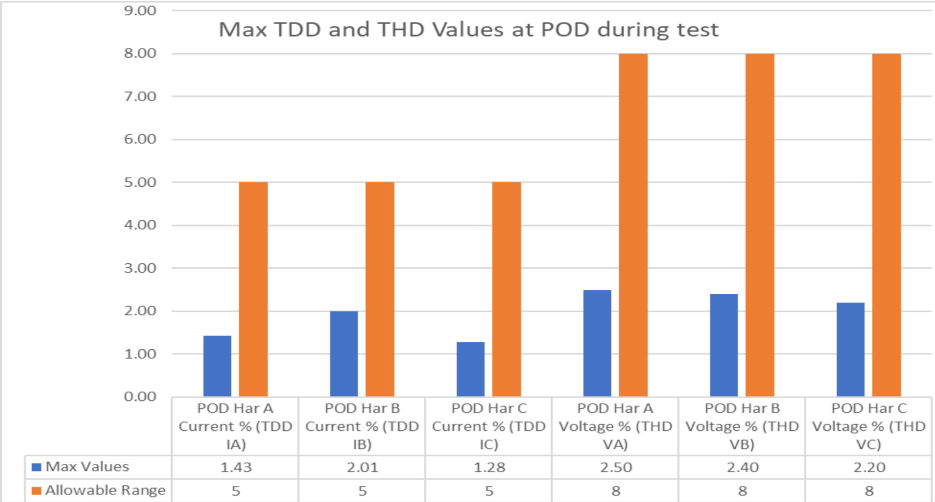

Figure 6 Maximum TDD and THD values versus IEE519 Standard during power quality test at the POD

b. Anti-Islanding test case

The main objective of this test was to evaluate the BESS's ability to disconnect from the grid upon loss of utility voltage (Inverters were set in the grid following). The following highlighted outcomes summarize the most substantial findings from the anti-islanding test case:

- The anti-Islanding logic in the BESS worked as expected with no issues. The POI recloser was opened and the BESS immediately shut off all outputs and reset the P and Q setpoints to zero. There was one anomaly seen during the testing which is with the THD value that shot up to 9.3% when the POI closed. This was due to the inrush of the GSU transformer energizing and was expected. No other anomalies were observed.

c. Ramp rate test case

The main objective of this test was to:

- Evaluate the BESS response time to a change of Psetpoint.
- Evaluate the BESS ramp rate from idle mode to full charge and monitor voltage change, due to sudden change in BESS operation from full discharge to full charge.
- Evaluate the BESS response while decreasing the BESS output to 50% (charge and discharge). This test simulated power output curtail orders.

The Calculated Ramp Rate was defined as:

$$\begin{aligned} Required\ Ramp\ Rate(1-2\%)(1-MeteringSystemError) &\leq CalculatedRampRate \\ &\leq Required\ Ramp\ Rate(1+2\%)(1+MeteringSystemError) \end{aligned}$$

$$Calculated\ Ramp\ Rate = \frac{P_{end} - P_{start}}{T_{end} - T_{start}}$$

The following highlighted outcomes summarize the most substantial findings from the ramp rate test case:

- All ramp rate tests were as expected where the BESS slowly ramped the output up or down at the programmed ramp rate (Figure 7). The calculated ramp rate based on the testing was within 2% of the programmed ramp rate (Table 1). Both the TDD and THD levels at POD were less than 3%, well below the IEEE 519 tolerable amount.

- Voltage during this test varied on the high side of 498 when discharging and on the low side of 490 volts when charging. This is a variation of 1.6% of nominal and was to be expected with the changing load of charging or discharging of the BESS on the grid.

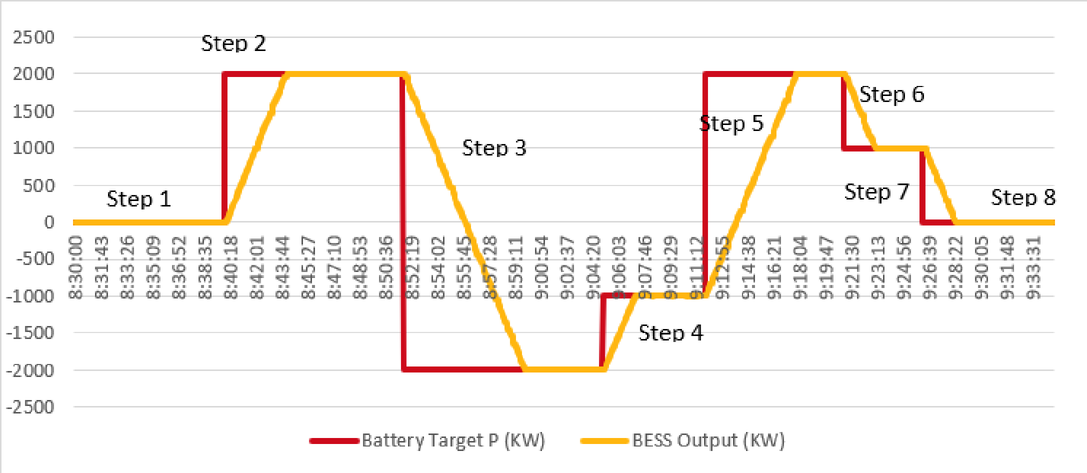

Figure 7 BESS Active Power Setpoints versus the BESS real power readings during ramp rate test

Table 1 Ramp Rate Test Results

Step	BESS Command Start Time	BESS Command Completion Time	Ramp Time in Seconds	Ramp Rate Actual kW/s	Programmed Ramp Rate kW/s	Deviation %
2	8:40:05	8:44:07	242	8.26	8.333	0.822
3	8:51:51	8:59:52	481	8.31	8.333	0.203
4	9:05:14	9:07:15	121	8.26	8.333	0.822
5	9:11:50	9:17:56	366	8.19	8.333	1.635
6	9:21:06	9:23:06	120	8.33	8.333	-0.004
7	9:26:30	9:28:30	120	8.33	8.333	-0.004

d. Back feeding test case

The main objective of this test was to evaluate the BESS's ability to operate in back-feeding mode following the SCADA commands and setpoints limiting back feeding, both in terms of power and energy.

The following highlighted outcomes summarize the most substantial findings from the back-feeding test case:

- Back feeding mode was successful at controlling the power level between the minimum and maximum levels set for the BESS. During testing, setpoints were chosen to control the power at the substation based on the load of the station and within reason of that loading. Figure 8 shows the results of the testing.
- During Step 2 the minimum and maximum setpoints were chosen to be the same and at 4000kW. The BESS was able to charge the BESS to bring the power level down from 4700kW to the setpoint of 4000kW and controlled the plant to that level. For Step 3 the min and max setpoints were set down to 3000 kW. Again, the BESS charge to absorb the 1800kW during the test period to keep the station at 3000kW level. Step 4 the Min and Max setpoints were chosen to be different to give the BESS an operating window of 3200kW and 3600kW respectively. During step 4 the loading in

the substation dropped to around 3000 kW and then dropped to 2019kW. During this time the BESS started to discharge to keep the power level between the Min and Max setpoints. During Step 5 back-feeding mode was turned off.

- During this test, TDD and THD levels were well within the IEEE 519 standard as shown in Figure 9.

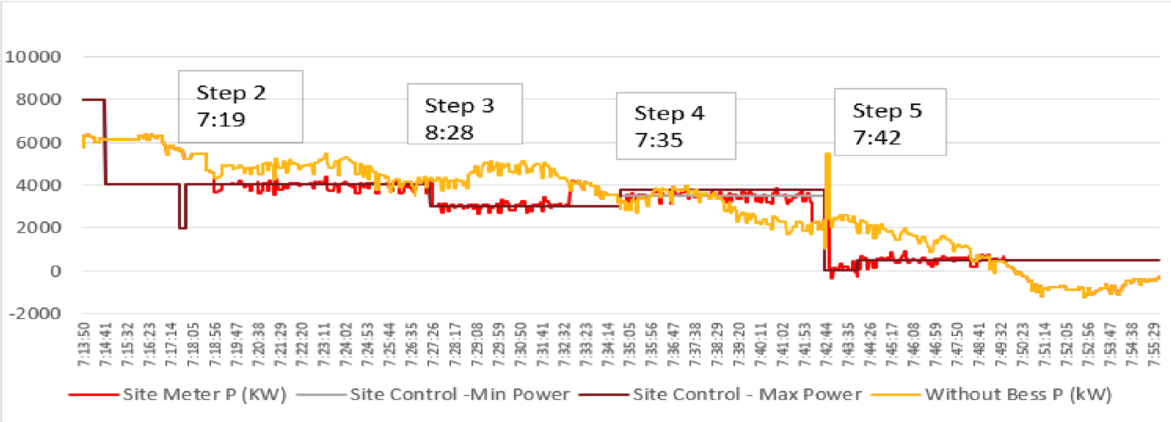

Figure 8 Commanded Power level vs Actual Power Level During Back Feeding Test Case

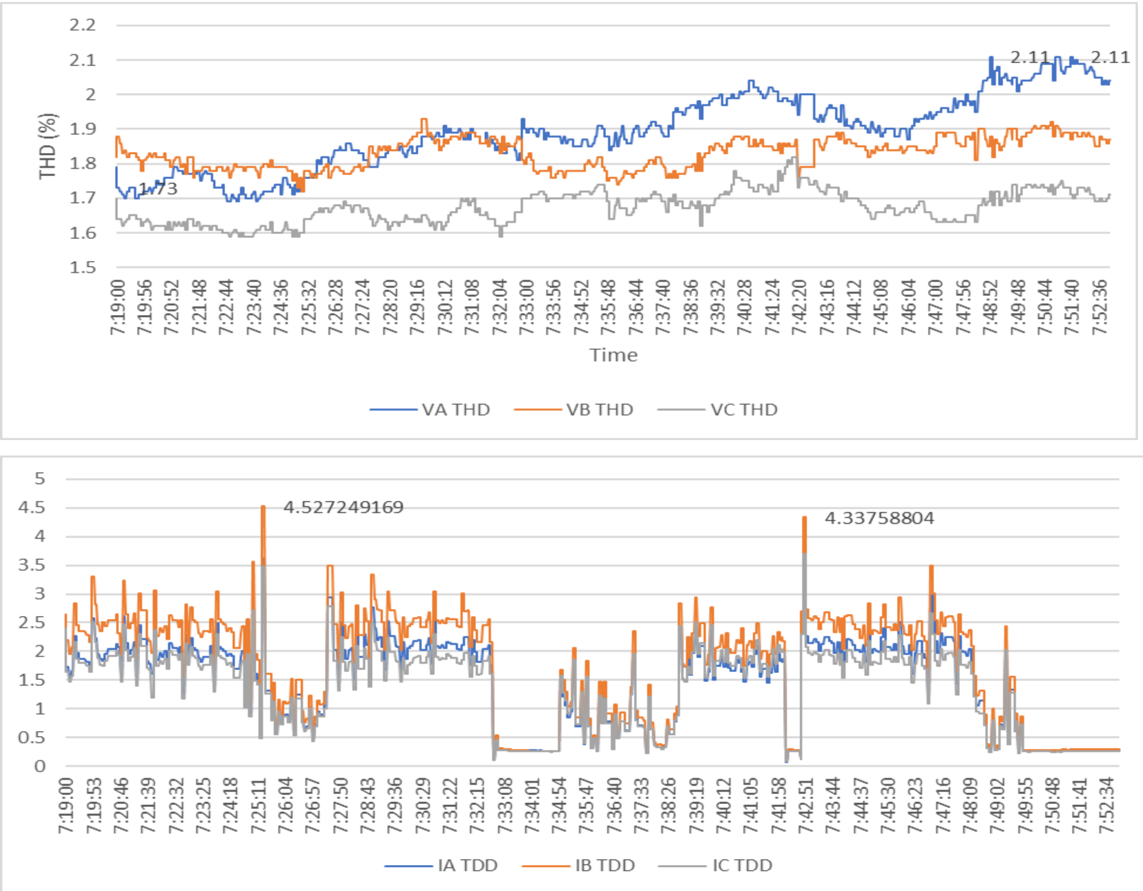

Figure 9 THD and TDD levels at POD during Back-Feeding Test

4 CONCLUSION

The main purpose of this paper was to discuss the importance of comprehensive testing protocols that can verify energy storage performance in grid deployment. The test plan development and approach for raw data collection and data analysis that can be used for a KPI evaluation were also presented. It was found that comprehensive performance evaluation testing beyond generic tests by the vendor is crucial to ensure the BESS performs as designed and meets the specified performance criteria and it helps to discover and correct problems before the system goes "online".

Furthermore, the test results showed the importance of evaluating the BESS plant under different operating conditions/modes (lower power levels or pure reactive power output) and not only the BESS maximum or minimum active power output. It also showed that a well-configured BESS with an appropriate ramp rate and settings can avoid/reduce voltage issues or harmonic distortion at different active and reactive power outputs.

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