Achieving Cooperative Community Equitable Solar Sources (ACCESS) Project

Performance Testing for Battery Energy Storage System Research with PNNL

Highlights

- NRECA, through the *Achieving Cooperative Community Equitable Solar Sources* (ACCESS) solar project, is working with multiple electric co-ops to research how to make solar energy affordable for communities with fewer financial resources and extend the benefits of solar development to low-and moderate-income (LMI) consumers.
- Battery Energy Storage Systems (BESS) can be employed to provide various ancillary services to the co-op distribution grids that, if properly monetized, could capture additional benefits for the co-ops from the deployed or soon to be deployed PV installations.
- Pacific Northwest National Laboratory (PNNL) will study the proposed co-op projects integrating BESS with PV to understand if and how the integrated PV/BESS assets can be utilized to achieve additional benefits.
- This advisory provides an overview of this research.

Project Overview

National Rural Electric Cooperative Association (NRECA), through the *Achieving Cooperative Community Equitable Solar Sources* (ACCESS) solar project, is working with multiple electric co-ops to research how to make solar energy affordable for communities with fewer financial resources and extend the benefits of solar development to low-and moderate-income (LMI) consumers. The participating co-ops are either in the process of deploying or have already deployed solar PV systems.

Battery Energy Storage Systems (BESS) can be employed to provide various ancillary services to the co-op distribution grids that, if properly monetized, could capture additional benefits for the co-ops from the deployed or soon to be deployed PV installations. As part of the ACCESS project, Pacific Northwest National Laboratory (PNNL) is studying the proposed co-op projects integrating BESS with PV to understand if and how the integrated PV/BESS assets can be utilized to achieve additional benefits. These insights will help NRECA and the ACCESS project participants consider a path forward for detailed investigation and demonstration of the benefits, with focus on the added benefits the BESS provides.

To evaluate the economic benefits of the BESS, reference tests need to be performed to characterize its performance. Performance can encompass many aspects relevant to economic benefits. These include the energy capacity, power capacity, the energy efficiency, the ramp rate, response time, and ability to follow a signal (based on the difference between requested and actual power). Details of such an analysis performed as part of the Washington Clean Energy Fund (WACEF) projects jointly funded by WACEF, U.S. DOE-OE and participating utilities can be accessed at https://www.osti.gov/servlets/purl/1602252/. This guide summarizes reference performance test procedures and relevant metrics for analysis of battery energy storage system (BESS) performance and performance stability.

The data produced from performance testing can be used to develop a model of how the battery's state of charge (SOC) changes as a function of the power. These models typically take the form:

$$\frac{dSOC}{dt} = f(P, SOC)$$

By accurately predicting the way the battery will perform in the field, a utility can operate it at maximum economic benefit.

Data Requirements

The data requirements for analyzing the performance are, at minimum: the power exchanged between the battery and the grid, the power requested of the battery, and the BESS SOC. Preferred data includes:

- Metered power at additional locations:
  - Measurement of alternating current (AC) power on both sides of transformer allows calculation of transformer efficiency.
  - Measurement of power of the AC and direct current (DC) side of the bi-directional inverter or power conversion system (PCS) allows calculation of PCS efficiency.
  - Measurement of auxiliary power consumption allows calculation of system round trip efficiency (RTE) with and without accounting for these losses.
- Measurement of DC current and voltage at the cell, module, string and system level allows for determination of battery internal resistance at several levels (cell, module, string, system), allowing assessment of uniformity in cell, module and string internal resistance, which can provide insights on performance and performance degradation.
- Measurement of temperature data at various levels enables assessing temperature distribution at the cell, module, string and system level; a non-uniform distribution can be a predictor for faster degradation.

For analyzing performance, typically one-minute time resolution is sufficient, but for analyzing pulse test and frequency regulation test results, a time resolution of at least one second is required. To establish baseline performance and subject the battery to preliminary use case testing, two months testing is typically sufficient, however more data does allow for better performance evaluation and for measuring any degradation in performance.

Test Procedures

The types of tests performed can be put into two categories: *reference performance tests* and *use case tests*. This document describes reference performance tests, and some select grid services tests, which are evaluated on all systems and allow estimation for the system's performance relative to its specifications. They can also be repeated over the test period, to measure the stability of the performance over time by comparison with initial test results, also referred to as *baseline performance*.

Reference performance tests are comprised of an energy capacity test, a pulse resistance test that also determines response time and ramp rate, and a grid services test that includes subjecting the battery to a generic frequency regulation signal and peak shaving signal.

- Energy capacity test: The BESS discharge and charge energy are measured at various power levels, with BESS round trip efficiency (RTE) calculated at the DC and AC level, with and without inclusion of auxiliary losses.
- Pulse resistance test: For charge and discharge, a 10-second pulse at rated power is applied at various state of charge (SOC) levels. Provides the ramp rate, response time, and battery DC internal resistance as a function of SOC.
- Grid services test: Applies generic frequency regulation signals[1] to shows the ability of the BESS to follow a rapidly changing signal. Also applies peak shaving signals[2], which shows the ability of the BESS to shave peaks [https://energystorage.pnnl.gov/pdf/PNNL-22010Rev2.pdf].

The use case tests are more specific to a given BESS installation site and are based on the available economic opportunities related to the site. Some examples of economic opportunities may include:

- demand charge reduction,
- transmission and distribution investment deferral,
- volt-VAR/conservative voltage reduction,
- outage mitigation,
- frequency regulation,
- energy arbitrage,
- renewable smoothing and firming, and
- load shaping.

These use case tests give a more specific view of a battery's performance for economically important use cases developed for the site.

A detailed test plan for PNNL's performance tests can be found at https://www.osti.gov/biblio/1474881, with individual test plans produced for each utility, and specific definitions of the tests performed and metrics analyzed.

[1] These generic signals have been used as a reference performance tests in some of the grid-scale energy storage projects PNNL has worked on.

[2] These generic signals have been used as a reference performance tests in some of the grid-scale energy storage projects PNNL has worked on.

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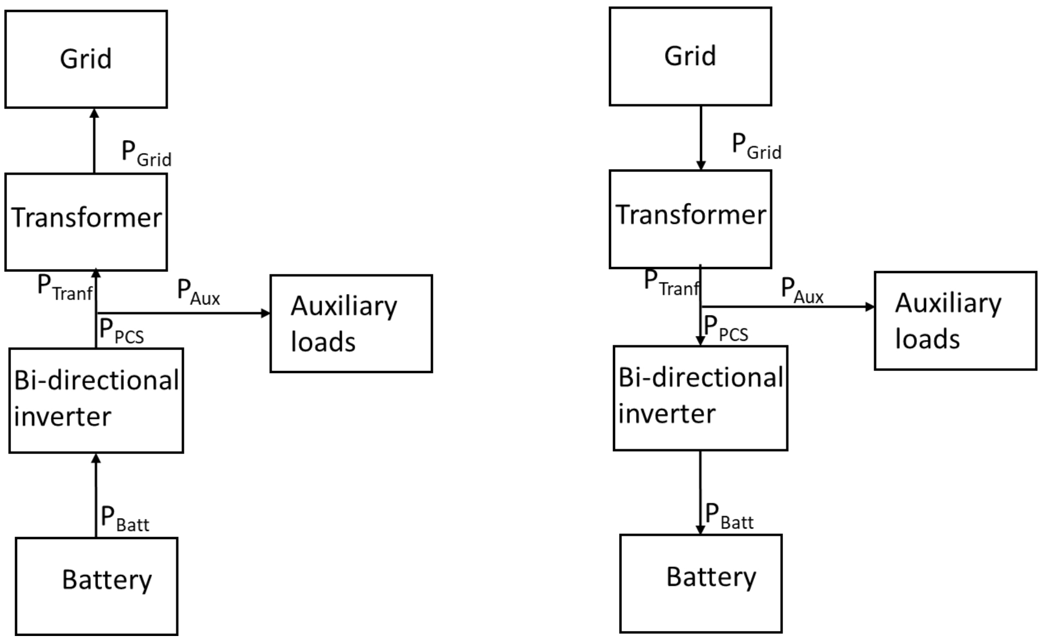
Analytics and Metrics

A typical power flow during discharge and charge for a Battery Energy Storage System is shown in Figure 1. Assigning direction of power flow during discharge as positive, charge occurs when $P_{Requested}$ is negative and vice versa. In this figure, P_{Batt} is DC, while the rest are AC power.

Figure 1. Power flow for a Battery Energy Storage System (left) discharge, (right) charge



During discharge, the efficiency for the bi-directional inverter or power conversion system (PCS) and transformer are given as:

$$\eta_{PCS} = \frac{P_{PCS}}{P_{Batt}}$$

$$\eta_{Trans} = \frac{P_{Grid}}{P_{Trans}}$$

During charge, the efficiency for the bi-directional inverter or power conversion system and transformer are given as:

$$\eta_{PCS} = \frac{P_{Batt}}{P_{PCS}}$$

$$\eta_{Trans} = \frac{P_{Trans}}{P_{Grid}}$$

The charge and discharge energy at various levels is given as follows:

The AC power exchange with the grid including auxiliary power consumption:

$$E_{chg\_grid} = \int (P_{Grid} < 0) P_{Grid} dt$$
$$E_{dis\_grid} = \int (P_{Grid} > 0) P_{Grid} dt$$

The AC power exchange with the grid excluding auxiliary power consumption:

$$E_{chg\_grid\_noaux} = E_{chg\_grid} + \frac{\int (P_{Grid} < 0) P_{Aux} dt}{\eta_{Trans}}$$
$$E_{dischg\_grid\_noaux} = E_{dis\_grid} + \eta_{Trans} \int (P_{Grid} > 0) P_{Aux} dt$$

The AC power exchange between transformer and PCS including auxiliary power consumption:

$$E_{chg\_Trans} = \int (P_{Grid} < 0) P_{Trans} dt$$
$$E_{dis\_Trans} = \int (P_{Grid} > 0) P_{Trans} dt$$

The AC power exchange between transformer and PCS excluding auxiliary power consumption:

$$E_{chg\_PCS} = \int (P_{Grid} < 0) P_{PCS} dt$$
$$E_{dis\_PCS} = \int (P_{Grid} > 0) P_{PCS} dt$$

The DC power exchange between the PCS and the battery excluding auxiliary power consumption:

$$E_{chg\_Batt} = \int (P_{Grid} < 0) P_{Batt} dt$$
$$E_{dis\_Batt} = \int (P_{Grid} > 0) P_{Batt} dt$$

Per standard convention, power is expressed in kilowatts (kW) or megawatts (MW); time in hours; and energy in kilowatts-hours (kWh) or megawatt-hours (MWh).

The energy discharged and charged is tabulated at each level as part of the energy capacity reference performance test. Periodic repetition of this test allows estimation of energy capacity stability.

Replacing the condition P_{Grid} < or > 0 with P_{req} < or > 0 provides corresponding charge and discharge energy excluding rest period when the site manager does not send power requests to the battery. This enables calculation of round-trip efficiency (RTE) at each level excluding power consumption during rest.

The RTE of the capacity performance tests at each level is given by the ratio of energy discharged to energy charged:

$$RTE = \frac{E_{dis}}{E_{chg}}$$

where E_{dis} is the energy discharged, and E_{chg} is the energy charged.

Also note that for this formula to hold, the SOC range for each half cycle must be the same, where a charge or discharge comprises a half cycle.

The approach outlined above is applicable to all grid services, including peak shaving generic duty cycle, where the battery is subjected to constant power charge and discharge of various durations.

For the pulse tests, the communication latency or lag is determined by taking the difference between the time when the site manager sends a power request and the time that the battery starts delivering or absorbing the requested power:

$$\tau_{lag} = t_{response\ start} - t_{power\ requested}$$

The ramp rate is calculated by simply dividing the power[3] during the peak of the pulse by the time it took to get there from rest:

$$Ramp\ rate = \frac{P_{peak}}{t_{peak\ power} - t_{response\ start}}$$

The response time is given by:

$$\tau_{response} = t_{peak\ power} - t_{response\_start}$$

Note that the power during the peak of the pulse has to be within 1% of the requested power for the BESS response to be termed adequate.

To calculate the internal resistance, the difference in DC voltage between the start and peak of the pulse is divided by the difference in current over the same time period:

$$IR = \frac{V(t = t_{peak\ power}) - V(t = t_{response\ start})}{I(t = t_{peak\ power}) - I(t = t_{response\ start})}$$

Finally, for tests such as the frequency regulation duty cycle where the battery's ability to follow a signal is measured, the root mean square error (RMSE) is calculated:

$$RMSE_{Power} = \sqrt{\frac{\int_{t_i}^{t_f} (P_{signal} - P)^2 dt}{t_f - t_i}}$$

where t_f and t_i are the final and initial times, respectively.

[3] Typically, for this test, this peak power is simply the rated power of the BESS.

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The BESS energy management system (EMS) needs to ensure that power exchanged with the grid, after accounting for auxiliary consumption and the PCS and transformer efficiencies, matches the requested power. A common error occurs at the software layer at PCS/EMS interface, when it commands the DC battery to provide or absorb power, such that P_{PCS} matches the requested power, thus ensuring deviation from the signal related to auxiliary power consumption and PCS and transformer efficiency.

The metrics described are applicable to multiple grid services. For example, RTE is applicable to all grid services except Volt/Var, which involves exchange of reactive power with the grid. Reference signal tracking applies to all grid services except those with constant power demand, such as peak shaving. Pulse test results for response time, ramp rate, and internal resistance are applicable for all grid services.[4] For all grid services, the SOC of the battery needs to be maintained within its safe and allowable operating envelope.

Learning Objectives

This research is pursuing the following learning objectives:

- Learn how NRECA, PNNL and multiple co-ops are working to expand the benefits of deploying solar PV and energy storage systems to communities with fewer financial resources.
- Learn how grid services may help co-ops offset the total installed DER/solar costs.
- Learn about potential grid benefits of PV smart inverters, including peak load and line loss reduction, switching operation minimization, and distribution grid investment deferral.
- Learn about the financial impacts (i.e., benefit, value, and cost to implement) of operating solar PVs, smart inverters, and battery storage to provide grid services.
- Learn about BESS performance and reliability in the field.
- Learn about the participating co-ops' (Oklahoma EC and OPALCO) experience with solar PV, battery storage, and valuation of distribution grid services.
- Share other use cases that are near-term that may fit electric co-op operations.

Additional Resources

- ACCESS Website: https://www.cooperative.com/programs-services/bts/access/Pages/default.aspx

Authors

This advisory was written by Alasdair Crawford and Vilayanur Viswanathan of PNNL.

Contacts for Questions

Tolu Omotoso, NRECA Energy Solutions Director: Tolu.Omotoso@nreca.coop

Lisa Slaughter, NRECA Research Software Engineer and Data Scientist: Lisa.Slaughter@nreca.coop

[4] For volt/VAR signals, response time and ramp rate can be calculated, internal resistance is not applicable.

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