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Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems

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Prepared by

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Richland, Washington

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Albuquerque, New Mexico

for the Office of Electricity Delivery and Energy Reliability (OE1)

Funded by the Energy Storage Systems Program of the U.S. Department of Energy
Dr. Imre Gyuk, Program Manager

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Foreword

The *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems* (PNNL-22010) was first issued in November 2012 as a first step toward providing a foundational basis for developing an initial standard for the uniform measurement and expression of energy storage system (ESS) performance. Based on experiences with the application and use of that document, and to include additional ESS applications and associated duty cycles, test procedures and performance metrics, a first revision of the November 2012 Protocol was issued in June 2014 (PNNL-22010 Rev. 1). As an update of the 2014 revision 1 to the Protocol, this document (the April 2016 revision 2 to the Protocol) is intended to supersede the June 2014 revision 1 to the Protocol and provide a more user-friendly yet more robust and comprehensive basis for measuring and expressing ESS performance. This foreword[1] provides general and specific details about what additions, revisions, and enhancements have been made to the June 2014 Protocol and the rationale for them in arriving at this April 2016 Protocol (PNNL-22010 Rev. 2 / SAND2016-3078 R).

Dynamic Updating Process

Because energy storage technology development and deployment are dynamic, and as a result, the technologies and the applications and metrics needing to be covered in test standards continue to evolve, the provisions in the Protocol must continue to evolve to more fully address the wide scope and purpose stated in Sections 1 and 2 of the Protocol. For instance, further enhancements have been made since the initial publication of the Protocol in 2012, including the addition of one more storage application in the June 2014 revision 1 to the Protocol, and five more applications in this April 2016 revision 2 to the Protocol, along with refinements to the way some performance metrics are determined. This April 2016 revision 2 to the Protocol also includes new system performance metrics and additional general information and technical specifications associated with ESSs. The dynamic nature of storage technology development and the growing demand for performance information by the many different entities involved with energy storage deployments supports continual and ongoing work to enhance the Protocol. The continuing need for uniformity and comparability of the reported performance information for all storage technologies and the growing need for more types of performance-related information suggests that the Protocol will need to be revised and republished at reasonable intervals in the future to best serve the needs of all those who want to document ESS performance or who need such documentation to make decisions about the application and use of ESSs.

The development of the first edition of a brand new standard can take considerable time, especially when those participating in development of the standard must “start from scratch.” Once approved and published, standards are generally updated and revised on a three- to five-year cycle and, in some cases, interim addenda covering needed revisions or enhancements to a standard are also issued. When first published in 2012, it was a goal that the Protocol would provide a foundational basis for brand new standards covering the topic of ESS performance so that standards development organizations (SDOs) did not have to “start from scratch.” That has been realized through the use of the Protocol by U.S. SDOs as

[1] The information presented in this foreword is not part of the protocol. It is merely informative and does not contain requirements necessary for conformance with or use of the protocol.

well as internationally through International Electrotechnical Commission (IEC) Technical Committee 120 who, among others, are developing an IEC standard for measuring and expressing ESS performance using the Protocol as a basis for the provisions in the standard. In addition to these formal standards development efforts by SDOs, the Energy Storage Integration Council (ESIC), under the auspices of the Electric Power Research Institute (EPRI), is also developing information for utilities to use in fostering their consideration and application of energy storage technology that in part covers ESS performance. Such efforts outside those of SDOs provide an additional opportunity for deployment of the Protocol in the short term until formal standards are approved and published by the sponsoring SDO.

As formal standards are completed and available from and updated by SDOs, ongoing Protocol enhancement efforts will continue to provide recommendations and relevant documentation that can support updating of those standards. Until the standards are completed and published, this document and future versions of it provide the foundation and focal point for a uniform, consistent, and comparable basis for measuring and expressing system performance. The intention is to continuously enhance the Protocol based on a process open to all stakeholders on an equitable basis that provides them an opportunity to participate and provide input, while also being sensitive to the need for continuity as enhancements to the Protocol are developed over time. Hence, the Protocol is expected to be updated at least biennially or more frequently if warranted through needed subgroups focusing on specific issues that again are open to any and all stakeholders. The updating process will include a cutoff time after which additional revisions will be deferred to the next revision cycle. Work on the deferred revisions will continue, but publication of an updated Protocol will occur no more frequently than annually.

Protocol Enhancement Overview

The enhancements contained in this document are based on a number of concurrent activities that were undertaken predominantly during 2015. One set of activities, hosted by Pacific Northwest National Laboratory and Sandia National Laboratories, involved the addition of criteria to cover five new applications for ESSs. Those new applications are photovoltaic (PV) smoothing, volt/var support, renewables (solar) firming, power quality, and frequency control. An overview of the revisions to the Protocol associated with each of these five new applications is provided below, but in general, the revisions involved the development of a duty cycle for each new application and guidance on how to determine the values of the relevant metrics for each application. Beyond the addition to the Protocol of criteria to cover new applications and metrics, minor adjustments were made to the Protocol based on experiences from its application and use along with a significant change to simplify the organization of the document to make it more user friendly.

In response to needs of the utility sector as presented on their behalf through the EPRI ESIC, a number of enhancements were made to the Protocol. One focuses on the inclusion of general information and technical specifications associated with ESSs that utilities and other ESS users need above and beyond the performance metrics and test procedures covered in the Protocol. Other revisions were focused on technical clarifications and enhancements. For instance, capacity typically denotes power in the context of the grid. Hence, *energy capacity* (which has been used in prior editions of the protocol) has been replaced by *energy* in this edition of the Protocol to avoid confusion. While consideration was given to a recommendation to now use state of energy to describe the ESS state, state of charge (SOC) has been retained because SOC associated with batteries is what the battery management system relies on in controlling the ESS. Since the Protocol also applies to other types of storage (e.g., other than batteries) SOC is also appropriate to capture their state. The EPRI ESIC also suggested that 100% SOC should be the maximum SOC and 0% SOC should be the minimum SOC when conducting certain tests. However, to require the ESS to be charged to 100% SOC and discharged to 0% SOC is overly prescriptive and could compromise an ESS where the manufacturer may not want their ESS to be discharged to 0% SOC. Instances involving terms that were defined but not used in the document were identified and those terms deleted from the definitions. Definitions of some of the new applications for an ESS were also enhanced based on input from the EPRI ESIC in addition to including an equation for considering auxiliary power when auxiliary loads are powered by separate power sources. One comment suggested that an ESS can be used for power quality only in an islanded mode. It is not clear that is the case, and the provisions covering this new application were not changed from the final draft developed by the subgroup that developed the power-quality–related provisions in the Protocol. In addition, the 1-minute, 1–5 minute, and 10-minute peak power tests for this application were identified as not necessary. Since the overload capability of the power conversion system depends on duration, it was decided these tests would be retained as drafted by the subgroup. A comment about the rigor of data sampling frequency was also provided. Based on the application and use of the Protocol for frequency regulation, which has been covered in the document since late 2012, data every second appears to be necessary for frequency regulation and other applications where the ESS is subjected to signals frequently. For peak shaving or energy arbitrage, data every 10 seconds was considered sufficient. On this issue, those developing the document feel the data acquisition frequency should be at least double the rate of the signal being sent to the ESS.

As noted above, the intent of this document is to provide a foundation for formal standards developed by SDOs. The process for development and updating of this document is dynamic and intended to provide all stakeholders the opportunity to provide input through subgroups that are established to focus on additions and enhancements to the document (e.g., new applications, new metrics, and adjustments based on use of the document).

New Organization of Content

The organization of the November 2012 Protocol and its June 2014 revision was somewhat complicated in that it contained more sections than necessary in outlining the steps associated with using the Protocol. It also repeated a considerable amount of content for each ESS application that could have been presented once. This organization, while somewhat cumbersome, did make it easier to choose an application and then follow through the Protocol for all the relevant provisions for that application. In essence, the Protocol contained a separate “track” for each of the initial two and then the one additional application added in June 2014, even though the content in each track was in many cases identical. In revising the Protocol to include five more applications and address additional metrics, it became clear that continuing this organization would increase the complexity of using the Protocol (i.e., now eight separate tracks) and make it less desirable to apply or to use as a basis for more formal standards. This April 2016 revision 2 to the Protocol has eliminated the separate-track approach and replaced it with three core sections that can be more easily applied to any ESS and the eight applications now covered in the Protocol. In addition, this organization will facilitate the seamless inclusion of additional applications and metrics over time while not compromising the ease of use of the document.

Section 4 of the Protocol provides an overview of the Protocol and how it is to be applied to any ESS. Section 5 provides the detail associated with the relevant performance metrics, test procedures to measure performance data associated with the metrics, as well as the duty cycle that is relevant to each application and is used to guide testing associated with duty-cycle relevant metrics. Section 6 simply provides the guidance for uniformly reporting the value of each metric based on the requirements in Section 5, covering testing, data gathering, and use of the data in calculating the relevant metrics associated with the ESS. This makes it much easier to address those items that are not dependent on duty cycle one time for all ESSs regardless of application. Beyond that, the testing, measurement, and calculation of the metrics that are related to duty cycle and unique to each application and their reporting is also only presented once, noting that they would have to be repeated for each of the applications for which the ESS was intended based on subjecting the ESS to a duty cycle that is unique to each of the eight applications covered in the Protocol.

New Applications

As noted in the overview, five new ESS applications have been added to the three applications (peak shaving, frequency regulation and islanded microgrids) covered in the June 2014 revision 1 to the Protocol. These are listed in Table 4.3 of the Protocol, which now covers eight applications. Each of these five new applications is then addressed in the same manner as the prior three applications; that is, they are listed along with the metrics that are applicable to each application, provisions have been added to provide a duty cycle for each new application, and the measurements to make when applying the duty cycle, determination of applicable performance metrics from these measurements, and the details associated with reporting those metrics are outlined. Specific detail on each of these new applications is provided in the following descriptions.

PV Smoothing

PV smoothing is the use of an ESS to mitigate rapid fluctuations in variable PV power output. The purpose of PV smoothing is to mitigate frequency variation and stability issues that can arise at both feeder and transmission levels in high penetration PV scenarios to help meet ramp rate requirements. At the feeder level, PV smoothing is implemented to mitigate voltage flicker and voltage excursions outside desired bands. At the transmission level, PV variability can require additional operating reserve to be set aside and can cause traditional generation to cycle more than otherwise. The method by which the ESS can provide smoothing of PV output power is to absorb or supply power at appropriate times as determined by a control system resulting in a less variable composite power signal at the feeder and/or transmission level.

Permission was given by the Public Service Company of New Mexico (PNM) to the PV smoothing subgroup of the Protocol Working Group to use PV power output (expressed in kW) and battery power output (expressed in kW) from the PNM Prosperity Project for construction of the PV smoothing duty cycle [see Roberson et al. (2014) for a description and analysis of the project]. The data featured one-second time resolution and is archived going back to 2011.

The duty cycle is constructed by capturing one-hour "slices" of PV generation from different days and splicing these slices together into a composite signal of 10 hours in length. The majority of these slices represent moderate to very high levels of PV variability. Thus, the composite signal will lead to an aggressive tracking signal. Different times of the day and times of the year can be captured by one signal. The tracking signal is then computed by subtracting the 30-minute moving average of the composite "day" from the composite signal itself. The duty cycle is obtained by normalizing the tracking signal to the rated power of the smoothing battery. Care was taken to ensure that the full "day" signal as well as each hour of this day is sufficiently close to net energy neutral.

The relevant metrics for PV smoothing are listed below.

Reference performance metrics

- system rating
- round-trip energy efficiency
- response time
- ramp rate
- energy
- energy stability

Duty-cycle–specific metrics

- reference signal tracking
- SOC excursion
- duty-cycle round-trip efficiency
- maximum ambient temperature, measured in degrees Fahrenheit.

Volt/Var

A volt/var application addresses fluctuations in grid voltage by providing volt-amperes reactive (var) support, injecting vars as grid voltage dips and absorbing vars as grid voltage increases. The ESS is assumed to be deployed only for volt/var support; hence, the full power rating of the ESS is available for this duty cycle. This work builds on the work done by the Smart Inverter Working Group (SIWG) convened by the California Public Utility Commission (CPUC) and the California Energy Commission. The SIWG provided a set of recommendations to the CPUC on February 7, 2014. Based on these recommendations, the three investor-owned utilities in California— Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company—proposed revisions to the California Electric Tariff Rule 21. The CPUC has not yet ruled on the proposed revisions.

Based on these proposed revisions, Underwriters Laboratories (UL), Sandia National Laboratories, EPRI, Xanthus Consulting, the SunSpec Alliance, Loggerware, utilities, and PV inverter manufacturers developed a protocol to test smart inverters under a California Solar Initiative grant (Johnson et al. 2013a, Johnson et al. 2013b, Johnson et al. 2014, UL 2015).

The relationship developed by the SIWG of ESS var output as a function of grid voltage was used to develop duty cycles for the volt/var application by simulating grid voltage at representative feeder locations using GridLAB-D™. The voltage at the point of common coupling for a PV system at one end of a 4 kV feeder was also subjected to the SIWG relationship to develop duty cycles. The metrics that were determined to be relevant for volt/var are listed below. Note that duty cycle round-trip efficiency, which is a metric for other applications, is not relevant to volt/var applications since no real power is being exchanged.

Reference performance metrics:

- round-trip efficiency
- response time and ramp rate
- energy
- energy stability

Duty-cycle–specific metrics:

- reactive power ramp rate at 50% SOC (This is a new metric and uses the same procedure as real power ramp rate.)
- round-trip efficiency
- reference signal tracking
- ΔSOC_volt/var, which is the difference between the final and initial SOC
- ΔSOC_active standby, which is the difference between the final and initial SOC at the end of an active standby period of the same duration as the volt/var duty cycle with auxiliary loads turned on, with the initial SOC the same as the value at the start of the volt/var duty cycle
- Wh_discharge, which is the real energy injected (with and without the volt/var duty cycle)
- Wh_charge, which is the real energy absorbed (with and without the volt/var duty cycle)
- Wh_net, which is the net energy (injected or absorbed) (with and without the volt/var duty cycle)

Renewables Firming

Renewables (solar) firming is the application of an ESS to provide energy to supplement renewable (solar) generation such that their combination produces steady power output over a desired time window. More precisely, the purpose of renewables firming is to provide energy (or conversely, to *absorb* energy) when renewable generation falls below some threshold (or conversely, *exceeds* this threshold). This application is performed to provide steady power output over a desired time window, usually a period of multiple hours. Typically, the threshold is based upon the forecasted nominal renewable power generation over the desired time window. Thus, the ESS is compensating for the forecast uncertainty in actual renewable generation during that time window. The method by which the ESS performs this application is described as follows. The ESS discharges power during periods for which renewable generation falls short of the threshold and absorbs power when renewable generation exceeds this threshold.

Generally, to yield multiple hours of steady power output, the time periods over which the ESS attempts to firm power output are normally in the range of minutes, with 15-minute time windows being common. The key differentiator between smoothing and firming applications can be explained as follows. Smoothing is applied to limit ramp rates, typically in the one-second to one-minute time periods. Firming is more appropriately applied in the 15-minute to several-hour time periods.

As with PV smoothing, data from the PNM Prosperity Project was used for construction of the renewables (solar) firming duty cycle [see Roberson et al. (2014) for a description and analysis of the project]. The construction process is similar to PV smoothing except that the time windows of interest are in the minutes to hours range, rather than seconds to minutes.

The relevant metrics for renewables (solar) firming are listed below.

Reference performance metrics:

- system rating
- round-trip energy efficiency
- response time
- ramp rate
- energy
- energy stability

Duty-cycle–specific metrics:

- reference signal tracking
- SOC excursion
- duty-cycle round-trip efficiency
- maximum ambient temperature, measured in degrees Fahrenheit

Power Quality

A sag or interruption in voltage can cause power disturbances that negatively impact power quality. This problem can be more common in distribution systems compared to transmission systems. Energy storage can mitigate voltage sags by injecting real power for up to a few tens of seconds. The application of an ESS to address power quality does not require the ESS to provide enough energy for customers to ride through an outage of greater than 10-minute duration. The duty cycle consists of continuous discharge at peak power for durations of 1, 5, and 10 minutes, where peak power is defined as maximum power delivered by the ESS for each of those time durations. The vendor and/or end user determines the SOC range for each duty cycle. Since power quality involves discharge, the starting SOC can be as high as 100%, with the lower limit at 20% (to ensure the ESS can provide peak power at the lower limit of the SOC range).

The ESS ramps to the power specified and stays there for the specified duration. The duty-cycle duration is adjusted such that total discharge capacity does not exceed energy withdrawn at rated power for one hour. This is to ensure that an unnecessarily heavy burden of energy requirement is not placed on the ESS, which could necessitate a derating of its power. In the development of the duty cycle for this application, it was determined that, for power-intensive applications, derating the power to satisfy an arbitrarily long duty cycle does not appear to be practical. The metrics that are relevant to a power quality application of ESS are listed below.

Reference performance metrics:

- round-trip efficiency
- response time and ramp rate
- energy
- energy stability

Duty-cycle–specific metrics:

- peak discharge power for durations of 1, 5, and 10 minutes
- duty-cycle round-trip efficiency
- reference signal tracking
- SOC excursion

Frequency Control

The conventional name for the service provided by an ESS in this application is frequency response, but for the purposes of the Protocol, the term “frequency control” was selected. In this service, there is a sudden loss of generation that must be made up through a discharge from the ESS. There can also be a sudden loss of load, requiring the ESS to charge, however that situation is not a net zero energy signal (unlike frequency regulation), since power flows in one direction during this service—discharge or charge.

In revising the Protocol to cover a frequency control application, it was assumed that tertiary frequency control is provided by other generators and that the ESS provides primary and secondary frequency control. The primary frequency control lasts 30 seconds; from that point until 20 minutes has elapsed, the secondary frequency control process occurs. As secondary frequency control starts at 30 seconds, the power provided by assets for primary frequency control decrease, and the power levels provided by primary and secondary controls sum to a constant.

If the ESS provides only primary frequency control, it ramps up to its 1-minute peak power and stays there for 30 seconds. Here, peak power is defined as the maximum power the ESS can provide for 1 minute continuously, which is a new metric relevant to this application.

If the ESS provides both primary and secondary frequency control, it simply ramps up to its 20-minute peak power (the maximum power the ESS can provide for 20 minutes) and stays there for 20 minutes.

Duty cycles for primary and secondary frequency control were developed, with the control events lasting up to 30 seconds and 20 minutes, respectively. The energy storage power used at an actual 2 MW storage system as the grid frequency deviated from its nominal frequency was also used as a basis to develop a linear relationship between storage power and normalized grid frequency deviation. The distribution grid frequency data was obtained from a utility for spring, summer, autumn, and winter; using the linear relationship that was developed, a duty cycle was developed for each of the four seasons. The metrics that were determined to be relevant for volt/var are listed below.

Reference performance metrics:

- round-trip efficiency
- response time and ramp rate
- energy
- energy stability

Duty-cycle–specific metrics

- peak power for 1 minute during charge and discharge

- peak power for 20 minutes during charge and discharge
- duty-cycle round-trip efficiency
- reference signal tracking

New Metrics

As discussed above, a new duty cycle had to be developed for each of the five new applications. While no new general metrics were added to the Protocol to cover these new applications, there were new metrics deemed relevant to each of the new duty cycles. These new metrics are listed below for each of the new applications that had new metrics included in the Protocol.

Volt/Var

- reactive power ramp rate at 50% SOC, determined using the same procedure as real power ramp rate. The ESS is brought to 50% SOC and the time taken to go from 0 to 100 percent reactive power in the positive direction (capacitive) and in the negative direction (inductive) is measured.
- ΔSOC_volt/var – the ΔSOC between the end and the beginning of the volt/var duty cycle
- ΔSOC_active_standby – the ΔSOC between the end and the beginning of a 24-hour active standby with auxiliary load turned on, with the initial SOC the same as the value at the start of the volt/var duty cycle
- the real energy injected (with and without the volt/var duty cycle)
- the real energy absorbed (with and without the volt/var duty cycle)
- the net energy (injected or absorbed) (with and without the volt/var duty cycle)

Power Quality

- peak power at discharge of 1, 5, and 10 minutes.

Frequency Control

- peak power at 1 minute and 20 minutes for charge and discharge

Technical Specifications

As noted above, the EPRI ESIC requested that additional information be included in the Protocol that utilities and others could use in making decisions about the application and use of an ESS. This additional information was developed by a working group of the ESIC, and included performance metrics that were already covered in the June 2014 revision 1 to the Protocol. The information requested also included general information relevant to ESSs as well as certain technical specifications associated with an ESS—that is, items not necessarily related to the performance of an ESS for any specific ESS application, but information broadly applicable to all ESS regardless of application. Section 4.2 of the June 2014 revision 1 to the Protocol provided for a description of the ESS including its weight, volume, and footprint (area). That section has been enhanced and the April 2016 revision 2 to the Protocol includes a Table 4.4.1 of general information and technical specifications that include those prior items and adds additional items, such as operating temperature range and required clearances.

Acronyms and Abbreviations

AC	alternating current
CPUC	California Public Utility Commission
DAS	data acquisition system
EPRI	Electric Power Research Institute
ESIC	Energy Storage Integration Council
ESS	energy storage system
IEEE	Institute of Electrical and Electronics Engineers
kW	kilowatt(s)
kWh	kilowatt-hour(s)
min	minute(s)
MW	megawatt(s)
PNM	Public Service Company of New Mexico
P_R	rated power
PV	photovoltaic
RR	ramp rate
RR_C	charge ramp rate
RR_D	discharge ramp rate
RT	response time
RT_C	charge response time
RT_D	discharge response time
RTE	round-trip energy efficiency
SDO	standards development organization
SDR	self-discharge rate
SELR	standby energy loss rate
SIWG	Smart Inverter Working Group
SOC	state of charge
var	volt-ampere(s) reactive
Wh	watt-hour(s)

Contents

Foreword ... iii
Acronyms and Abbreviations ... xiii
Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems ... 1
1.0 Purpose ... 1
2.0 Scope ... 1
3.0 Definitions ... 1
4.0 Overview ... 4
4.1 Intent. ... 4
4.2 Description of the Energy Storage System. ... 5
4.3 Identification of the ESS Application. ... 5
4.3.1 Peak Shaving (Management). ... 5
4.3.2 Frequency Regulation. ... 7
4.4 ESS Specifications and Performance Metrics. ... 7
4.4.1 Subsystems and Components. ... 7
4.4.2 System Ratings. ... 7
4.5 Measurement Procedure and Determination of Performance Metrics. ... 10
4.5.1 Inputs ... 10
4.5.2 Outputs ... 10
4.6 Reporting and Displaying Information, Specifications and Performance ... 11
5.0 Test Methods and Procedures ... 11
5.1 Comprehensive Data Recording. ... 11
5.2 Reference Performance. ... 11
5.2.1 Stored Energy Capacity. ... 11
5.2.2 Round-Trip Energy Efficiency. ... 13
5.2.3 Response Time and Ramp Rate. ... 14
5.2.4. Standby Energy Loss Rate. ... 17
5.2.5. Self-Discharge Rate. ... 17
5.3 Application Duty Cycles. ... 18
5.3.1 Peak Shaving Application Duty Cycle. ... 18
5.3.2 Frequency Regulation Duty Cycle. ... 20
5.3.3 Islanded Microgrid Duty Cycle. ... 20
5.3.4 PV Smoothing Duty Cycle. ... 22
5.3.5 Volt/Var Support Duty Cycle. ... 23
5.3.6 Renewables (Solar) Firming Duty Cycle. ... 26
5.3.7 Power Quality Duty Cycle. ... 27
5.3.8 Frequency Control Duty Cycle. ... 30

5.4 Duty-Cycle Performance. 34
5.4.1 Duty-Cycle Round-Trip Efficiency. 35
5.4.2 Reference Signal Tracking. 35
5.4.3 State-of-Charge Excursions. 37
5.4.4 Energy Capacity Stability 37
5.4.5 Additional Metrics 37
6.0 Reporting ESS General Information, Specifications, and Performance Results 39
6.1 Energy Storage System Description, General Information, and Technical Specifications. 39
6.2 Energy Storage System Reference Performance. 40
6.3 Energy Storage System Duty-cycle Performance. 42
7.0 Referenced Standards 44
8.0 References 44
Normative Appendix A – Duty-Cycle Signal for Peak-Shaving Applications of Energy Storage Systems A.1
Normative Appendix B – Duty-Cycle Signal for Frequency-Regulation Applications of Energy Storage Systems B.1
Normative Appendix C – Duty-Cycle Signal for Islanded Microgrid Applications of Energy Storage Systems C.1
Normative Appendix D – Duty-Cycle Signal for PV Smoothing Applications of Energy Storage Systems D.1
Normative Appendix E – Duty-Cycle Signal for Volt/Var Support Applications of Energy Storage Systems E.1
Normative Appendix F – Duty-Cycle Signal for Renewables (Solar) Firming Applications of Energy Storage Systems F.1
Normative Appendix G – Duty-Cycle Signal for Power Quality Applications of Energy Storage Systems G.1
Normative Appendix H – Duty-Cycle Signal for Frequency Control Applications of Energy Storage Systems H.1

Protocol[1] for Uniformly Measuring and Expressing the Performance of Energy Storage Systems

1.0 Purpose

This Protocol provides a set of "best practices" for characterizing energy storage systems (ESSs) and measuring and reporting their performance. It serves as a basis for assessing how an ESS will perform with respect to key performance attributes relevant to different applications. It is intended to provide a valid and accurate basis for the comparison of different ESSs. By achieving the stated purpose, the Protocol will enable more informed decision-making in the selection of ESSs for various stationary applications.

2.0 Scope

The Protocol identifies general information and technical specifications relevant in describing an ESS and also defines a set of test, measurement, and evaluation criteria with which to express the performance of ESSs that are intended for energy-intensive and/or power-intensive stationary applications. An ESS includes a storage device, battery management system, and any power conversion systems installed with the storage device. The Protocol is agnostic with respect to the storage technology and the size and rating of the ESS.

The Protocol does not apply to single-use storage devices and storage devices that are not coupled with power conversion systems, nor does it address safety, security, or operations and maintenance of ESSs, or provide any pass/fail criteria.

3.0 Definitions

The following definitions shall be applied within the context of this protocol for the purposes of performance testing. To be useful, test procedures must include definitions to narrow the margin for interpretation and increase the repeatability of tests. Terms not defined shall have their normal dictionary meaning and be applied as such when using the Protocol.

Area Control Error. A measure of the deviation of the actual interchange energy from the scheduled interchange energy on the ties with adjacent balancing authorities coupled with a frequency error component, a meter error component, a time error correction term, and an inadvertent energy payback term.

Area Regulation. A control signal from the balancing authority to devices that will respond to the control signal within the time frame specified by the balancing authority through a calculation by the balancing authority's energy management system of the area control error.

Auxiliary Loads. Loads associated with the operation of an ESS such as, but not limited to, controls, cooling systems, fans, pumps, and heaters necessary to operate and protect the system.

[1] When referring to "this protocol" or simply the protocol, it is intended the reference be to the April 2016 revision 2 of the protocol (PNNL 22010 Rev. 2 / SAND2016-3078 R).

Balancing Authority. The responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a balancing authority area, and supports interconnection frequency in real time.

Black Start. Black start refers to the process of restoring electric power from a complete blackout, without relying on an external power source.

Duration. The discharge time at rated power from the upper SOC limit to the lower SOC limit as specified for the application.

Duty Cycle. A charge/discharge profile that represents the demands associated with a specific application that is placed on an ESS.

Energy Efficiency. The useful energy output divided by the energy input to the ESS expressed as a percentage (Johnson et al. 2013a), including all parasitic energies needed to run the system, such as heating or cooling.

Energy Storage System Manufacturer. The entity that designs and assembles the various components that compose the ESS.

Energy Storage System, Self-Contained. Energy storage systems where the energy storage devices such as cells, batteries, or modules and any necessary controls, ventilation, illumination, fire suppression, or alarm systems are assembled, installed, and packaged into a singular energy storage container or unit.

Energy Storage System, Pre-Engineered of Matched Components. Energy storage systems that are not self-contained systems but instead are provided as separate components of a system by a singular entity that are matched and intended to be assembled as an ESS at the system installation site.

Frequency Control. The application of an ESS to control grid frequency through the discharge of power when there is a sudden loss of power from a generation source, or an acceptance of power when there is a sudden loss of load on a generation source.

Frequency Regulation. Regulation of electric power frequency provided by generating units that are online and increase or decrease power as needed and that is provided by ESSs that provide "up" regulation by discharging and "down" regulation by charging. This is also considered as the use of generation, loads, and energy storage to control system frequency within a predetermined bandwidth and the inclusion of local devices, such as a generator governor, a relay, or a phasor management unit, that continuously measure frequency and then send a control signal to a device to increase or decrease the amount of energy injected into the grid or the amount of load on the grid.

Load Following over 24 hours. The application of an ESS to achieve a balance between electric supply and end-user demand within a specific area, over a 24-hour time window.

Microgrid. A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that can connect to and disconnect from the grid to enable it to operate in either grid-connected or island mode and is not limited by size, but by functionality.

Islanded Microgrid. An energy storage application that includes multiple loads and distributed energy generation and storage resources that is operated as an electrical island separate from the utility grid.

Peak Shaving. An energy storage application that requires a duration of discharge of the ESS during the daily on-peak period for electric power (on the order of 2 to 12 hours) and is intended to recharge in the daily off-peak period for electric power and be available again the following day.

Power Factor. The ratio of the real power (alternating current [AC]) flowing to the load to the apparent power (AC) in the circuit expressed as a dimensionless value between −1 and +1.

Power Performance, Electrical. The maximum electric power sustainable for a given duration of discharge.

Power Performance, Thermal. The maximum thermal power sustainable for a given duration of discharge.

Power Quality. Mitigation of voltage sags by injection of real power for up to a few tens of seconds.

Primary Frequency Response. Compensation for sudden loss of generation or load by discharging or charging for up to 30 seconds.

Secondary Frequency Response. Compensation for sudden loss of generation or load by discharging or charging, for up to 20 minutes.

PV Smoothing. The application of an ESS to mitigate rapid fluctuations in PV power output that occur during periods with transient cloud shadows on the PV array by adding power to or subtracting power from the output of a PV system in order to smooth out the high frequency components of the PV power.

Ramp Rate. The rate of change of power delivered by or absorbed by an ESS over time, expressed in megawatts per minute or as a percentage change in rated power over time (percent per minute).

Rated Power. The power performance of the ESS for a particular application.

Reference Performance Test. A set of tests performed at the beginning of the life of an ESS to establish the baseline initial performance of the ESS and at periodic intervals thereafter to determine the performance degradation of the ESS during its operating life.

Renewables (Solar) Firming. The application of an ESS to provide energy to supplement renewable (wind or solar) generation such that their combination produces steady power output over a desired time window.

Round-Trip Energy Efficiency (RTE). The useful energy output from an ESS divided by the energy input into the ESS over one duty cycle under normal operating conditions, expressed as a percentage.

Response Time. The time in seconds it takes an ESS to reach 100 percent of rated power during charge or to discharge100 percent of rated power during discharge from an initial power measurement taken when the ESS is at rest.

Stored Energy The amount of electric or thermal energy capable of being stored by an ESS, expressed as the product of the rated power of the ESS and the discharge time at rated power.

Voltage Unbalance. The limit at which phase voltage magnitudes and angles are different from the balanced condition; it is calculated by averaging the voltage values of the phases.

Voltage Unbalance, Polyphase System. The largest deviation from average phase voltage divided by the average phase voltage, expressed as a percent.

Volt/Var Support. The use of an ESS to provide reactive power or absorb reactive power, based on grid voltage.

4.0 Overview

4.1 Intent. The intent of this section is to provide an overview of the Protocol and how it is intended to be used, which is illustrated in Figure 4.1.

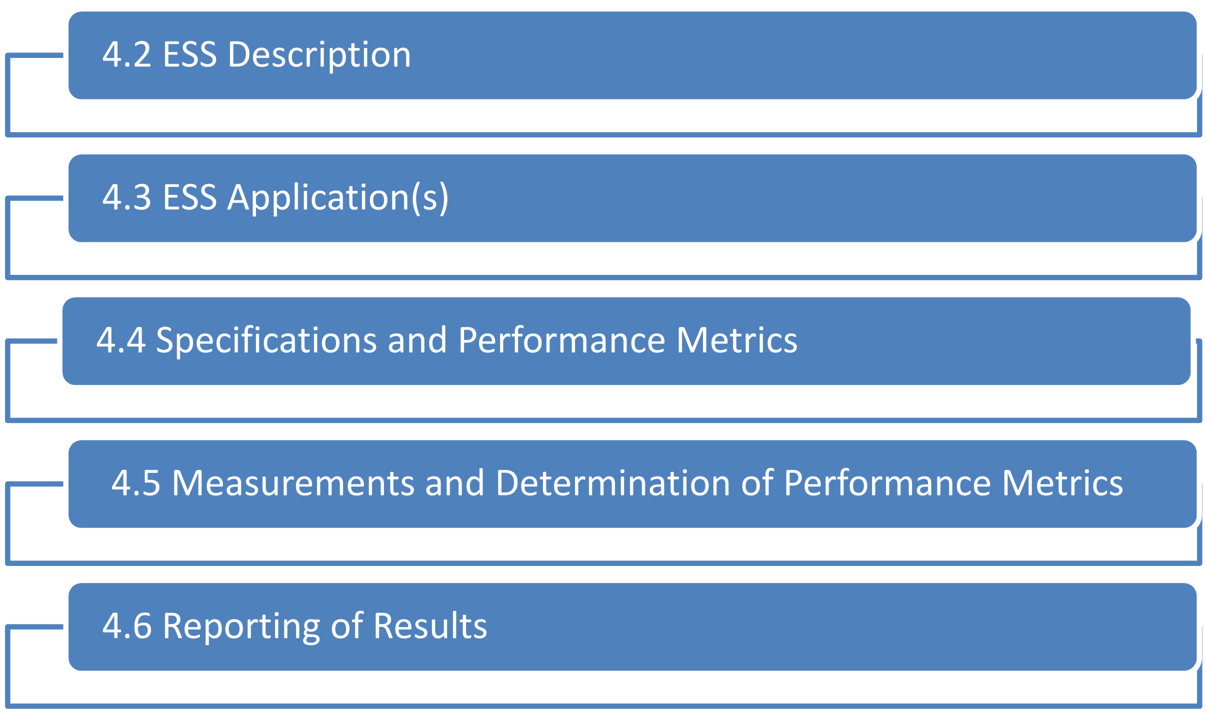


Figure 4.1. Protocol Overview

The assignment of responsibility throughout the Protocol refers to the manufacturer; however, in the case of an ESS that is neither self-contained nor pre-engineered comprising two or more factory-matched modular components intended to be assembled in the field, the manufacturer shall be considered the entity that designs the ESS and oversees its installation and commissioning. The application and use of the Protocol is intended for use beyond just manufacturers or designers of an ESS. It is intended that users of ESSs such as, but not limited to, utilities and building owners/operators who want to determine ESS performance, whether to verify what is reported by the manufacturer or designer or to determine performance for the first time, also use the Protocol to determine ESS performance.

4.2 Description of the Energy Storage System. The ESS shall be described by the ESS manufacturer via an ESS inventory, which shall include any devices, controls, inverters, auxiliary devices, and other components associated with the ESS.

The description shall identify the boundary within which the ESS, as described in Section 2.0, resides and the type and purpose of each input and output that crosses the ESS boundary. In describing the ESS, the manufacturer shall also provide information necessary to clearly define the communication interface across the ESS boundary. This shall include a description of the type, quality, and the source of and destination for all information sent from and received by the ESS. This information shall be available for application and use in designing the interfaces to be used for tests and data collection associated with the application of this protocol.

4.3 Identification of the ESS Application. The intended application(s) of the ESS shall be taken from Table 4.3 and included in the reporting conducted pursuant to Section 6.3. Identification of the intended application(s) for a self-contained or a matched assembly of components pre-engineered comprising two or more factory-matched modular components intended to be assembled in the field shall be conducted by the manufacturer of the ESS. Identification of the intended application(s) for an ESS not having a singular manufacturer but instead is composed of an assembly of components to make up the ESS shall be conducted by the designer of the ESS. Upon procurement of the ESS a utility shall be permitted to identify additional applications for the ESS. When additional applications for the ESS are designated by the utility implementing the ESS installation the utility shall be responsible for the application of the Protocol for any additional applications beyond those covered by the manufacturer or system designer.

Table 4.3. Energy Storage System Applications

Peak Shaving (Management)	Volt/Var
Frequency Regulation	Renewables (Solar) Firming
Islanded Microgrids	Power Quality
PV Smoothing	Frequency Control

4.3.1 Peak Shaving (Management). Energy storage systems intended for peak-shaving applications shall also be classified as all-electric or electric/thermal systems and identified by their application classification in accordance with Sections 4.3.1.1 through 4.3.1.11.

4.3.1.1 Energy Time Shift (Arbitrage). Energy time shift (arbitrage) shall be considered a use classification of an ESS in a peak-shaving (management) application where the system is charged during low energy-price periods and discharged during high energy-price periods, where the ESS owner either pays wholesale market energy rates plus a delivery charge or pays time-of-day retail rates.

4.3.1.2 Electric Supply Capacity. Electric supply capacity shall be considered a use classification of an ESS in a peak-shaving (management) application where the storage capacity of the system is used to defer the installation of new electric generation capacity, such as, but not limited to, a relatively small storage system or series of systems where growth has created a need for generation that cannot be satisfied in the short term and the storage system would be expected to supply load over the full period when the excess capacity is needed.

4.3.1.3 Load Following. Load following shall be considered a use classification of an ESS in a peak-shaving (management) application where the system is used to reduce ramp rate magnitudes so that conventional load-following generating units can better moderate cycling and be brought on at, or near, full load.

4.3.1.4 Transmission Congestion Relief. Transmission congestion relief shall be considered a use classification of an ESS in a peak-shaving (management) application that is a special case of the energy time-shift use classification in Section 4.3.1.1, where electric transmission congestion leads to price differences across a transmission system at the same point in time. In this use classification, the storage system shall be located on the load side of the congested network, charged during low-price periods when the system is not congested, and discharged during high-price time periods when prices have increased due to congestion.

4.3.1.5 Distribution System Upgrade Deferral. Distribution system upgrade deferral shall be considered a use classification of an ESS in a peak-shaving (management) application where the system responds to a situation in which a piece of equipment on the distribution system, including power line conductors, experiences loadings that approach the distribution system equipment's rated capacity, thereby allowing the existing distribution system equipment to remain online longer until other conditions necessitate upgrading the distribution system equipment.

4.3.1.6 Transmission System Upgrade Deferral. Transmission system upgrade deferral shall be considered a use classification of an ESS in a peak-shaving (management) application identical to the distribution upgrade deferral application covered in Section 4.3.1.5, except that it applies to higher voltages and higher power conditions found on the electric transmission system.

4.3.1.7 Retail Demand-Charge Management. Retail demand-charge management shall be considered a use classification of an ESS in a peak-shaving (management) application where the system is applied and used to minimize the demand charge from a utility over the course of each month.

4.3.1.8 Wind Energy Time Shift (Arbitrage). Wind energy time shift shall be considered a use classification of an ESS in a peak-shaving (management) application where electric power generated from a wind technology during low-wholesale price periods is stored and then delivered during high wholesale price periods.

4.3.1.9 Photovoltaic Energy Time Shift (Arbitrage). Photovoltaic energy time shift shall be considered a use classification of an ESS in a peak-shaving (management) application where electric power generated from PV technology is stored and then delivered to the system when needed.

4.3.1.10 Renewable Capacity Firming. Renewable capacity firming shall be considered a use classification of an ESS in a peak-shaving (management) application that involves the coupling of intermittent renewable generation with a specific capacity and type of energy storage that allows for an increase in the ability of the renewable generation to participate in the capacity market.

4.3.1.11 Baseload Generation Time Shift. Baseload generation time shift shall be considered a use classification of an ESS in a peak-shaving (management) application where an ESS is configured to allow baseload units to operate at full capacity during lighter nighttime loads, and deliver energy to the system in a way that minimizes or displaces higher-cost peaking generation.

4.3.2 Frequency Regulation. Energy storage systems intended for use in frequency regulation shall be permitted to represent area regulation as used by a balancing authority to meet North American Electric Reliability Corporation Balancing Authority Performance Control Standards.

4.4 ESS Specifications and Performance Metrics. The general information and technical specifications in Table 4.4.1 shall be provided for each ESS regardless of the intended application of the ESS and reported in accordance with Section 6.1. The reference performance information in Table 4.4.2 shall be provided for each ESS regardless of the intended application of the ESS in accordance with the procedures in Section 5.2 and reported in accordance with Section 6.2. The duty-cycle performance information in Table 4.4.3 shall be provided for each application for which the ESS is intended to be used by applying the applicable duty cycle(s) from Section 5.3 in accordance with the procedures in Section 5.4, and reported in accordance with Section 6.3.

4.4.1 Subsystems and Components. The manufacturer shall identify all subsystems and major components that compose the ESS on a schedule of ESS components that lists each subsystem or major component by name and model number. The schedule shall also list the input and output of each component in accordance with the provisions in Sections 4.5.1.1 and 4.5.1.2. Where the ESS is constructed from a number of separate components (neither self-contained nor a matched assembly of components pre-engineered comprising two or more factory-matched modular components intended to be assembled in the field), these responsibilities of the manufacturer shall apply to the entity that is designing the system and overseeing its installation and commissioning (designer/installer) based on information provided to it by the manufacturer(s) of the components making up the ESS.

4.4.2 System Ratings. Ratings for ESSs covering rated power, energy available at rated power, and the performance of the ESS associated with the items in Tables 4.4.2 and 4.4.3 taken at the beginning of life shall be based on a set of ambient operating conditions specified by the manufacturer of the ESS. The manufacturer shall also provide an indication of how the performance of the ESS with respect to the metrics in Tables 4.4.2 and 4.4.3 is expected to change over time, to account for time and use of the system, and report that in accordance with Section 6.4.

The determination and reporting of ratings for ESSs shall be in accordance with Institute of Electrical and Electronics Engineers (IEEE) Standard 1679 as expanded herein to provide more-specific test procedures that apply to all ESSs regardless of application (i.e., reference performance) and to the intended application(s) of the ESS (i.e., duty-cycle performance). Such expansion shall include use of the duty cycle(s) in Section 5.3 during testing relevant to the intended ESS application and taking measurements needed to determine the values for the metrics in Table 4.4.3 that express the performance of ESSs for the applications the ESS is intended to support.

Table 4.4.1. General Information and Technical Specifications

Subject	Description
Enclosure Type	A description of the system enclosure, including any enclosure supplied with the system, provided as a part of the site installation and/or comprised of building assemblies associated with the installation
Equipment Footprint	L × W of system including all ancillary components (sq. ft.)
Height	Equipment height plus safe clearance distances above the equipment (ft.)
Weight	Weight of each individual subsystem (power conversion system ESS, accessories, etc.), including maximum shipping weight of largest item that will be transported to the project site (lbs.)
Operating Temperature Range	The ambient temperature range at which the system is designed to operate (°F)
Grid Communication Protocols/Standards	List of communications-related protocols and standards with which the ESS is compliant
General Description of the Energy Storage System	Identification of the energy storage technology type (e.g., battery type, flywheel, etc.) used in the ESS
Warranty & Replacement Schedule	Warranty inclusions and exclusions, including replacement schedules and time span of warranty and any limitations
Expected Availability of System	Percentage of time that the ESS is in full operation performing application-specific functions, taking into account both planned and unplanned down-time
Rated Continuous Discharge Power	The rate at which the ESS can continuously deliver energy for the entire specified SOC range of the storage device that comprises the ESS
Rated Apparent Power	The real or reactive power (leading and lagging) that the ESS can provide into the AC grid continuously without exceeding the maximum operating temperature of the ESS
Rated Continuous Charge Power	The rate at which the ESS can capture energy for the entire SOC range of the storage device that comprises the ESS
Rated Continuous AC Current (discharge and charge)	The AC current that the ESS can provide into the grid continuously and can accept from the grid continuously without exceeding the maximum operating temperature of the ESS
Output Voltage Range	The range of AC grid voltage under which the ESS will operate in accordance with the ESS specification
Rated Discharge Energy	The accessible energy that can be provided by the ESS at its AC terminals when discharged at its beginning of life and end of life
Minimum Charge Time	The minimum amount of time required for the ESS to be charged from minimum SOC to its rated maximum SOC

Table 4.4.2. Reference Performance

Subject	Description
Stored Energy (Section 5.2.1)	The amount of electric or thermal energy capable of being stored by an ESS, expressed as the product of rated power of the ESS and the discharge time at rated power
Round-Trip Energy Efficiency (5.2.2)	The useful energy output from an ESS divided by the energy input into the ESS over one duty cycle under normal operating conditions, expressed as a percentage
Response Time (Section 5.2.3)	The time in seconds it takes an ESS to reach 100 percent of rated power during charge or from an initial measurement taken when the ESS is at rest
Ramp Rate (Section 5.2.3)	The rate of change of power delivered to or absorbed by an ESS over time, expressed in megawatts per second or as a percentage change in rated power over time (percent per second)
Reactive Power Response Time (Section 5.2.3)	The time in seconds it takes an ESS to reach 100 percent of rated apparent power during reactive power absorption (inductive) and sourcing (capacitive) from an initial measurement taken when the ESS is at rest
Reactive Power Ramp Rate (Section 5.2.3)	The rate of change of reactive power delivered to (inductive) or absorbed by (capacitive) an ESS over time expressed as Mvar per second or as a percentage change in rated apparent power over time (percent per second)
Internal Resistance (Section 5.2.3)	The resistance to power flow of the ESS during charge and discharge
Standby Energy Loss Rate (Section 5.2.4)	Rate at which an ESS loses energy when it is in an activated state but not producing or absorbing energy, including self-discharge rates and energy loss rates attributable to all other system components (i.e., battery management systems, energy management systems, and other auxiliary loads required for readiness of operation)
Self-Discharge Rate (Section 5.2.5)	Rate at which an ESS loses energy when the storage medium is disconnected from all loads, except those required to prohibit it from entering into a state of permanent non-functionality

Table 4.4.3. Duty-Cycle Performance

Subject	Description
Duty-Cycle Round-Trip Efficiency (Section 5.4.1)	The useful energy output from an ESS divided by the energy input into the ESS over a charge/discharge profile that represents the demands associated with a specific application that is placed on an ESS, expressed as a percentage
Reference Signal Tracking (Section 5.4.2)	The ability of the ESS to respond to a reference signal
State-of-Charge Excursions (Section 5.4.3)	The maximum and minimum SOC attained by the ESS during the execution of the duty cycle
Energy Capacity Stability (Section 5.4.4)	The energy capacity at any point in time as a percentage of the initial energy capacity
ΔSOC_volt/var (Section 5.4.5.1)	The difference between the final and initial SOC shall be reported, along with the initial SOC
ΔSOC_active standby (Section 5.4.5.1)	The difference between the final and initial SOC at the end of an active standby of the same duration as the volt/var duty cycle with auxiliary load turned on, with the initial SOC the same as the value at the start of the volt/var duty cycle, shall be reported.
Wh_discharge (Section 5.4.5.1)	The real energy injected into the grid (with and without volt/var duty cycle)
Wh_charge (Section 5.4.5.1)	The real energy absorbed from the grid (with and without volt/var duty cycle)
Wh_net (Section 5.4.5.1)	The net energy (injected into or absorbed from the grid) (with and without volt/var duty cycle)
Peak Power (Section 5.4.5.2 or Section 5.4.5.3 for Power Quality or Frequency Control applications, respectively)	The peak power the ESS can provide for a specific duration

4.5 Measurement Procedure and Determination of Performance Metrics. Measurements shall be conducted in accordance with the test conditions, data acquisition conditions, and test procedures in Section 5.0, the use of which is intended to generate and make available the accurate and repeatable data necessary to calculate the reference performance metrics in Table 4.4.2 and duty-cycle performance metrics relevant to the intended ESS application(s) in Table 4.4.3. In determining system performance, the energy use associated with determining a particular metric shall be converted to a single consistent and comparable metric. All required conversions necessary to derive the reported value of the metric shall be in accordance with American National Standards Institute/American Society of Heating, Refrigerating and Air Conditioning Engineers (ANSI/ASHRAE) Standard 105.

4.5.1 Inputs The input of each subsystem and major component in terms of electrical power and/or thermal or non-electrical energy shall be determined in accordance with recognized standards and those standards used shall be reported in conjunction with the data reported in Section 6.0.

4.5.2 Outputs The output of each subsystem and major component in terms of electrical power and/or thermal energy shall be determined in accordance with recognized standards and those standards used shall be reported in conjunction with the data reported in Section 6.0.

4.6 Reporting and Displaying Information, Specifications and Performance The general information, technical specifications and reference performance of the ESS and duty-cycle performance for each intended application of the ESS shall be reported in accordance with the provisions in Section 6.0 and included in a permanent label affixed to the system or included with the ESS specifications.

The reporting of ESS performance in accordance with the provisions in Section 6.0 shall not preclude the reporting of other information, technical specifications, reference and duty-cycle performance metrics or data associated with the ESS that is not provided for in this document. Where such additional information is to be provided by the ESS manufacturer, it shall be reported on the label required in Section 6.1, 6.2, or 6.3 as applicable, or included with the ESS specifications, and accompanied by a reference to the standard, measurement method, or other basis for determining the information reported and, if relevant, the duration of and increments in time at which the measurements were taken and the error margin associated with those measurements.

5.0 Test Methods and Procedures

5.1 Comprehensive Data Recording. All measurements of charge rate, input current and voltage, output current and voltage, thermal output, system temperatures, ambient conditions, and other parameters that must be measured shall be collected simultaneously at a temporal resolution applicable to the function of the ESS and ESS metrics to which the measured data are being applied and in accordance with recognized standards applicable to the measurements being taken. All parameters measured and recorded shall be used in determining and reporting ESS performance in accordance with this section and Section 6.0. All tests shall be conducted on the entire ESS as defined by the manufacturer or designer/installer of the ESS in accordance with the provisions in Section 4.2.

5.2 Reference Performance. Reference performance tests shall be conducted for all ESSs regardless of intended application(s) in accordance with this section, and the results shall be used to determine ESS performance that can be subsequently used as a baseline to assess any changes in the condition of the ESS and performance over time and use. Reference performance tests shall be conducted to determine baseline performance of the ESS prior to duty-cycle testing under Sections 5.3 and 5.4. These tests shall be repeated at regular intervals specified by the manufacturer or as directed by the end user during operation of the ESS for the purpose of facilitating a comparison of performance stability of the ESS over the course of its operating lifetime. Such intervals shall be selected to identify how the testing or operation affects the performance of the ESS and shall be in units of time, number of cycles, or energy throughput.

5.2.1 Stored Energy A stored energy test shall be performed in accordance with this section and is intended to be used to determine the stored energy of the ESS at the rated electrical or thermal power of the ESS as specified by the manufacturer.

5.2.1.1 Test Overview. The ESS shall be discharged to the lower SOC limit specified by the manufacturer. In conducting the stored energy test, the manufacturer shall describe a detailed and documented charging procedure within the specifications of the ESS for charging the ESS in less than 12 hours to the upper SOC limit of the ESS. In addition, the manufacturer shall provide the rated power for the ESS for the constant-power discharge to its lower SOC limit. All stored energy capacity tests conducted on the same ESS shall remain consistent and allow for properly tracking performance degradation.

Energy storage system power during charge and discharge shall be recorded at regular intervals of time or at step or percentage variances at a rate that is documented by the manufacturer to provide a statistically valid resolution. The associated energy input and output of the ESS shall be calculated from the recorded power. The stored energy capacity test assumes the ESS powers the auxiliary loads.

5.2.1.2 Stored Energy Test Routine. The ESS shall be tested for its stored energy at selected power in accordance with this section. The measurements shall be collected in accordance with Section 5.2.1.1 throughout all steps associated with the test. These measurements shall be permitted to be repeated for multiple discharge power levels for various durations and/or end SOCs, to determine baseline energy at multiple power levels. The recharge rate for each of these power levels shall also be permitted to vary in accordance with the ESS manufacturer's recommendation.

1. The ESS shall be charged to its upper SOC limit by charging at rated power in accordance with the system manufacturer's specifications and operating instructions. That upper SOC shall be measured and recorded as T_{max} (thermal storage without phase change), or P_{max} (thermal storage with phase change, where P is percentage mass of the solid phase for a solid-liquid phase change, and percentage mass of liquid phase for a liquid-to-gas phase change), corresponding to the upper SOC, under the manufacturer-specified charge conditions. For electrical ESSs, the SOC as reported by the battery management system or the flywheel management system shall be recorded. The energy input during charge, Wh_{Ci}, into the ESS during ESS charging, including all parasitic losses, shall be measured directly during charging and recorded as the charge energy of the ESS. This energy shall be measured from SOC_{taper} described in Step 1 for the case when each cycle consists of a charge followed by a discharge, and Step 4 when each cycle consists of a discharge followed by a charge.
2. Where the ESS requires a rest time after charging and prior to discharging in accordance with the manufacturer's specifications and operating instructions, the system shall be left at rest in an active state for 5 minutes.
3. The ESS shall be discharged to its lower SOC limit in accordance with the ESS manufacturer's specifications and operating instructions. That lower SOC shall be recorded as the manufacturer-specified T_{min} (thermal storage without phase change), or P_{min} (thermal storage with phase change, where P is percentage mass of the solid phase for a solid-liquid phase change, and percentage mass of liquid phase for a liquid-to-gas phase change), corresponding to that lower SOC, under the manufacturer-specified discharge conditions. For electrical ESSs, the SOC as reported by the battery management system or the flywheel management system shall also be recorded. If during discharge the ESS discharge power decreases by 2% or more before the lower SOC is reached, the discharge shall be continued to the minimum SOC and the discharge energy shall be recorded up to the point where the power reaches 98% of initial power. This SOC shall be denoted as SOC_{taper} for each discharge. The energy output to SOC_{taper}, $Wh_{Di,}$ from the ESS during ESS discharge shall be calculated from the power measurements during discharge and recorded
4. The ESS shall be left at rest in an active standby state for the same period of time selected under Step 2 above.
5. The ESS shall be charged to its upper SOC limit in accordance with the system manufacturer's specifications and operating instructions. That upper SOC shall be measured and recorded as T_{max} (thermal storage without phase change), or P_{max} (thermal storage with phase change, where P is percentage mass of the solid phase for a solid-liquid phase change, and percentage mass of liquid

phase for a liquid-to-gas phase change), corresponding to the upper SOC, under the manufacturer-specified charge conditions. For electrical ESSs, the SOC as reported by the battery management system or the flywheel management system shall be recorded. The energy input during charge, Wh_{Ci}, into the ESS during ESS charging, including all parasitic losses, shall be measured directly during charging and recorded as the charge energy of the ESS. This energy shall be measured from SOC_{taper} described in Step 1 for the case when each cycle consists of a charge followed by a discharge, and Step 4 when each cycle consists of a discharge followed by a charge.

6. Steps 2 through 5 above shall be repeated four times for a total of 5 cycles..

   The reference performance test value for stored energy shall be calculated as the mean of the values of W_{Di} and Wh_{Ci} as measured under Step 3 for discharge and Step 5 for charge associated with each test and the standard deviation also calculated and reported in accordance with Section 6.2.

7. Steps 2–5 shall be repeated at power levels of 75%, 50%, and 25% of rated power, after bringing the ESS to its upper SOC limit. Since only one cycle is done at each power level, the measured charge and discharge energy values are reported.

5.2.2 Round-Trip Energy Efficiency. A round-trip energy efficiency (RTE) test shall be conducted in conjunction with the stored energy test in Section 5.2.1 to determine the amount of energy that an ESS can deliver relative to the amount of energy injected into the ESS during the subsequent charge.

5.2.2.1 Round-Trip Energy Efficiency Calculation. The RTE of the ESS is the efficiency based on the three test cycles and shall be determined in accordance with Equation 5-1 based on the data secured from the tests conducted in accordance with the provisions in Section 5.2.1. Where constant power cannot be held during the test, the use of average power shall be considered acceptable and this noted when reporting RTE in accordance with the provisions in Section 6.2.

$$Round\ trip\ efficiency = \left(\frac{\sum_1^3 (Wh_{Di})}{\sum_1^3 (Wh_{Ci})}\right) \tag{5-1}$$

where:

- 3 is the number of test cycles conducted during the tests under Section 5.2.1
- i is the number of each test cycle
- WhD_i is the electrical energy in watt-hours at rated power kilowatts or the electrical equivalent in Wh of thermal energy delivered (output) by the system measured and recorded as Wh_{Di} for cycle i
- WhC_i is the watt-hour input (AC) into the system during system charging, including all parasitic losses, measured and recorded as WhC_i for cycle i.

For an ESS configuration where the auxiliary load is powered separately, the round-trip efficiency shall be calculated in accordance with Equation 5-2.

$$Round\ trip\ efficiency = \left(\frac{\sum_1^3 (Wh_{Di} - Aux_{Di})}{\sum_1^3 (Wh_{Ci} + Aux_{Ci} + Aux_{Ri})}\right) \tag{5-2}$$

where

- Aux_{Di} is the energy consumption by auxiliary loads during discharge for cycle i
- Aux_{Ci} is the energy consumption by auxiliary loads during charge for cycle i
- Aux_{Ri} is the energy consumption by auxiliary loads during rest after discharge and charge for cycle i.

The RTE of individual cycles of an ESS where the ESS is powering auxiliary loads shall be determined in accordance with Equation 5-3.

$$Round\ trip\ efficiency\ for\ cycle\ i = \frac{Wh_{Di}}{Wh_{Ci}} \tag{5-3}$$

The RTE of individual cycles of an ESS where auxiliary loads are powered by a source other than the ESS shall be determined in accordance with Equation 5-4.

$$Round\ trip\ efficiency = \left(\frac{Wh_{Di} - Aux_{Di}}{Wh_{Ci} + Aux_{Ci} + Aux_{Ri}}\right) \tag{5-4}$$

The applicable calculation in Equations 5-1 through 5-4 shall then be repeated for each cycle.

The RTE shall be reported in accordance with Section 6.2 as a function of the charge and discharge power.

5.2.3 Response Time and Ramp Rate. The response time (RT) and ramp rate (RR) to determine the amount of time required for the ESS output to transition from no discharge to full discharge rate and from no charge to full charge rate at rated power and also rated reactive power shall be determined for the ESS in accordance with this section. The RT and RR at both rated power and rated reactive power shall be reported in accordance with Section 6.2.

5.2.3.1 Test Overview. The manufacturer shall provide information about rated power (energy capacity) as required by the provisions in Section 5.2.1. The response time shall be measured in accordance with Figure 5.2.3.1 starting when the signal (command) is received at the ESS boundary as established in Section 4.2 and continuing until the ESS discharge power output (electrical or thermal) reaches 100 ±2% of its rated power.

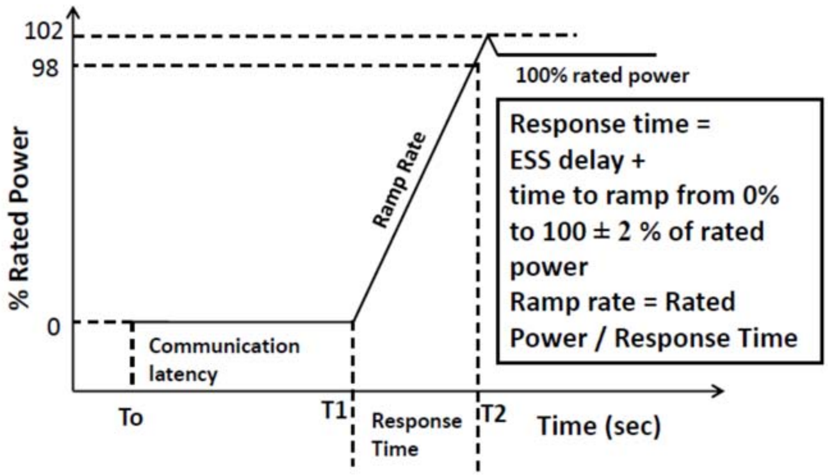


Figure 5.2.3.1. Response Time Test

5.2.3.2 Discharge Test Routine. The discharge response time (RT_D) test shall be conducted in accordance with the following procedure and the discharge response time calculated in accordance with Equation 5-5.

1. The ESS shall be at the 50% SOC and in an active standby state.
2. The data acquisition system (DAS) shall be configured to record a time stamp T_0 when a command to change set point from rest to discharge is sent to the ESS.
3. The DAS shall be configured to record a time stamp T_1 when the ESS starts responding to the discharge command signal.
4. The DAS shall be configured to record a time stamp T_2 when the output of the ESS reaches 100 ±2% of its rated power capacity. The acquisition rate of data shall be at least twice as fast as the rated power capacity divided by the discharge ramp rate of the ESS, as determined in accordance with Equation 5-6a, and at least one intermediate data point shall be acquired as the ESS transitions from rest to full discharge.
5. The ESS shall be configured to respond to a step change in power output set point according to the ESS manufacturer's specifications.
6. The DAS shall be started and shall command the power output of the ESS to change to full rated discharge power output, and T_1 and T2 shall be measured and recorded.
7. The DAS shall be reset to a state to begin recording data and the ESS placed in a state of active standby.

$$RT_D = T2 - T1 \qquad (5\text{-}5)$$

where RT_D is the discharge response time in seconds; T1 is the beginning time stamp, in seconds, when the ESS starts responding to the discharge signal; and T2 is the end time stamp, in seconds, when the output of the ESS reaches 100 ± 2% of its rated power output.

The discharge ramp rate (RR_D) shall be calculated in accordance with Equation 5-6a and expressed in megawatts per second.

$$RR_D = [P_{T2}]/[T_2 - T_1] \quad (5\text{-}6a)$$

where P_{T2} is the power output of the ESS recorded at time T_2 (100 ±2% of rated power capacity); T_1 is the beginning time stamp, in seconds, when the ESS starts responding to the discharge signal; and T_2 is the end time stamp, in seconds, when the output of the ESS reaches 100 ±2% of its rated power output.

The discharge ramp rate shall also be expressed as percent rated power per second (RR_{Dpct},) in accordance with Equation 5-6b.

$$RR_{Dpct} = RR_D / P_R \times 100 \quad (5\text{-}6b)$$

where P_R is the rated power of the ESS.

The manufacturer shall provide information about the rated apparent power of the ESS, and the tests in Section 5.2.3.2 shall be repeated by replacing the rated power with the rated apparent power to determine the reactive power response time. When the reactive power is provided by the ESS (capacitance behavior), this mode shall correspond to the discharge mode. When the ESS absorbs reactive power (inductive behavior), this mode shall correspond to the charge mode.

5.2.3.3. Charge Test Routine. The charge response time (RT_C) test shall be conducted in accordance with the following procedure and the charge response time calculated in accordance with Equation 5-7.

1. The ESS shall be at the 50% SOC and in an active standby state.
2. The DAS shall be configured to record a time stamp T_0 when a command to change set point from rest to charge is sent to the ESS.
3. The DAS shall be configured to record a time stamp T_1 when the ESS starts responding to the charge command signal.
4. The DAS shall be configured to record a time stamp T_2 when the input to the system reaches 100 ±2% of its rated power capacity. The acquisition rate of data shall be at least twice as fast as the rated power capacity divided by the ramp rate of the ESS, as determined in accordance with Equation 5-8a, and at least one intermediate data point shall be acquired as the ESS transitions from rest to full charge.
5. The ESS shall be configured to respond to a step change in power input set point according to the ESS specifications provided by the manufacturer.
6. The DAS shall be started and shall command the power input to the ESS to change to full rated charge power input, and T_1 and T_2 shall be measured and recorded.
7. The DAS shall be reset to a state to begin recording data and the ESS placed in a state of active standby.

$$RT_C = T_2 - T_1 \quad (5\text{-}7)$$

where RT_C is the charge response time in seconds; T_1 is the beginning time stamp, in seconds, when the ESS starts responding to the charge signal; and T_2 is the end time stamp, in seconds, when the input to the ESS reaches 100 ±2 % of its rated power output.

The charge ramp rate (RR_C) shall be calculated in accordance with Equation 5-8a and expressed in megawatts per minute.

$$RR_C = [P_{T2}]/[T_2 - T_1] \times 60 \qquad (5\text{-}8a)$$

where P_{T2} is the power input to the ESS recorded at time T_2 (100 ±2% of rated power capacity).

The charge ramp rate (RR_C) shall also be expressed as percent rated power per minute (RR_{Cpct}) in accordance with Equation 5-8b.

$$RR_{Cpct} = RRC/\ P_R \times 100 \qquad (5\text{-}8b)$$

where P_R is the rated power of the ESS.

Where DC measurement is available, the internal resistance for both discharge and charge shall be calculated as the ratio of the change in DC voltage and DC current at the end of 10 seconds, in accordance with Equation 5-9.

$$\text{Internal resistance (ohms)} = V(10s) - V(initial))/I(10s) \qquad (5\text{-}9)$$

Where V(10s) and I(10s) are DC voltage and current at the end of 10 seconds, and V(initial) is initial DC voltage, with I(initial) equal to 0.

The manufacturer shall provide information about the rated reactive power of the ESS and the tests in Section 5.2.3.3 shall be repeated by replacing the rated power with the rated reactive power to determine the reactive power ramp rate. When the reactive power is provided by the ESS (capacitive behavior), this mode shall correspond to the discharge mode. When the ESS absorbs reactive power (inductive behavior), this mode shall correspond to the charge mode.

5.2.4. Standby Energy Loss Rate. The standby energy loss rate (SELR) shall be determined in accordance with the following procedure.

1. The ESS shall be charged to 100% SOC.
2. The ESS shall be discharged at rated power to minimum SOC and the capacity recorded as $Wh_{initial}$.
3. The ESS shall be charged to 100% SOC and the ESS rested for 1 week. The contactor shall remain closed during this rest period.
4. The ESS shall be discharged at rated power to the minimum SOC and the capacity recorded as Wh_{1week}.
5. The SELR (% of energy loss/day) shall be calculated in accordance with Equation 5-10 using the values recorded in Step 2 and Step 4.

$$\text{SELR (\% energy loss/day)} = (Wh_{initial} - Wh_{1week})/(Wh_{initial} \times 7) \times 100 \qquad (5\text{-}10)$$

The SELR shall be reported in accordance with Section 6.2.

5.2.5. Self-Discharge Rate. The self-discharge rate (SDR) shall be determined in accordance with the following procedure.

1. The ESS shall be charged to 100%.
2. The ESS shall be discharged at rated power to the minimum SOC and the capacity recorded as $Wh_{initial}$.
3. The ESS shall be charged to 100% SOC and the ESS rested for 1 week with the contactor open.
4. The contactor of the ESS shall be closed and the ESS discharged at rated power to the minimum SOC and the capacity recorded as Wh_{1week}.
5. The self-discharge rate of the ESS shall be calculated in accordance with Equation 5-11 using the values recorded in Step 2 and Step 4

$$\text{SDR (\% energy loss/day)} = (Wh_{initial} - Wh_{1week})/(Wh_{initial} \times 7) \times 100 \quad (5\text{-}11)$$

The SDR shall be reported in accordance with Section 6.2.

5.3 Application Duty Cycles. The duty cycles presented in Sections 5.3.1 through 5.3.8 shall be used to generate the necessary data to be used as a basis for determining and reporting the operational effectiveness of an ESS in a particular application in accordance with Section 5.4. Details associated with the generation of and basis for the duty cycles are provided in Appendixes A through H.

The ESS manufacturer shall be permitted to use one or more alternative duty cycle(s) for one or more applications in addition to the duty cycles provided in this section in conducting any of the testing covered in Section 5.4. Where this is done, the manufacturer shall provide a description of and rationale for each alternative duty cycle chosen, shall conduct all tests required herein while subjecting the ESS to each alternative duty cycle chosen and report all performance measures as required in Section 6.3 under the designation “alternative duty cycle [insert source or name].”

5.3.1 Peak Shaving Application Duty Cycle. The duty cycles presented in this section shall be used in the determination of the performance of systems intended for peak-shaving (management) applications and shall use charge and discharge time windows instead of normalized power levels or discharge rates to allow the duty-cycle profile to be applied in the same manner to different technologies regardless of system size, type, age, and condition. The duty cycles applied in determining system performance shall be in accordance with Figure 5.3.1 and the provisions in Sections 5.3.1.1 through 5.3.1.4. In applying the duty cycles, the discharge power and SOC range for each duty cycle shall be selected such that the power remains constant throughout the required discharge period (6 hours, 4 hours and 2 hours for duty cycles A, B, and C, respectively, shown in Figure 5.3.1).

Each duty cycle shall have a total charge time of 12 hours: the required discharge period duration and a float window after charge and discharge that bring the total duration for each of the A, B, and C duty cycles to one 24-hour period. While Figure 5.3.1 displays the duty cycles for a midnight-to-midnight day with an evening peak, for the purposes of testing, the test starts with a discharge at 13:00 hours for duty cycle A, 14:00 hours for duty cycle B and 15:00 hours for duty cycle C. Prior to the test, the ESS shall be brought to the maximum SOC by charging at rated power. When conducting performance tests using duty cycles A, B, and C, the ESS shall be returned to the same SOC as the SOC at the start of the test, which in this case is the maximum SOC. As such, each duty cycle A, B, and C consists of a discharge, followed by active standby, discharge, active standby, and a top-off charge to bring the ESS to the initial SOC.

The development and use of an alternative duty cycle in addition to the required duty cycle shall be permitted in accordance with Section 5.4. See Appendix A for information relevant to the development of an alternative peak-shaving duty cycle.

5.3.1.1 Charge Window. During the charge window, the ESS shall be charged at constant power in a 12-hour time period to bring the ESS to its upper SOC limit.

5.3.1.2 Float Window. During the float window, the upper SOC limit shall not be maintained and the operation of any internal support loads for the ESS, such as, but not limited to, heating, ventilation, and air-conditioning systems, shall continue to operate as required in accordance with the ESS manufacturer's specifications and operating instructions. Discharging of the ESS that does not serve a load external to the ESS shall be permitted during the float window.

5.3.1.3 Discharge Window. During the discharge window, the ESS shall be discharged at constant power until the minimum SOC level for the discharge power used, as specified by the ESS manufacturer, is reached.

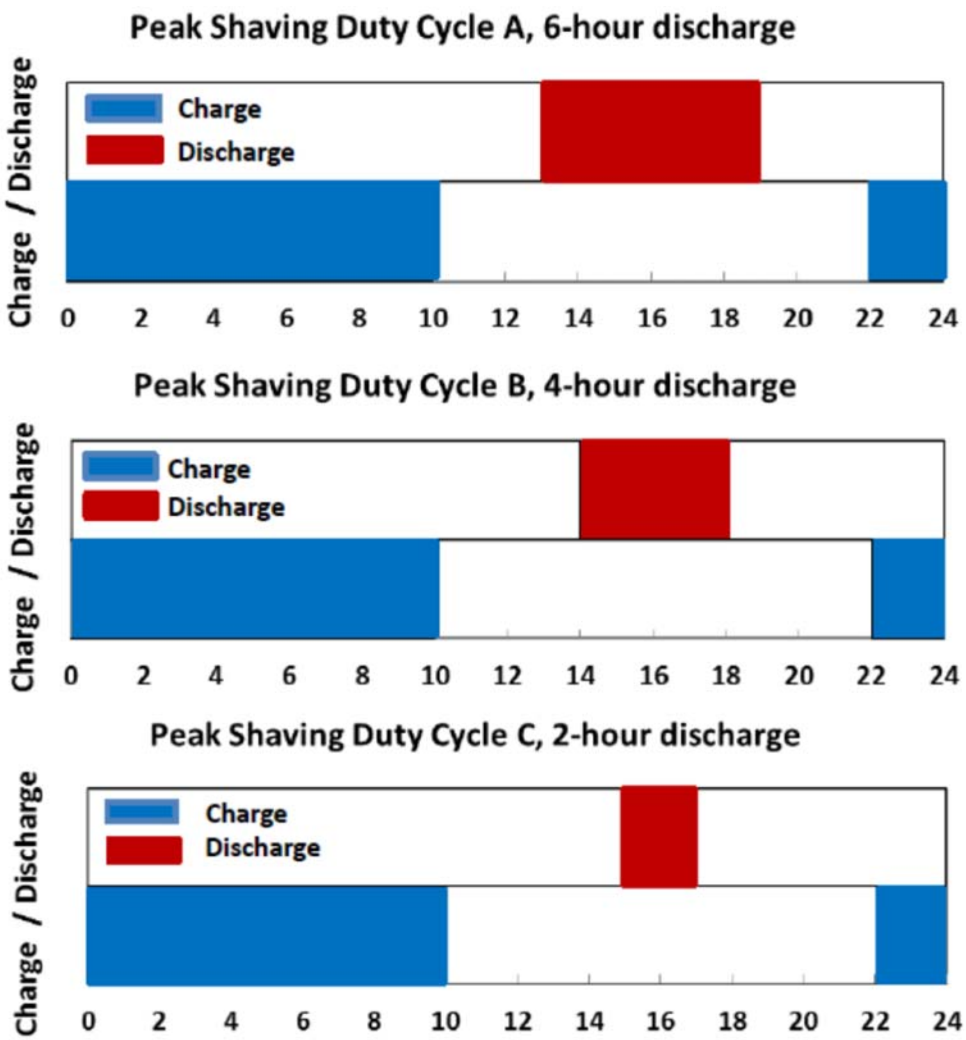


Figure 5.3.1. Peak-Shaving Duty Cycles X-axis is Time in hours

5.3.1.4 Application of the Duty Cycle. Performance testing shall consist of bringing the ESS to the desired initial SOC before applying duty cycle A, followed by one application of duty cycle A shown in Figure 5.3.1. Following the application of duty cycle A, the ESS shall be brought back to its initial SOC. When that initial SOC is realized, the ESS shall be brought to the desired initial SOC before applying duty cycle B, followed by one application of duty cycle B in Figure 5.3.1. Following the application of duty cycle B, the ESS shall be brought back to its initial SOC. When that initial SOC is realized, the ESS shall be brought to the desired initial SOC before applying duty cycle C followed by one application of duty cycle C, as shown in Figure 5.3.1. Following the application of duty cycle C, the ESS shall be brought back to its initial SOC.

5.3.2 Frequency Regulation Duty Cycle. The duty cycle presented in Figure 5.3.2 shall be applied in determining the performance of an ESS for a frequency-regulation application. The duty cycle in Figure 5.3.2 is shown as power normalized with respect to the rated power of the ESS over a 24-hour time period, where positive represents discharge from the ESS and negative charge into the ESS as a function of time in hours. A reference to the raw data upon which Figure 5.3.2 is based is included in Appendix B. The initial SOC shall be set per the manufacturer's specifications and operating instructions. At the end of the application of the duty cycle in conducting the testing under Section 5.4, the ESS shall be brought back to its initial SOC.

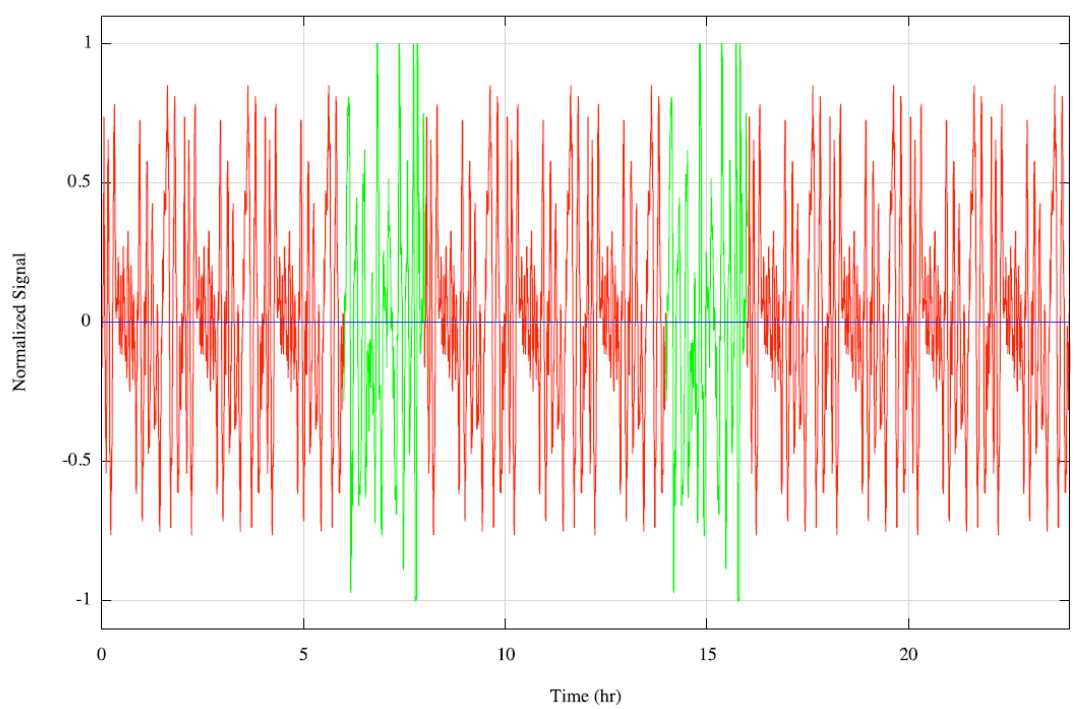


Figure 5.3.2. Frequency-Regulation Duty Cycle

5.3.3 Islanded Microgrid Duty Cycle. The duty cycles presented in Figures 5.3.3 a, b, and c shall be applied in determining the performance of an ESS in an islanded microgrid application. The duty cycles in Figures 5.3.3 a, b, and c are shown as power normalized with respect to the rated power of the ESS over a 24-hour time period, where a positive sign represents charge into the ESS and a negative sign represents discharge from the ESS as a function of time in hours. The initial SOC shall be set per the manufacturer's specifications and operating instructions. At the end of the application of the duty cycle in conducting the testing under Section 5.4, the ESS shall be brought back to its initial SOC. A reference to the data upon which Figures 5.3.3 a, b, and c are based is included in Appendix C.

The first duty cycle in Figure 5.3.3a corresponds to the use of ESSs in islanded microgrids including renewables and frequency regulation. The second duty cycle in Figure 5.3.3b corresponds to the use of ESSs in islanded microgrids with renewables, and without frequency regulation. The third duty cycle in Figure 5.3.3c corresponds to the use of ESS in islanded microgrids without renewables and without frequency regulation.

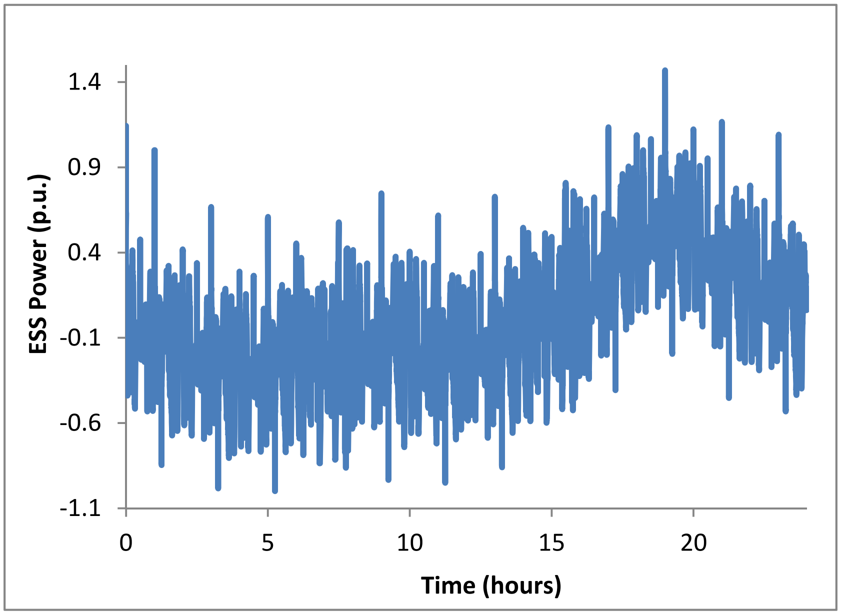


Figure 5.3.3a. Duty Cycle – Renewables with Frequency Regulation

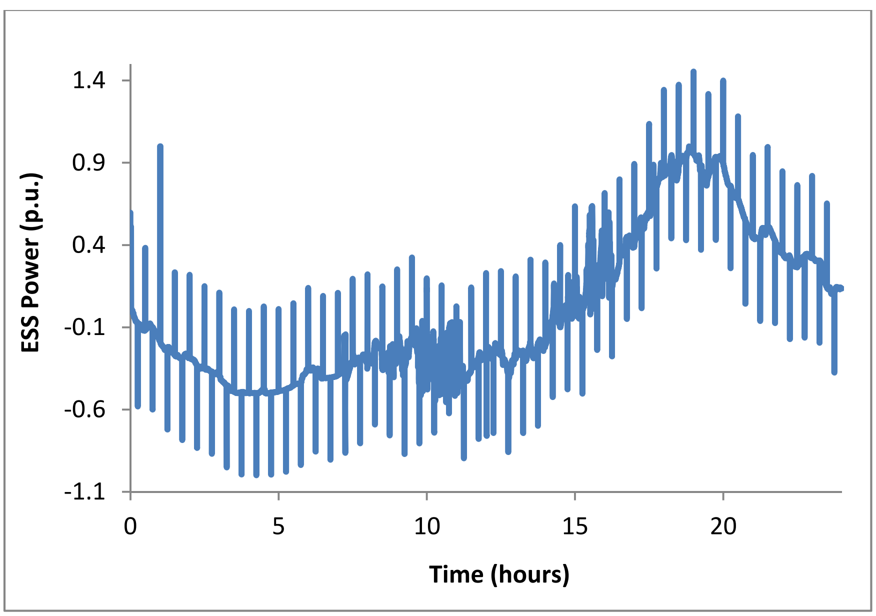


Figure 5.3.3b. Duty Cycle – Renewables with No Frequency Regulation

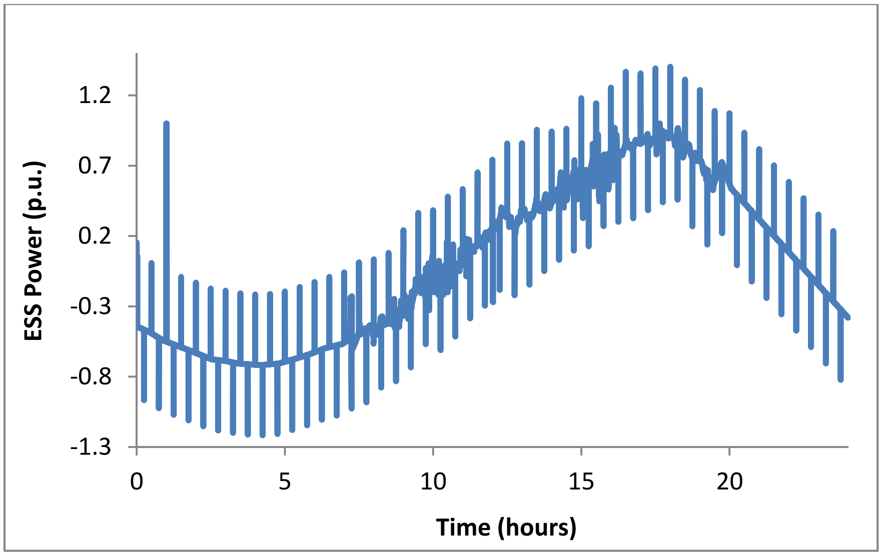


Figure 5.3.3c. Duty Cycle – No Renewables or Frequency Regulation

5.3.4 PV Smoothing Duty Cycle. The duty cycle presented in Figure 5.3.4 shall be applied in determining the performance of an ESS in a PV smoothing application. The duty cycle in Figure 5.3.4 is shown as power normalized with respect to the rated power of the ESS over a 10-hour time period, where a positive sign represents charge into the ESS and a negative sign represents discharge from the ESS as a function of time in hours. The initial SOC shall be set per the manufacturer's specifications and operating instructions. At the end of the application of a duty cycle in conducting the testing under Section 5.4, the ESS shall be brought back to its initial SOC before the application of another duty cycle. A reference to the data upon which Figure 5.3.4 is based is included in Appendix D.

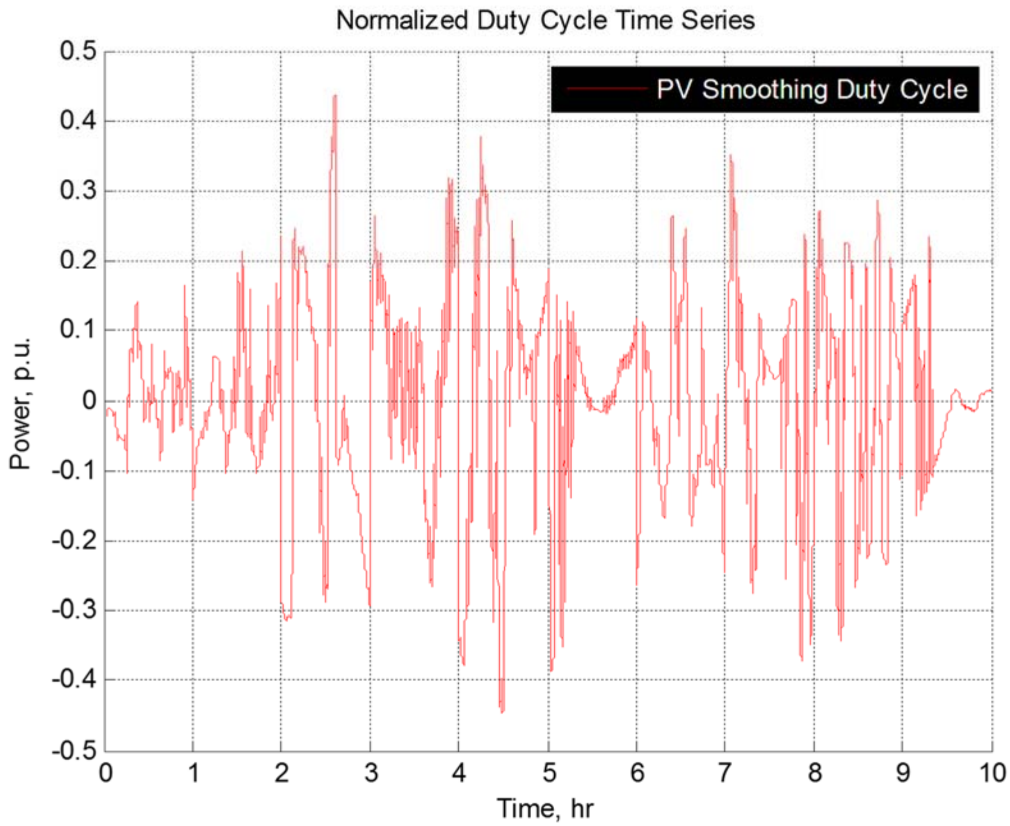


Figure 5.3.4. Duty Cycle – PV Smoothing

5.3.5 Volt/Var Support Duty Cycle. The duty cycles presented in Figures 5.3.5a through 5.3.5e shall be applied in determining the performance of an ESS for a volt/var support application. The duty cycles shown in Figures 5.3.5a through 5.3.5e are shown as power normalized with respect to the rated power of the ESS, where a positive sign represents reactive power injected into the grid by the ESS (e.g., capacitive behavior) and a negative sign represents reactive power absorbed from the grid by the ESS (e.g., inductive behavior) as a function of time in hours. Figures 5.3.5a and 5.3.5b apply to reference case 1 associated with volt/var support where the ESS is managing the grid voltage within 94 to 106% of its nominal voltage at a PV system's point of common coupling with the end of a feeder.[2] Figure 5.3.5a is the least aggressive duty cycle, while Figure 5.3.5b corresponds to the most aggressive duty cycle. Figures 5.3.5c through 5.3.5e are associated with volt/var support where the ESS is managing the grid voltage within 94 to 106% of its nominal voltage at three locations on a feeder using the most aggressive duty cycle. The initial SOC shall be set at 50%. At the end of the application of each duty cycle in conducting the testing under Section 5.4, the ESS shall be brought back to its initial SOC before the application of another duty cycle. A reference to the data upon which Figures 5.3.5a through e are based is included in Appendix E.

[2] Simulated feeder voltage for heavy PV penetration sent by Jay Johnson of Sandia National Laboratories by email on May 7, 2015 to Vilayanur Viswanathan of PNNL.

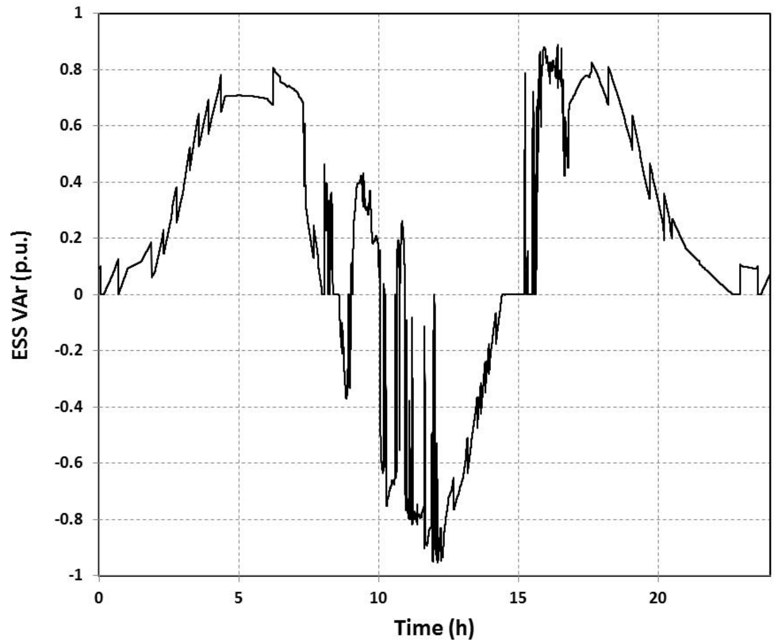


Figure 5.3.5a. Volt/Var Support Duty Cycle – PV and Grid Interaction – Least Aggressive

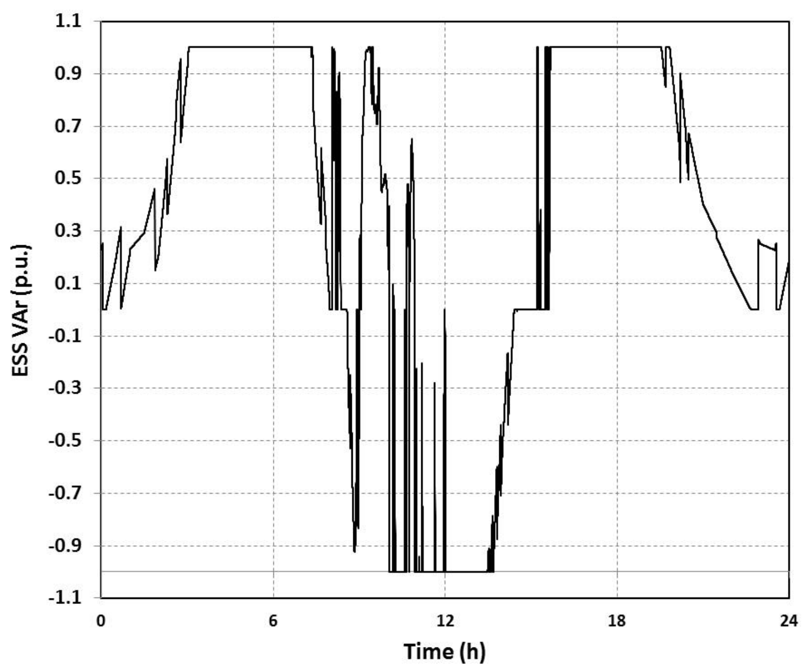


Figure 5.3.5b. Volt/Var Support Duty Cycle – PV and Grid Interaction – Most Aggressive

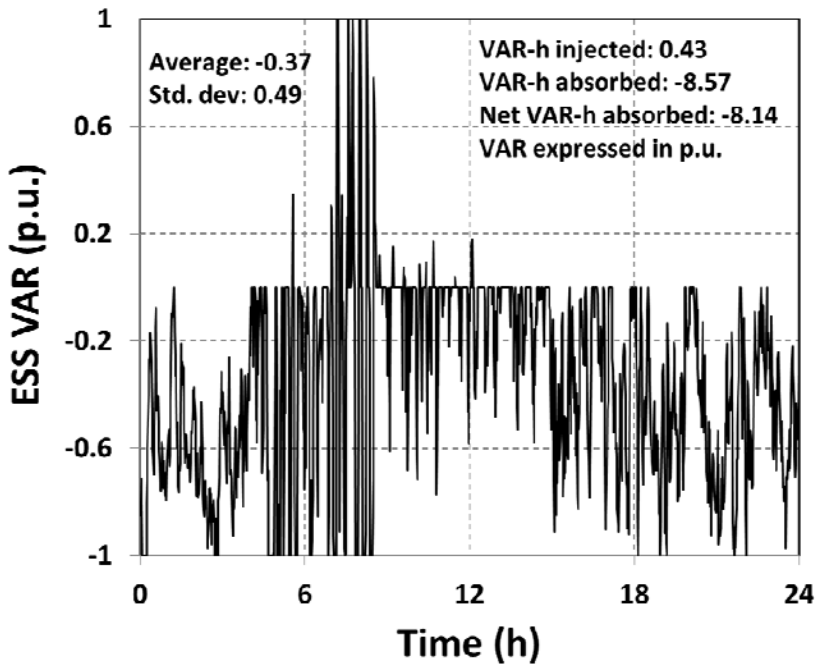


Figure 5.3.5c. Volt/Var Support Duty Cycle – Grid Voltage on Either Side of the Reference Voltage

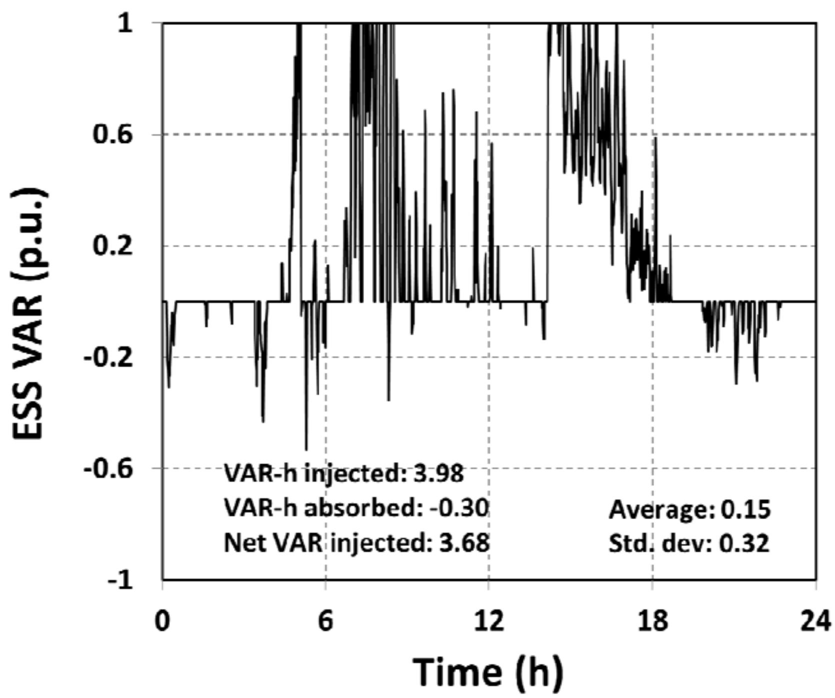


Figure 5.3.5d. Volt/Var Support Duty Cycle –Grid Voltage Less than the Reference Voltage

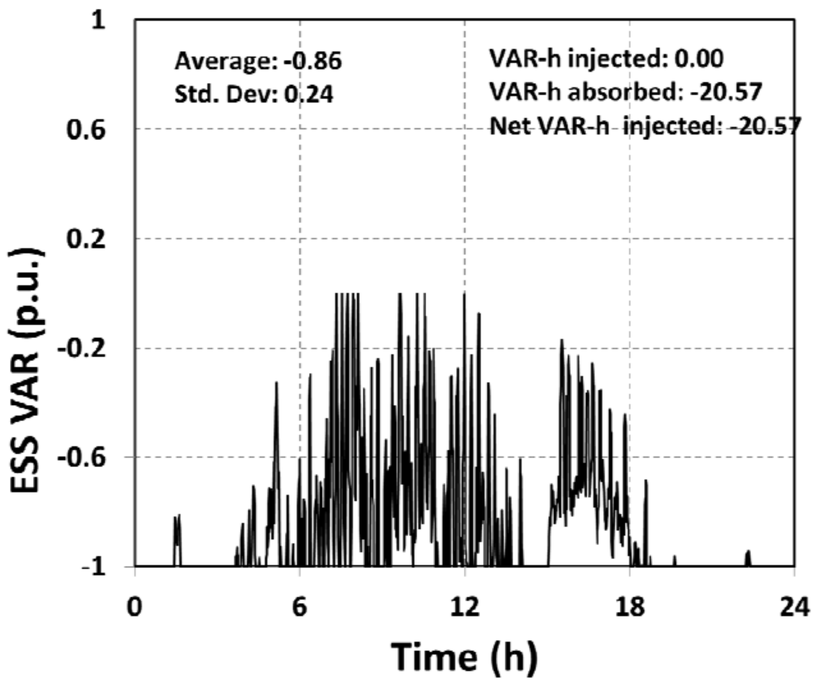


Figure 5.3.5e. Volt/Var Support Duty Cycle – Grid Voltage Greater than the Reference Voltage

5.3.6 Renewables (Solar) Firming Duty Cycle. The duty cycle presented in Figure 5.3.6 shall be applied in determining the performance of an ESS in a renewable (solar) firming application. The duty cycle shown in Figure 5.3.6 is shown as power normalized with respect to the rated power of the ESS, where a positive sign represents charge into the ESS and a negative sign represents discharge from the ESS as a function of time in hours. A reference to the data upon which Figure 5.3.6 is based is included in Appendix F.

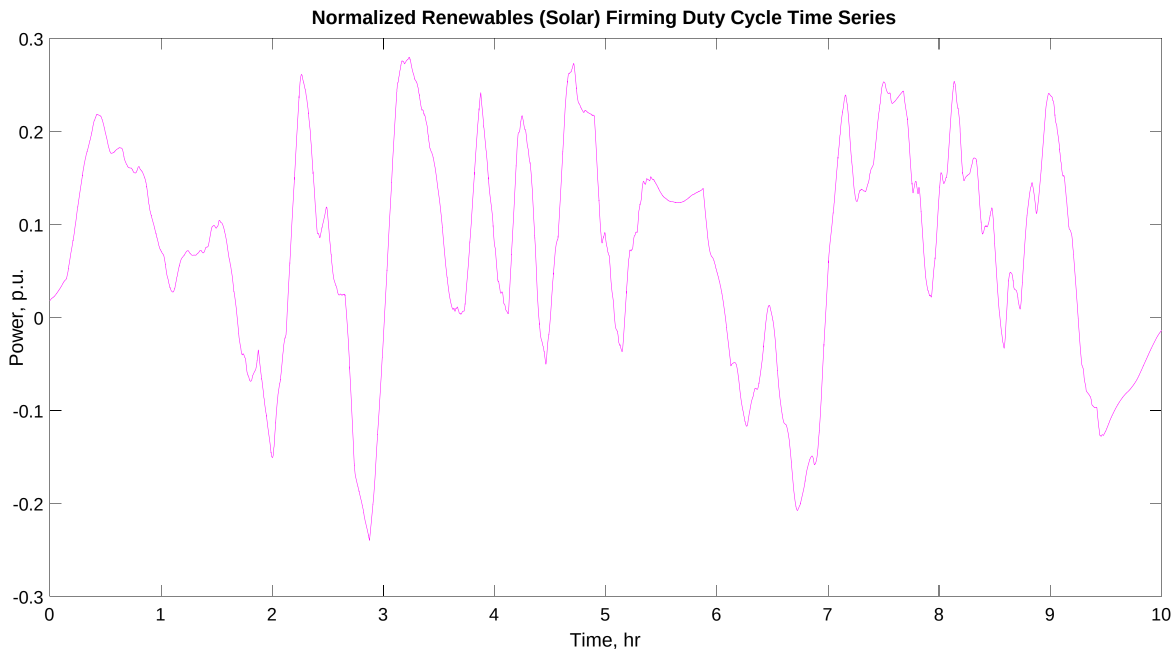


Figure 5.3.6. Duty Cycle – Renewable (Solar) Firming

5.3.7 Power Quality Duty Cycle. The duty cycles presented in Figures 5.3.7a through 5.3.7c shall be applied in determining the performance of an ESS for a power quality application. The duty cycles shown in Figures 5.3.7a through 5.3.7c are shown as continuous discharge at peak power for durations of 1, 5, and 10 minutes respectively. In Figures 5.3.7a and 5.3.7b, the first graph in each pair shows the entire duty cycle and the second graph in each pair shows a magnified portion of the duty cycle in order to provide detail on the discharge characteristics. The duty cycle in Figure 5.3.7a corresponds to the use of ESSs in a power quality application for a duration of 24 hours where there is a continuous ESS discharge of 1-minute duration every 30 minutes. The duty cycle in Figure 5.3.7b corresponds to the use of ESSs in a power quality application for a duration of 12 hours where there is a continuous ESS discharge of 5 minutes in duration every 45 minutes. The duty cycle in Figure 5.3.7c corresponds to the use of ESSs in a power quality application for a duration of 6 hours where there is a continuous ESS discharge of 10 minutes in duration every 60 minutes. The initial SOC shall be brought to its maximum SOC. At the end of the application of each duty cycle in conducting the testing under Section 5.4, the ESS shall be brought back to its initial SOC before the application of another duty cycle. A reference to the data upon which Figures 5.3.7 a, b, and c are based is included in Appendix G.

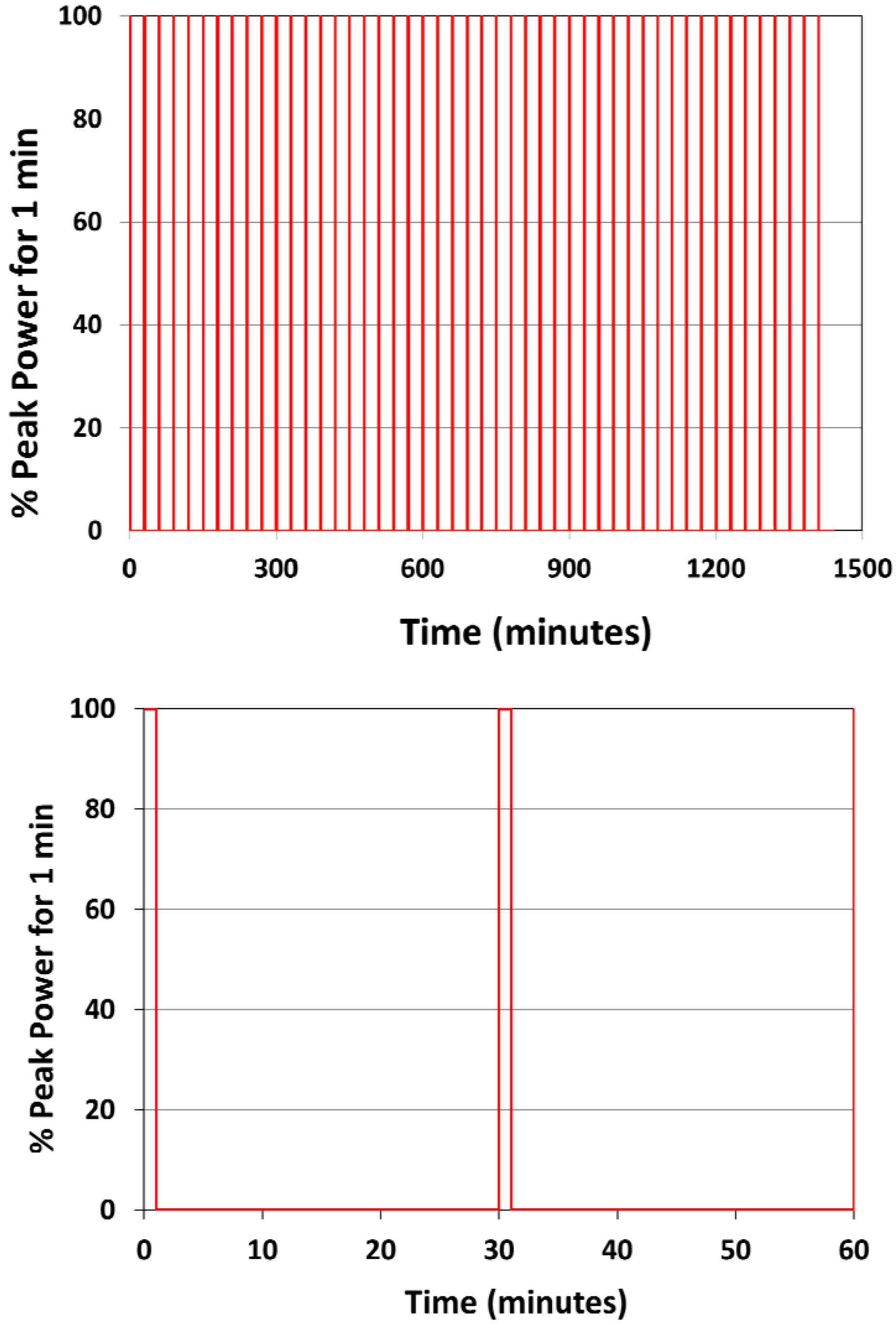
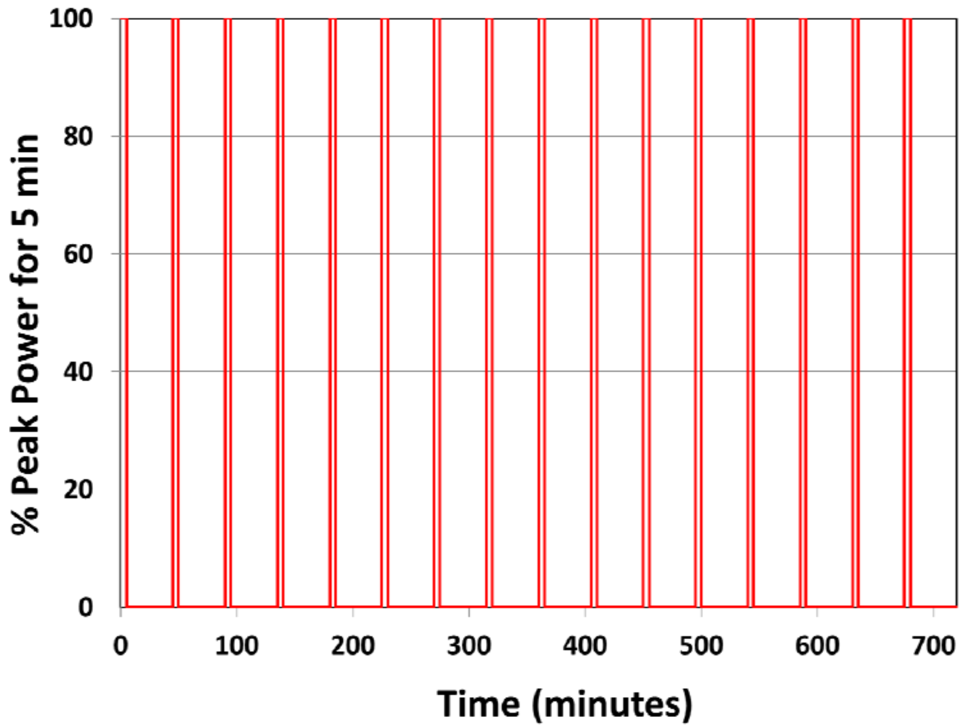


Figure 5.3.7a. Power Quality 24-Hour Duty Cycle for 1-Minute Continuous Discharge shown over 24 Hours and over 1 Hour.



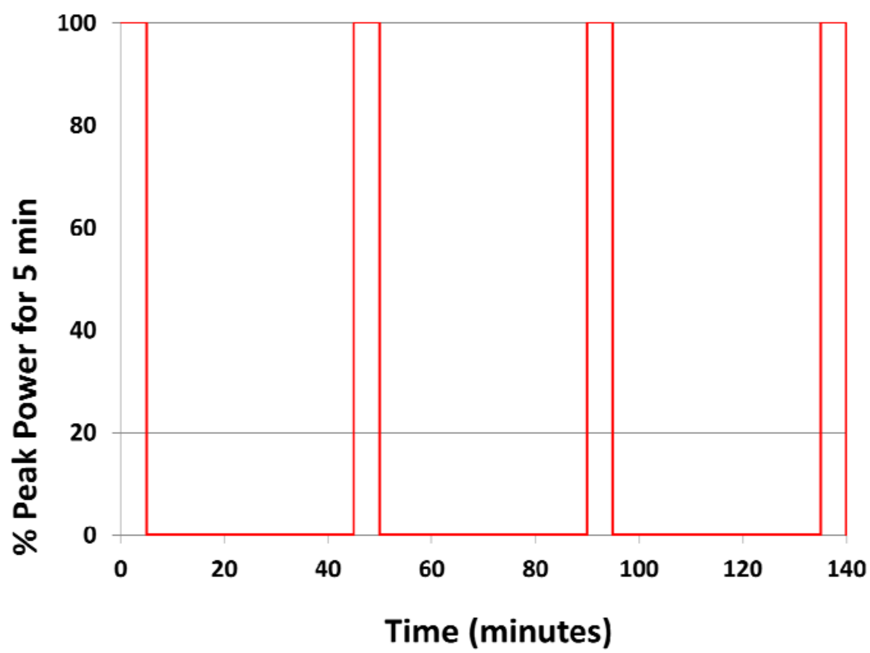


Figure 5.3.7b. Power Quality 12-Hour Duty Cycle for 5-Minute Continuous Discharge shown over 12 Hours and over 140 Minutes.

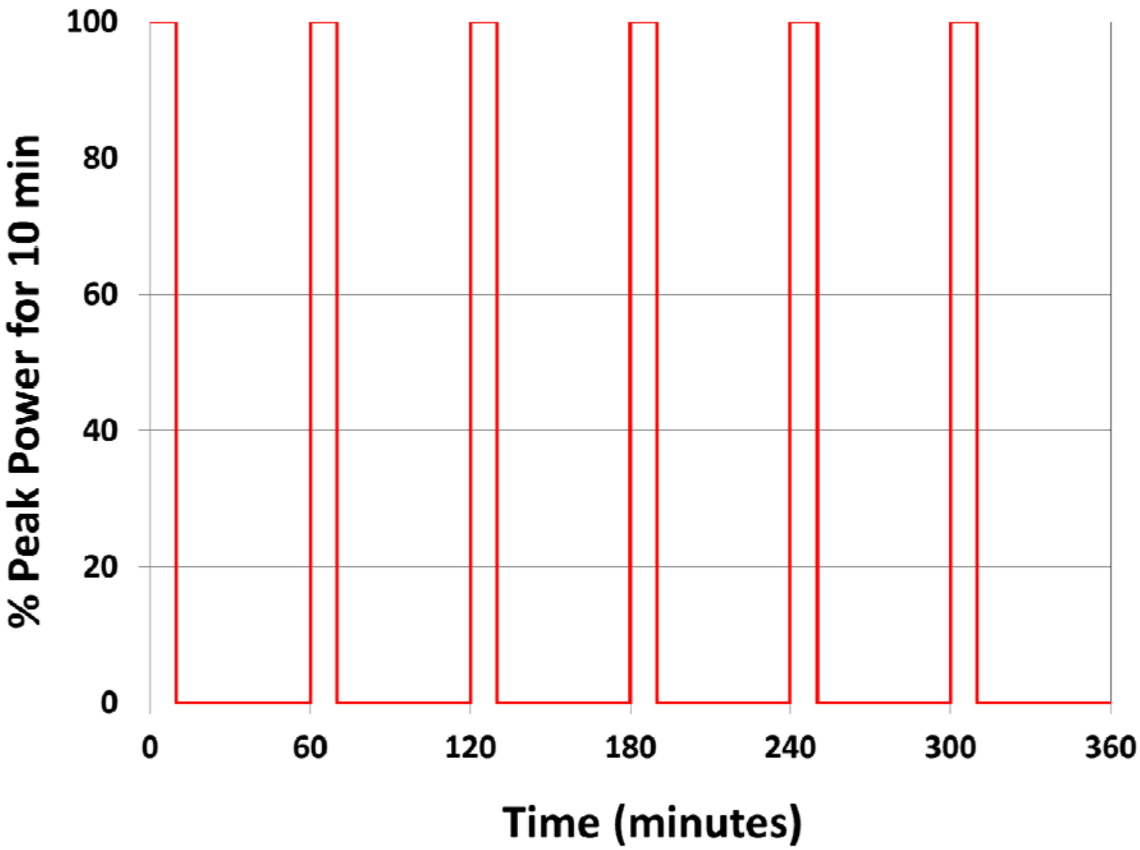
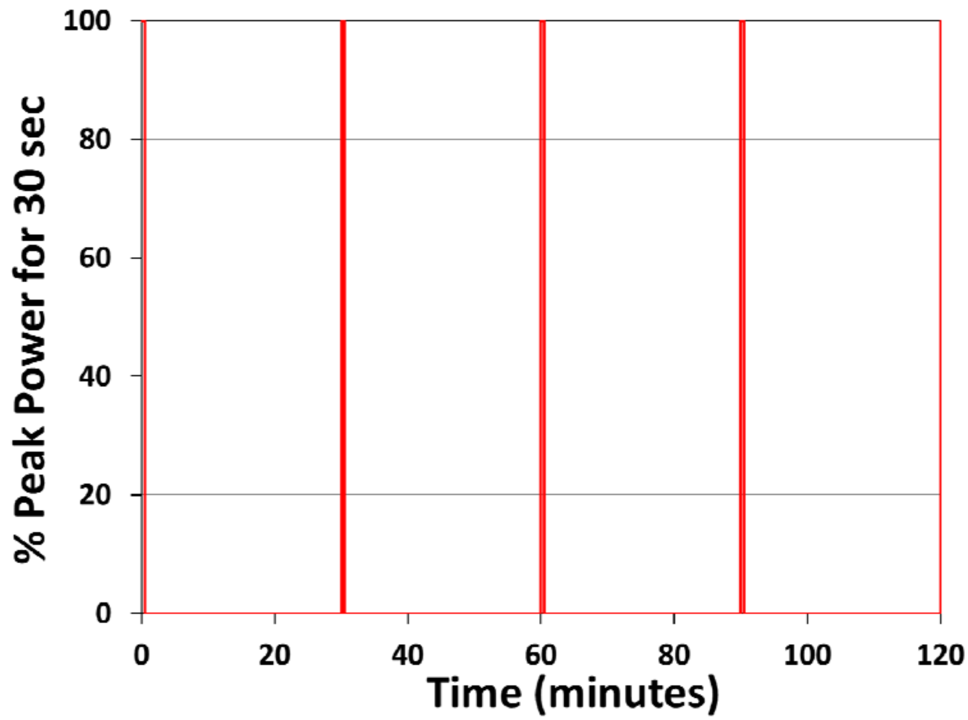


Figure 5.3.7c. Power Quality 6-Hour Duty Cycle for 10-Minute Continuous Discharge Shown over 6 Hours.

5.3.8 Frequency Control Duty Cycle. The duty cycles in Figures 5.3.8 a through5.3.8 e shall be applied in determining the performance of an ESS in a frequency control application. The duty cycles shown in Figures 5.3.8a covers a primary frequency control situation during a sudden loss of generation. This duty cycle corresponds to an ESS discharge for 30 seconds at 1-minute peak power, a rest for 29 minutes, and then repeats this same pattern of use over a period of 24 hours or to a point in time when the low SOC limit of the ESS is reached. The top portion of this figure is the entire duty cycle over 24 hours, while the bottom portion shows the magnified portion of the duty cycle in order to provide detail on the discharge characteristics. The duty cycles in Figures 5.3.8b covers a secondary frequency control situation where the duty cycle duration is such that energy withdrawn or absorbed does not exceed the energy at rated power for one hour. This duty cycle corresponds to a continuous 20-minute ESS discharge, a rest for 40 minutes, and then repeats of this same pattern of use over a period of 24 hours or to a point in time when the low SOC limit of the ESS is reached. While captions to Figures 5.3.8a and 5.3.8b only mention discharge, the duty cycles represented in these figures apply to both discharge (sudden loss of generation) and charge (sudden loss of load). The initial SOC shall be set at maximum SOC for sudden loss of generation, and at minimum SOC for sudden loss of load. The duty cycles in Figure 5.3.8c covers a dynamic frequency control situation for each season of the year. The initial SOC shall be set at 50% for dynamic frequency regulation. At the end of the application of each duty cycle in conducting the testing under Section 5.4, the ESS shall be brought back to its initial SOC by charging (for sudden loss of generation) or discharging (for a sudden loss of load) at rated power before the application of another duty cycle. A reference to the data upon which Figures 5.3.8a through 5.3.8e are based is included in Appendix H.



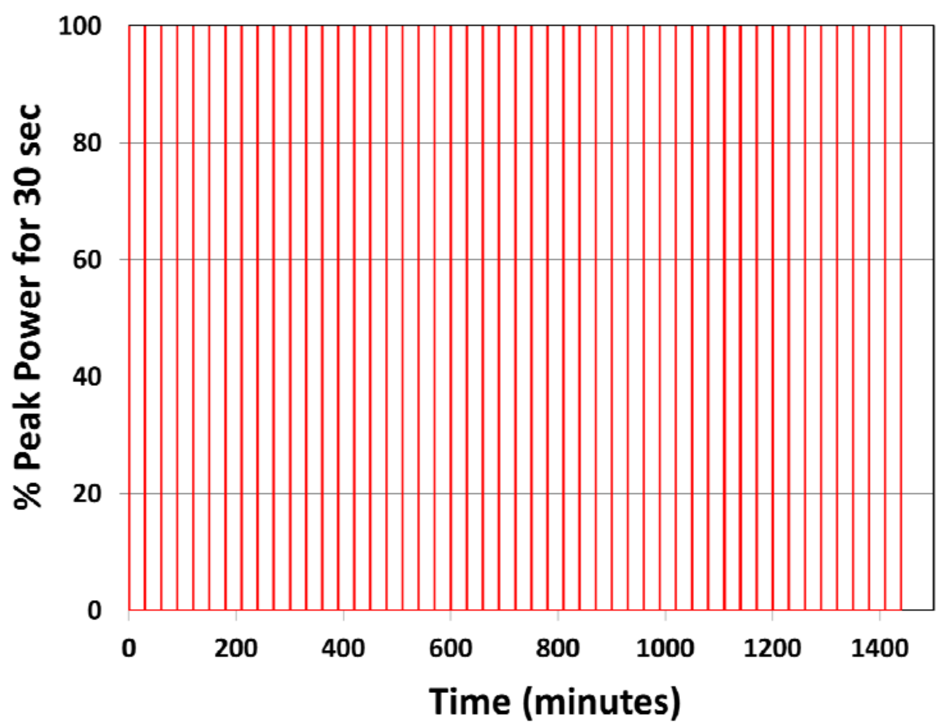


Figure 5.3.8a. Primary Frequency Control Signal: 24-hour duty cycle with 30-Second Discharge every half hour shown over 3 hours and 24 hours

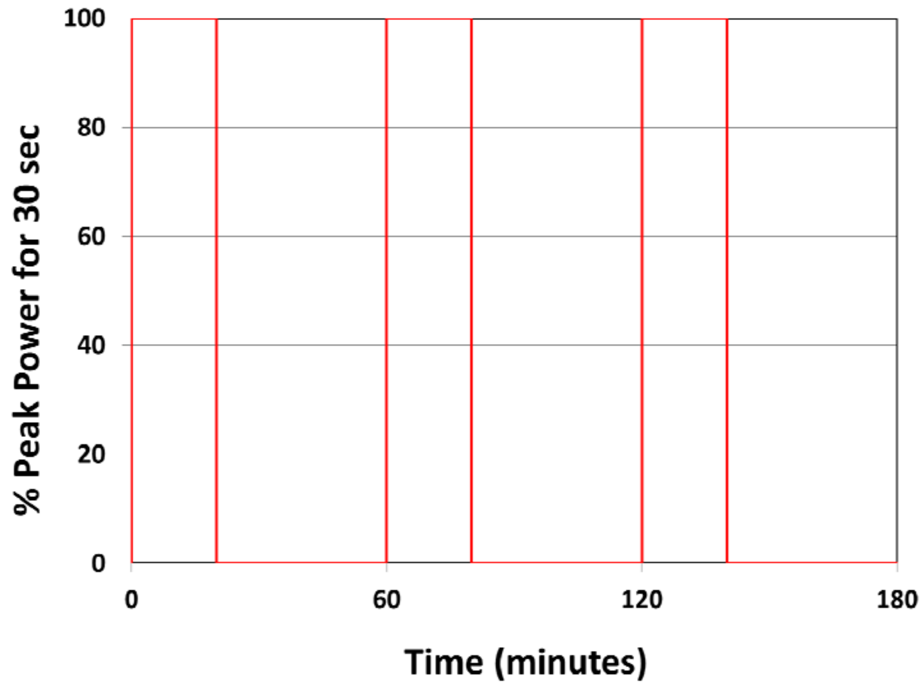


Figure 5.3.8b. Secondary Frequency Control Signal: 20-Minute Discharge Every Hour over 3 Hours

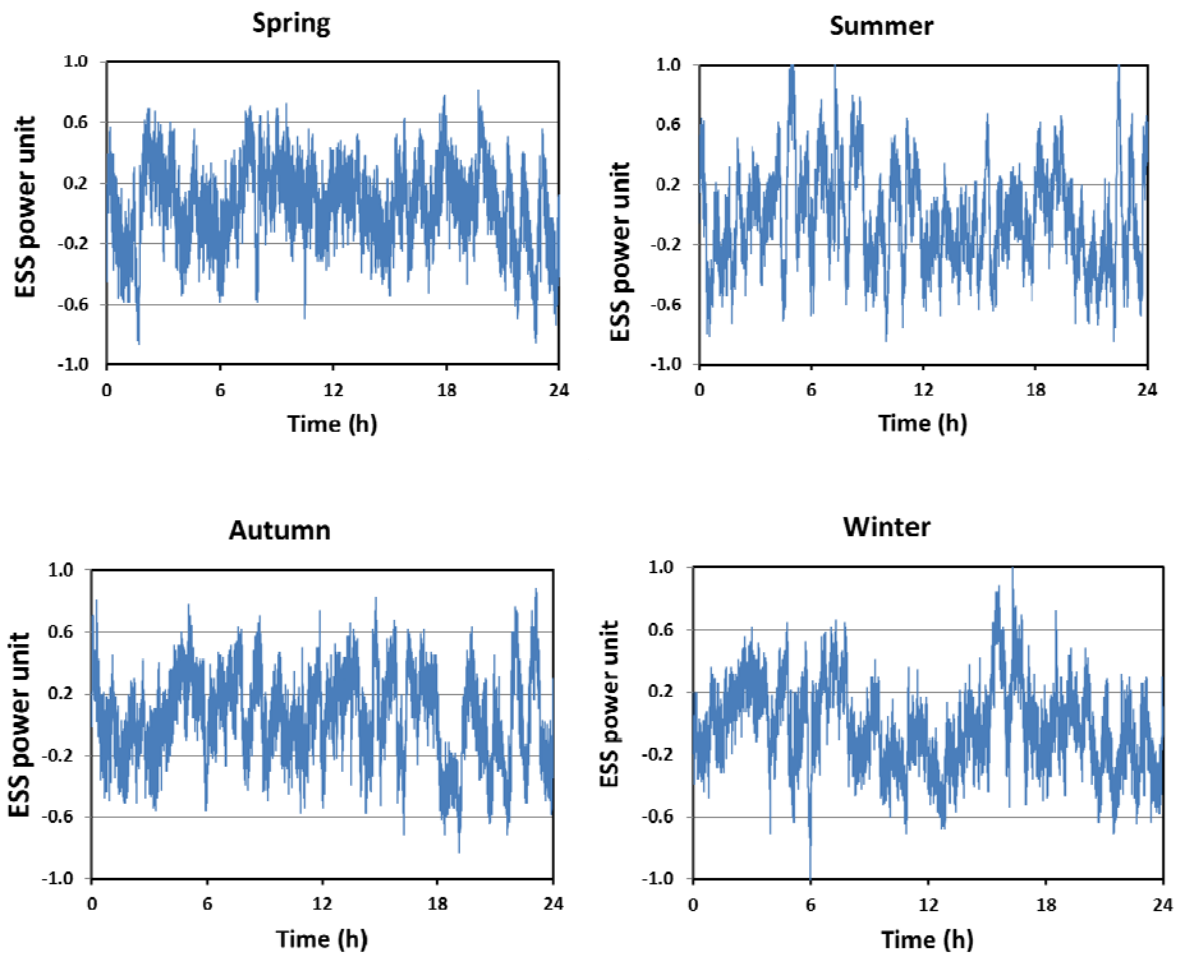


Figure 5.3.8c. Dynamic Frequency Control Signal – Spring, Summer, Autumn and Winter

5.4 Duty-Cycle Performance. The ESS performance metrics in Section 5.4 are dependent on the intended application(s) of the ESS as determined in accordance with Section 4.3 and the use of the relevant duty cycle(s) in Section 5.3 during the tests required in this section. The results from all tests conducted in accordance with this section shall be used to determine baseline ESS duty-cycle performance that can be subsequently used to assess any changes in the condition of the ESS and performance over time and use. The tests presented in this section shall be repeated at regular intervals specified by the manufacturer during cycle testing for same-system comparison purposes. Such intervals shall be selected to identify how the testing or operation affects the performance of the ESS and shall be in units of time, number of cycles, or energy throughput. Duty-cycle performance tests shall be conducted for each intended application of an ESS using the duty cycles as defined in Sections 5.3.1 through 5.3.8. Prior to initiating any of the duty-cycle performance tests, the initial SOC shall be set per the manufacturer's specifications and operating instructions. Where an ESS is to be evaluated under more than one duty cycle, the ESS shall be brought back to the same initial SOC used as a basis for testing conducted under the first duty cycle before application of one or more duty cycles.

As provided in Section 5.3, the ESS manufacturer shall be permitted to apply one or more alternative duty cycles beyond those provided in Section 5.3. When an alternative duty cycle is applied, the manufacturer shall provide a description of and rationale for the alternative duty cycle and shall conduct all tests required in Section 5.4 for the intended ESS application(s) while subjecting the ESS to the alternative duty cycle(s).

Table 5.4 indicates which duty-cycle performance metrics in Section 5.4 are relevant for each of the ESS applications covered by this document. In determining the performance of an ESS for a power quality or frequency control application, testing in accordance with Sections 5.4.5.2 and 5.4.5.3, respectively, shall be performed first, followed by the testing in accordance with Sections 5.4.1 through 5.4.4.

Table 5.4. Duty-Cycle Metrics Applicable to Each ESS Application

Metric	Peak Shaving (5.3.1)	Frequency Regulation (5.3.2)	Microgrid (5.3.3)	PV Smoothing (5.3.4)	Volt/Var[1] (5.3.5)	Renewables (Solar) Firming (5.3.6)	Power Quality[2] (5.3.7)	Frequency Control[3] (5.3.8)
Duty Cycle RTE (5.4.1)	X	X	X	X		X	X	X
Reference Signal Tracking (5.4.2)		X	X	X	X	X	X	X
SOC Excursions (5.4.3)	X	X	X	X	X	X	X	X
Energy Capacity Stability (5.4.4)	X	X	X	X	X	X	X	X

1. Volt/var also has duty-cycle metrics for ramp rate, ΔSOC_volt/var, ΔSOC_active_standby, Wh_discharge, Wh_charge and Wh_net.
2. PQ also has a duty-cycle metric for peak discharge power for 1, 5, and 10 minutes.
3. FC also has a duty-cycle metric for peak charge and discharge power for 1 and 20 minutes.

5.4.1 Duty-Cycle Round-Trip Efficiency. The duty-cycle round-trip efficiency of the ESS shall be determined in accordance with this section. The tests as described in items 1 through 5 below shall be conducted separately for each intended application of the ESS while applying the duty cycle in Section 5.3 relevant to each intended application of the ESS. The results shall be reported in accordance with Section 6.3 separately for each intended application of the ESS.

> **Exception:** Duty-cycle round-trip efficiency is not applicable to ESSs intended for volt/var support applications.

The manufacturer shall charge and discharge the ESS in accordance with this section using the duty cycle in Section 5.3 applicable to the intended application(s) of the ESS.

1. The ESS shall be brought to the initial desired SOC as dictated by a given $T_{initial}$, or $P_{initial}$ in accordance with the duty cycle in Section 5.3 applicable to the intended application of the ESS by adding or removing the necessary amount of energy at the rated power of the ESS as provided by the manufacturer's specifications. For electrical ESSs, the SOC as reported by the battery management system or the flywheel management system shall be recorded.
2. The ESS shall then be subjected to the duty cycle in Section 5.3 that is applicable to the intended application of the ESS.
3. Where the duty cycle being applied has multiple profiles, Steps 1 through 3 shall be repeated for all other profiles in the duty cycle.

The duty-cycle round-trip efficiency at each discharge power level of a duty cycle with one profile, or each profile in a duty cycle with multiple profiles, shall be determined by dividing the energy removed (output) from the ESS at a given power by the energy required to recharge (input) the ESS accounting for auxiliary loads as described in Section 5.2.2. When the discharge power tapers off, the duty-cycle round-trip efficiency shall be calculated for the SOC range corresponding to constant power as described in Section 5.2.2. The percentage of discharge duration for which constant power was maintained shall be reported, along with average power. The duty-cycle round-trip efficiency shall be reported for the entire SOC range of the duty cycle, along with the average discharge power (discharge duration ÷ discharge time).

The duty-cycle round-trip efficiency as a function of discharge power shall be determined by dividing the energy removed from the ESS at a given power by the energy required to recharge the ESS and reported in accordance with Section 6.3. Any auxiliary loads shall be accounted for as described in Section 5.2.2 and also reported in accordance with Section 6.3. When an application has multiple duty cycles, the charge and discharge energy shall include the energy to bring the ESS back to initial SOC after each duty cycle.

5.4.2 Reference Signal Tracking. The ability of the ESS to respond to a signal for the duration of the duty cycle for each intended application of the ESS reflects the ability of the ESS to track the signal. The tests in Section 5.4.2.1 shall be conducted separately for each intended application of the ESS while applying the duty cycle in Section 5.3 relevant to each intended application of the ESS as described in 5.4.1. The results shall be reported in accordance with Section 6.3 separately for each intended application of the ESS.

> **Exception:** Reference signal tracking is not applicable to ESSs intended for peak-shaving applications.

5.4.2.1 Calculation Procedure. The ability of the ESS to respond to a signal for the duration of the relevant duty cycle(s) from Section 5.3 that reflect the ability of the ESS to track the signal shall be defined and determined by the manufacturer of the ESS in accordance with the provisions of this section. The balancing signal shall be changed in accordance with duty cycle(s) from Section 5.3 for each intended application of the ESS.

The manufacturer of the ESS shall also determine and report separately the total percentage tracking and the times when the ESS stops tracking and restarts tracking as an indication of whether the ESS is capable of tracking high peaks and/or high energy half-cycles. The manufacturer shall also determine whether the ESS can go through the required duration of the duty cycle without reaching the lower or upper SOC limits. This shall be performed during the application of the relevant duty cycle as described in Section 5.3, and any time during that period when the ESS indicates an ability or inability to follow the signal shall be reported. An inability to follow the signal shall be considered a situation where the ESS cannot deliver or absorb required signal power during the duration when the balancing signal is to be changed and cannot deliver or absorb the required signal energy during the duration when the signal remains above or below the x-axis.

The ability of the ESS to respond to a reference signal shall be recorded during the duty-cycle round-trip efficiency test. The residual sum of squares or the sum of the square of errors between the balancing signal (P_{signal}) and the power delivered or absorbed by the ESS (P_{ess}) shall be calculated in accordance with Equation 5-12 and used to estimate the inability of the ESS to track the signal.

$$\Sigma \, (P_{signal} - P_{ess})^2 \tag{5-12}$$

where P_{signal} is the balancing signal and P_{ess} is ESS power (watts).

The measurements shall be taken at every point in time that the ESS receives a change in the balancing signal. The sum of the absolute magnitudes of the difference between the balancing signal and ESS power shall be calculated in accordance with Equation 5-13.

$$\Sigma \, |P_{signal} - P_{ess}| \tag{5-13}$$

where P_{signal} is the balancing signal and P_{ess} is ESS power (watts).

The sum of the absolute magnitudes of the difference between the balancing signal energy and ESS energy shall be calculated in accordance with Equation 5-14 and reported by the manufacturer of the ESS to account for the inability of the ESS to follow the signal due to the ESS reaching the SOC limits provided in the manufacturer’s specifications and operating instructions.

$$\Sigma\ |E_{signal} - E_{ess}| \quad (5\text{-}14)$$

where E_{signal} is the signal energy for a half-cycle, with half-cycle being the signal of the same sign (above or below the x-axis), and E_{ess} is the energy supplied to or absorbed by the ESS for each half-cycle.

The total time the ESS cannot follow the signal and the percentage tracked where $(P_{signal} - P_{ess}) \div P_{signal}$ is less than 0.02 shall be determined in accordance with Equation 5-15.

When $|\ (P_{signal} - P_{ess}) \div P_{signal}\ |$ is less than 0.02, the ESS shall be considered to track the signal. The percentage of time the signal is tracked during the duration of the duty cycle provided in Section 5.3 based on the application(s) for the ESS shall be determined in accordance with Equation 5-15

$$\text{\% of time signal is tracked} = [\text{time signal is tracked (h)} \div \text{duration of the duty cycle (h)}] \times 100 \quad (5\text{-}15)$$

5.4.3 State-of-Charge Excursions. The SOC of the ESS shall be monitored and continuously updated during all testing that is conducted under Section 5.4 for each intended application of the ESS. During the conduct of the tests, the ESS SOC shall not cross the thresholds provided in the manufacturer's specifications and operating conditions. The SOC excursion shall be reported in accordance with the provisions in Section 6.3.

> **Exception:** SOC excursion monitoring is not applicable to ESSs intended for frequency control applications.

5.4.4 Energy Stability. The energystability of the ESS shall be determined by dividing the stored energy by the initial stored energy of the ESS. Stored energy shall be determined in accordance with Section 5.2.1. The energy stability of an ESS for any application shall be determined before and after subjecting the ESS to the duration of the duty cycle(s) in Section 5.3 applicable to the intended ESS application(s) and reported in accordance with the provisions in Section 6.3.

5.4.5 Additional Metrics. In addition to the duty-cycle metrics in Sections 5.4.1 through 5.4.4, ESSs shall also meet the provisions of Section 5.4.5.1 through 5.4.5.3 as applicable to the intended application for the ESS.

5.4.5.1 Volt/Var. Energy storage systems used in a volt/var application shall also have the information in items (1) through (5) recorded during the testing conducted in accordance with Sections 5.2 and 5.4, and reported in accordance with Section 6.3.

1. The initial and final SOC as well as the difference between the final and initial SOC (ΔSOC)
2. The difference in SOC at the end of an active standby (ΔSOC_{AS}) having the same duration as the volt/var duty cycle, with auxiliary loads turned on, with the initial SOC the same as the value at the start of the volt/var duty cycle
3. The real energy injected (with and without volt/var duty cycle) as Wh discharge
4. The real energy absorbed (with and without volt/var duty cycle) as Wh charge
5. The net energy (injected or absorbed) (with and without volt/var duty cycle) as Wh net.

5.4.5.2 Power Quality. Energy storage systems used in a power quality application shall also be tested to determine the peak discharge power of the ESS at 1, 5, and 10 minute intervals in accordance with the following procedure, and reported in accordance with Section 6.3. After a determination of peak discharge power in accordance with this section, the duty cycle in Section 5.3.7 shall be applied to the ESS and testing performed as required in Sections 5.4.1 through 5.4.4.

1. The ESS shall be brought to the desired starting SOC (default is upper end of SOC limit for discharge) by charging or discharging the ESS in accordance with the manufacturer's recommendation.
2. The ESS shall be discharged at 1.25 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the discharge time recorded.
3. The ESS shall be recharged to the starting SOC.
4. The ESS shall be discharged at 1.5 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the discharge time recorded.
5. The ESS shall be recharged to the starting SOC.
6. The ESS shall be discharged at 2 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the discharge time recorded.
7. The ESS shall be recharged to the starting SOC.
8. The ESS shall be discharged at 3 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the discharge time recorded.
9. The ESS shall be recharged to the starting SOC.
10. The ESS shall be discharged at 5 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the discharge time recorded.
11. The ESS shall be recharged to the starting SOC.
12. The ESS shall be discharged at10 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the discharge time recorded.
13. The discharge power shall be plotted in relation to discharge time to derive the peak power at 1 minute, 5 minutes, and 10 minutes.

5.4.5.3 Frequency Control. Energy storage systems used in frequency control application shall be tested for peak discharge power in accordance with Section 5.4.5.2 at intervals of 1 and 20 minutes, and reported in accordance with Section 6.3. Energy storage systems shall also be tested to determine their peak charge power at 1- and 20-minute intervals in accordance with the following procedure, and reported in accordance with Section 6.3. After a determination of peak discharge power in accordance with this section, the duty cycle in Section 5.3.8 shall be applied to the ESS and testing performed as required in Sections 5.4.1 through 5.4.4.

1. The ESS shall be brought to the desired starting SOC (default is upper end of SOC limit for discharge) by charging or discharging the ESS in accordance with the manufacturer's recommendation.
2. The ESS shall be charged at 1.25 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the charge time recorded.
3. The ESS shall be discharged to the starting SOC.
4. The ESS shall be charged at 1.5 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the charge time recorded.
5. The ESS shall be discharged to the starting SOC.
6. The ESS shall be charged at 2 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the charge time recorded.
7. The ESS shall be discharged to the starting SOC.
8. The ESS shall be charged at 3 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the charge time recorded.
9. The ESS shall be discharged to the starting SOC.
10. The ESS shall be charged at 5 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) the charge time recorded.
11. The ESS shall be discharged to the starting SOC.
12. The ESS shall be charged at10 times rated power or maximum power (whichever is lower) until the lower SOC limit is reached or power tapers off (whichever comes first) and the charge time recorded.
13. The charge power shall be plotted in relation to charge time to derive the peak power at 1 minute and 20 minutes.

6.0 Reporting ESS General Information, Specifications, and Performance Results

6.1 Energy Storage System Description, General Information, and Technical Specifications. The manufacturer of the ESS shall provide a description of the ESS in written form accompanied by necessary specifications and data to cover the information required in Section 4.2. In addition, the manufacturer shall complete Table 6.1 for the ESS and provide a copy of the completed table in the literature provided by the manufacturer that covers the ESS. The manufacturer shall be permitted to provide information on more than one ESS in a single table by creating additional columns for the information in the table and labeling each column by the model number, name, or other appropriate designation for each ESS covered in the table.

Table 6.1. ESS General Information and Technical Specifications

Subject	Information
Enclosure Type	
Equipment Footprint (sq.ft.)	
Height (ft.)	
Weight (lbs.)	
Operating Temperature Range (°F)	
Grid Communication Protocols/Standards	
General Description of the Energy Storage System	
Warranty & Replacement Schedule	
Expected Availability of System (%)	
Rated Continuous Discharge Power (kW)	
Rated Apparent Power (kW)	
Rated Continuous Charge Power (kW)	
Rated Continuous AC Current (discharge and charge)	
Output Voltage Range (V)	
Rated Discharge Energy (kWh)	
Minimum Charge Time (hrs.)	

6.2 Energy Storage System Reference Performance. The manufacturer of the ESS shall complete Table 6.2 and attach a copy of this table to the ESS. In addition, the manufacturer shall provide a copy of this table in the literature provided by the manufacturer to describe each specific ESS covered by the literature.

Table 6.2. Reference Performance

Subject	Information
Stored Energy Capacity at Rated Power (each cycle starts with discharge)[a]	Discharge Power (kW) ______ Discharge Energy (kWh) / Aux Energy (kWh) Cycle 1 ____ ____ Cycle 2 ____ ____ Cycle 3 ____ ____ Cycle 4 ____ ____ Cycle 5 ____ ____ Sum ____ ____ Last Charge ________ Charge Power (kW) ______ Charge Energy (kWh) / Aux Energy (kWh) Cycle 1 ____ ____ Cycle 2 ____ ____ Cycle 3 ____ ____ Cycle 4 ____ ____ Cycle 5 ____ ____ Sum ____ ____ Sum ______ Rest Aux (kwh) ____ ____ ____ ____ ____ ____
Cumulative Round-Trip Efficiency at Rated Power [b]	___________% at _____________ kW Power basis for the test = ___________________(constant or average) Auxiliary load power source = _______________(ESS or separate)
Individual cycle RTE [c]	Cycle 1 _____% at _____ kW Cycle 2 _____% at _____ kW Cycle 3 _____% at _____ kW Cycle 4 _____% at _____ kW Cycle 5 _____% at _____ kW
Stored Energy at Various % of Rated Power	Rated discharge power (kW) __________ Discharge Energy (kWh) / Aux Energy (kWh) 25% ____ ____ 50% ____ ____ 75% ____ ____ Sum Rated charge power (kW) _________ Charge Energy (kWh) / Aux Energy (kWh) 25% ____ ____ 50% ____ ____ 75% ____ ____ Sum Rest Aux (kwh) ____ ____ ____
Stored Energy at Various % of Rated Power	25% ____% at ____ kW 50% ____% at ____ kW 75% ____% at ____ kW Total
Response Time (real power)	Discharge response time (RT_D) = ______ seconds Charge response time (RT_C) = ______ seconds
Ramp Rate (real power)	Discharge ramp rate (RR_D) = _____ MW/sec _____% rated power/sec Charge ramp rate (RR_C) = _____ MW/sec _____% rated power/sec
Internal Resistance	________ (ohms)

Reactive Power Response Time	Discharge response time (RP RT_D) = _____ seconds Charge response time (RP RT_C) = _____ seconds.
Reactive Power Ramp Rate	Discharge ramp rate (RP RR_D) = ____ Mvar/sec ____% rated power/sec Charge ramp rate (RP RR_C) = ____ Mvar/sec ____% rated power/sec
Standby Energy Loss Rate	Standby energy loss rate (SELR) =__________% energy loss/day
Self-Discharge Rate	Self-discharge rate (SDR) =__________% energy loss/day

(a) Where additional testing is performed beyond the minimum required two cycles, an additional row shall be added for each cycle and the total charge and discharge energy shall be the sum of all values reported and the RTE based on those totals.
(b) When auxiliary loads are powered separately, Equations 5-2 shall be used.
(c) When auxiliary loads are powered separately, Equations 5-4 shall be used

6.3 Energy Storage System Duty-cycle Performance. The manufacturer of the ESS shall complete Table 6.3 for each intended application of the ESS as outlined in Section 4.4 based on the tests conducted as directed in Section 5.4 and the duty cycle in Section 5.3 and attach a copy of this table to the ESS for each intended application. In addition the manufacturer shall provide a copy of this table in the literature provided by the manufacturer to describe each specific ESS covered by the literature and the intended application(s) of each ESS covered. For an ESS used in peak shaving, power quality, or frequency control applications, the duty-cycle round-trip efficiency shall be reported in accordance with Table 6.3.1 by substituting the duty-cycle round-trip efficiency information in Table 6.3.1 for that in Table 6.3.

Table 6.3. Duty-Cycle Performance

Intended Application – ______________________________				
Subject	**Information**			
Duty-Cycle Round-Trip Efficiency [(a,b)]	Charge Energy (kWh) = Discharge Energy (kWh) = Auxiliary load (if powered separately) (kWh) = Duty cycle RTE =	Duty Cycle 1 ______________	Duty Cycle 2 ______________	Duty Cycle 3 ______________

Reference Signal Tracking)	$\Sigma (P_{signal} - P_{ess})^2$ = ________________ $\Sigma\|P_{signal} - P_{ess}\|$ = ________________ $\Sigma\|E_{signal} - E_{ess}\|$ = ________________ % of time signal is tracked = __________
State-of-Charge Excursions	Lowest SOC ______________ Highest SOC _____________ Ambient temperature during the test (°F) __________ Barometric pressure during the test (mm Hg)___________
Energy Stability	________ Percent of initial performance ________ Date of the test upon which the reported value is based ________ Ambient temperature during the test (F) ________ Barometric pressure during the test (Hg)
ΔSOC_(volt/var only)	Initial SOC = _____ Final SOC = _____ ΔSOC = _____
ΔSOC_active_standby _(volt/var only)	ΔSOC_{AS} = _____
Wh_discharge _(volt/var only)	Wh_discharge = _____ The real energy injected (with and without volt/var duty cycle)
Wh_charge _(volt/var only)	Wh_charge = _____ The real energy absorbed (with and without volt/var duty cycle)
Wh_net _(volt/var only)	Wh_net =_____
Peak discharge power (Power Quality only)	1 min ______ kW 5 min ______ kW 10 min ______ kW
Peak charge and discharge power (Frequency Control only)	1 min ______ kW discharge 1 min ______ kW charge 20 min ______ kW discharge 20 min ______ kW charge

(a) Results for each duty cycle for an application shall be reported separately. The power basis (constant power or average) shall be reported for peak shaving. For other applications, this does not apply.

(b) Use Equation 5-2 if auxiliary load powered separately. Assign Auxiliary load consumption to denominator. Repeat for each duty cycle type (e.g., microgrids have multiple duty cycles).

Table 6.3.1. Peak Shaving, Power Quality, Primary and Secondary Frequency Control Duty-Cycle Performance

<table>
<tr><th colspan="6">Intended Application – ____</th></tr>
<tr><th>Subject</th><th colspan="5">Information</th></tr>
<tr><td rowspan="6">Duty-Cycle Round-Trip Efficiency[(a)]</td><td colspan="2">Power (kW) _____</td><td colspan="2">Power (kW) ______</td><td>RTE (%)</td></tr>
<tr><td>Charge (kWh)</td><td>Aux (kwh)</td><td>Discharge (kWh)</td><td>Aux (kWh)</td><td></td></tr>
<tr><td>Cycle A _____</td><td>Cycle A _____</td><td>Cycle A _____</td><td>Cycle A _____</td><td>A _____</td></tr>
<tr><td>Cycle B _____</td><td>Cycle B _____</td><td>Cycle B _____</td><td>Cycle B _____</td><td>B _____</td></tr>
<tr><td>Cycle C _____</td><td>Cycle C _____</td><td>Cycle C _____</td><td>Cycle C _____</td><td>C _____</td></tr>
<tr><td colspan="5">Power basis for the test = ___________________(constant or average)
Auxiliary load power source = _______________(ESS or separately)</td></tr>
</table>

(a) Results for each duty cycle for an application shall be reported separately. For example, for peak shaving, results shall be reported for duty cycle A, B, and C. As noted in 5.2, each duty cycle can begin with charge or discharge. The power basis (constant power or average) shall be reported for peak shaving. For other applications, this does not apply

7.0 Referenced Standards

7.1 Institute of Electrical and Electronics Engineers (IEEE) Standard 1679-2010. IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications.

7.2 American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 105-2014. ANSI/ASHRAE Standard Methods of Determining, Expressing, and Comparing Building Energy Performance.

7.3 Institute of Electrical and Electronics Engineers (IEEE) Standard 1459-2010. IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions.

8.0 References

Conover DR and VV Viswanathan. 2014. *Determination of the Duty Cycle for Energy Storage Systems Integrated with a Microgrid*. PNNL-23390, Pacific Northwest National Laboratory, Richland, Washington. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23390.pdf.

Conover DR, AJ Crawford, J Fuller, SN Gourisetti, and VV Viswanathan. 2016. *Determination of Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System*. PNNL-25316, Pacific Northwest National Laboratory, Richland, Washington. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25316.pdf.

Eyer J and G Corey. 2010. *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. SAND2010-0815, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2010-0815.pdf.

Ferreira SR and DA Schoenwald. 2013. *Duty-Cycle Signal for Frequency Regulation Applications of ESSs*. SAND2013-7315P, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2013-7315P.xlsx.

Johnson J, S Gonzalez, ME Ralph, A Ellis, and R Broderick. 2013a. *Test Protocols for Advanced Inverter Interoperability Functions – Appendices*. SAND2013-9875, Sandia National Laboratories, Albuquerque, New Mexico. http://energy.sandia.gov/wp-content/gallery/uploads/SAND2013-9875.pdf.

Johnson J, S Gonzalez, ME Ralph, A Ellis, and R Broderick. 2013b. *Test Protocols for Advanced Inverter Interoperability Functions – Main Document*. SAND2013-9880, Sandia National Laboratories, Albuquerque, New Mexico. http://energy.sandia.gov/wp-content/gallery/uploads/SAND2013-9880.pdf.

Johnson J, S Gonzalez, T Zgonena, M McGirr, J Hopkins, B Seal, F Cleveland, T Tansy, and B Fox. 2014. *Draft Electric Rule 21 Test Protocols for Advanced Inverter Functions*. http://sunspec.org/wp-content/uploads/2015/09/Rule_21_Advanced_DER_Test_Protocols-Final.pdf.

Roberson D, J Ellison, D Bhatnagar, and D Schoenwald. 2014. *Performance Assessment of the PNM Prosperity Electricity Storage Project: A Study for the DOE Energy Storage Systems Program.* SAND2014-2883, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2014-2883.pdf.

Schoenwald DA. 2016. *Determination of Duty Cycle for Energy Storage Systems in a PV Smoothing Application*. SAND2016-3474, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-3474.pdf

Schoenwald DA. 2016. *Determination of Duty Cycle for Energy Storage Systems in a Renewables (Solar) Firming Application*. SAND2016-3636, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-3636.pdf.

Schoenwald DA. 2016. *PV Firming Duty Cycle.* SAND2016-2544R, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-2544R.xlsx.

Schoenwald DA. 2016. *PV Smoothing Duty Cycle.* SAND2016-2543R, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-2543R.xlsx.

UL. 2015. UL1741 Supplement SA – *Grid Support Utility Interactive Inverters and Converters*. Underwriters Laboratories, Northbrook, IL.

Normative Appendix A

Duty-Cycle Signal for Peak-Shaving Applications of Energy Storage Systems

Normative Appendix A

Duty-Cycle Signal for Peak-Shaving Applications of Energy Storage Systems

In Section 5.3.1, the charge duration is fixed at 12 hours, and discharge durations are 6, 4, and 2 hours for duty cycles A, B, and C, respectively. The corresponding rest times after charge and discharge are 3, 4, and 5 hours, respectively.

Feedback from the Protocol Users Group indicated that the 12-hour charge window may be too long. Additional feedback indicated that the rest durations were too long. For example, for the 2-hour discharge duty cycle, 5 hours rest after charge and after discharge brings the total rest time to 10 hours. Based on the feedback, alternate duty cycles with charge duration varying from 4 to 12 hours, and rest durations after charge and discharge varying from 1 to 3 hours may be used. In addition, the x-axis in Figure 5.3.1 shows the hour of the day, with 0 hours corresponding to start of the day and 12 corresponding to noon. In the first version of the Protocol (November 2012) the duty cycle could be started at any time. In this version of the Protocol, the duty cycle is started at 22 hours (or 10 p.m.) each day. This allows a continuous charge, followed by rest and continuous discharge, followed by rest.

Rather than provide time of day on the x-axis, it may be preferred to show time from the start of the duty cycle on the x-axis. Each cycle starts with a charge from an initial state of charge (SOC), which is the estimated SOC from maximum SOC to the end of the constant power discharge period. At the end of the rest period after discharge, the energy storage system (ESS) is brought to its initial SOC by charge or discharge. The round-trip energy efficiency (RTE) is calculated as provided for in the Protocol, taking into account auxiliary power when applicable. The SOC excursion associated with this change in application of the duty cycle would also be reported.

An example of an alternative duty cycle is as follows. For duty cycle A, the ESS is brought to the SOC expected after a 6-hour discharge from the upper SOC limit for the ESS, followed by a 15-minute test. For duty cycle B, the ESS is brought to the SOC expected after a 4-hour discharge from the upper SOC limit for the ESS, followed by a 15-minute test. For duty cycle C, the ESS is brought to the SOC expected after a 2-hour discharge from the upper SOC limit for the ESS, followed by a 15-minute test.

The duty cycle in Fig. 5.3.1 is embedded in this document as a spreadsheet.

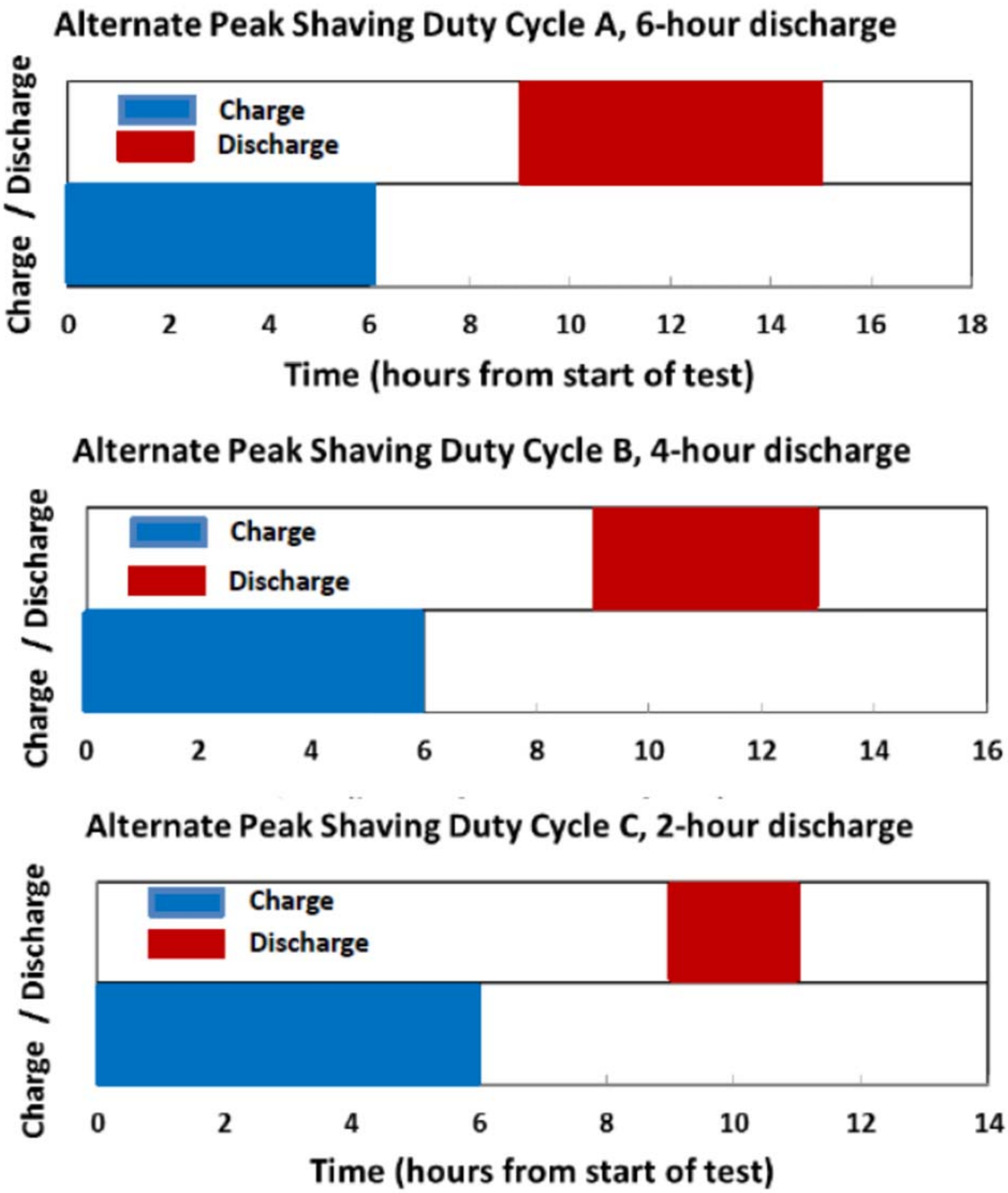


Figure A.1. Alternate Peak-Shaving Duty Cycles

Normative Appendix B

Duty-Cycle Signal for Frequency-Regulation Applications of Energy Storage Systems

Normative Appendix B

Duty-Cycle Signal for Frequency-Regulation Applications of Energy Storage Systems

The duty cycle to be applied in determining the performance of an ESS in a frequency-regulation application is provided in the file, "Duty-Cycle Signal for Frequency Regulation Applications of ESSs," SAND2013-7315P.[1]

In determining the duty cycle, the PJM balancing signal for the period April 1, 2011 through March 31, 2012 was analyzed.[2] The standard deviation over a 24-hour period was used as a metric for the aggressiveness of the signal. The signals were grouped into low, average, and high standard deviation days. A representative 2-hour average standard deviation signal was chosen, and a representative 2-hour high standard deviation signal was chosen. It was also noted that 24-hour signals were energy neutral. The average and high standard deviation signals were chosen such that they were energy neutral and had the same standard deviation as the average and high deviation signals over the one-year time frame. The duty cycle consisted of three 2-hour average signals, followed by one 2-hour high deviation signal, three 2-hour average signals, one 2-hour high deviation signal, and four 2-hour average signals.

The duty cycle in Fig. 5.3.2 is embedded in this document as a spreadsheet.

[1] Ferreira SR and DA Schoenwald. 2013. *Duty-Cycle Signal for Frequency Regulation Applications of ESSs*. SAND2013-7315P, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2013-7315P.xlsx.

[2] http://www.pjm.com/markets-and-operations/ancillary-services/mkt-based-regulation.aspx.

Normative Appendix C

Duty-Cycle Signal for Islanded Microgrid Applications of Energy Storage Systems

Normative Appendix C

Duty-Cycle Signal for Islanded Microgrid Applications of Energy Storage Systems

The duty cycles to be applied in determining the performance of an ESS as an islanded microgrid were developed for three scenarios:

1. Microgrid with renewables (where renewables consisted of a mix of solar and wind generation)
2. Microgrid with renewables but no frequency regulation
3. Microgrid with no renewables and no frequency regulation.

Each use case above involves storing some excess energy and providing it when needed, which is addressed in the peak-shaving application criteria in the Protocol. All of the above include var support, power quality, frequency response, and black start.

Data used as the basis for the duty cycles presented in Section 5.3.3 are presented in the report, “Determination of Duty Cycle for Energy Storage Systems Integrated with Microgrids,” PNNL-23390.[1]

The duty cycles in Fig. 5.3.3 are embedded in this document as a spreadsheet.

[1] Conover DR and VV Viswanathan. 2014. *Determination of the Duty Cycle for Energy Storage Systems Integrated with a Microgrid*. PNNL-23390, Pacific Northwest National Laboratory, Richland, Washington. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23390.pdf.

Normative Appendix D

Duty-Cycle Signal for PV Smoothing Applications of Energy Storage Systems

Normative Appendix D

Duty-Cycle Signal for PV Smoothing Applications of Energy Storage Systems

The construction of the duty cycle to be applied in determining the performance of an energy storage system in a photovoltaic (PV) smoothing application is described in the report, "Determination of Duty Cycle for Energy Storage in a PV Smoothing Application," SAND2016-3474.[1]

Data used as the basis for the duty cycle in Section 5.3.4 is presented in "PV Smoothing Duty Cycle," SAND2016-2543R.[2]

[1] Schoenwald DA. 2016. *Determination of Duty Cycle for Energy Storage Systems in a PV Smoothing Application*. SAND2016-3474, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-3474.pdf.

[2] Schoenwald DA. 2016. *PV Smoothing Duty Cycle*. SAND2016-2543R, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-2543R.xlsx.

Normative Appendix E

Duty-Cycle Signal for Volt/Var Support Applications of Energy Storage Systems

Normative Appendix E

Duty-Cycle Signal for Volt/Var Support Applications of Energy Storage Systems

The duty cycles to be applied in determining the performance of an ESS in volt/var support were developed for the following two use cases:

1. Volt/var support where the ESS is managing the grid voltage at a photovoltaic (PV) system's point of common coupling with the end of a feeder
2. Volt/var support where the ESS is managing the grid voltage at three locations on a feeder using the most aggressive duty cycle.

Each use case above involves storing some excess energy and providing it when needed, which is addressed in the peak-shaving application criteria in the protocol. All of the above include var support, power quality, frequency response, and black start.

Data used as the basis for the duty cycles in Section 5.3.5 are presented in the report, "Determination for Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System" PNNL-25316.[1]

The duty cycles in Fig. 5.3.5 are embedded in this document as a spreadsheet.

[1] Conover DR, AJ Crawford, J Fuller, SN Gourisetti, and VV Viswanathan. 2016. *Determination of Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System*. PNNL-25316, Pacific Northwest National Laboratory, Richland, Washington. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25316.pdf.

Normative Appendix F

Duty-Cycle Signal for Renewables (Solar) Firming Applications of Energy Storage Systems

Normative Appendix F

Duty-Cycle Signal for Renewables (Solar) Firming Applications of Energy Storage Systems

The construction of the duty cycle to be applied in determining the performance of an ESS in a renewable (solar) firming application is described in the report, "Determination of Duty Cycle for Energy Storage Systems in a Renewables (Solar) Firming Application," SAND2016-3636.[1]

Data used as the basis for the duty cycles in Section 5.3.6 are presented in "PV Firming Duty Cycle," SAND2016-2544R.[2]

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[1] Schoenwald DA. 2016. *Determination of Duty Cycle for Energy Storage Systems in a Renewables (Solar) Firming Application*. SAND2016-3636, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-3636.pdf.

[2] Schoenwald DA. 2016. *PV Firming Duty Cycle*. SAND2016-2544R, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2016-2544R.xlsx.

Normative Appendix G

Duty-Cycle Signal for Power Quality Applications of Energy Storage Systems

Normative Appendix G

Duty-Cycle Signal for Power Quality Applications of Energy Storage Systems

Data used as the basis for the duty cycles in Section 5.3.7 are presented in the report, "Determination for Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System," PNNL-25316.[1]

The duty cycles in Fig. 5.3.7 are embedded in this document as a spreadsheet.

[1] Conover DR, AJ Crawford, J Fuller, SN Gourisetti, and VV Viswanathan. *Determination of Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System*. PNNL-25316, Pacific Northwest National Laboratory, Richland, Washington.

Normative Appendix H

Duty-Cycle Signal for Frequency Control Applications of Energy Storage Systems

Normative Appendix H

Duty-Cycle Signal for Frequency Control Applications of Energy Storage Systems

Data used as the basis for the duty cycles in Section 5.3.8 are presented in the report, "Determination for Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System," PNNL-25316.[1]

For dynamic frequency control, the duty cycle deployed by a team of ERDF, SAFT, Schneider Electric, EDF R&D, ECLille, RTE, and Boralex at the Venteea site using a 2 MW, 1.3 MWh battery system will be used (Eyer and Corey 2010)[2]. This duty cycle was presented at the Electric Power Research Institute Energy Storage Integration Council (EPRI ESIC) Working Group 1 (WG1) meeting on July 10, 2015.

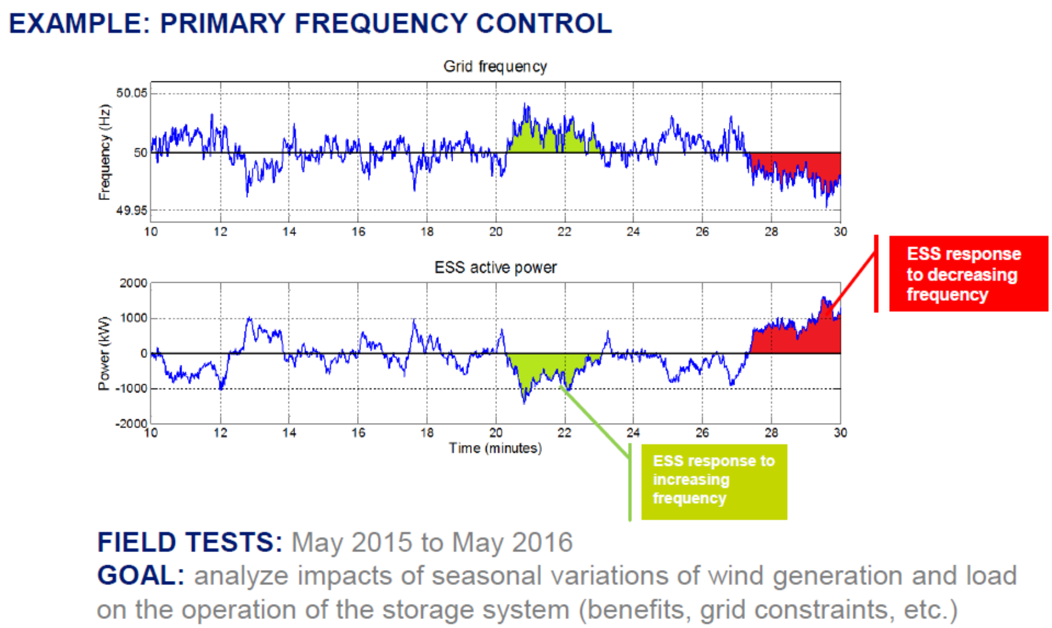

Figure H.1. Grid frequency and ESS Power at the Venteea Site

A linear curve fit, forcing the line through the origin, provided the following relationship:

$$\text{ESS p.u.} = -906.35 \times \text{normalized frequency deviation} + 0.0109. \quad \text{(H-1)}$$

This signal will be applied to the ESS to provide primary frequency control as a function of variation in grid frequency from the nominal frequency. Since our working group does not have access to grid

[1] Conover DR, AJ Crawford, J Fuller, SN Gourisetti, and VV Viswanathan. *Determination of Duty Cycles for Volt-Var, Power Quality, and Frequency Control Applications of an Energy Storage System*. PNNL-25316, Pacific Northwest National Laboratory, Richland, Washington.
[2] Eyer J and G Corey. 2010. *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. SAND2010-0815, Sandia National Laboratories, Albuquerque, New Mexico. http://www.sandia.gov/ess/publications/SAND2010-0815.pdf.

frequency data, the normalized ESS power as shown in the above figure (not the regression figure) will be applied for 2 hours (or repeated 4 times).

At the end of the duty cycle, the ESS is brought to its initial SOC by charging or discharging at rated power. The RTE is calculated as described earlier, taking into account auxiliary power when applicable.

Grid frequency data for four seasons were obtained from a utility, as shown below in Figure H.2. The linear fit shown in Equation H-1 was applied to the grid frequency data to generate the duty cycles shown in Figure H.3.

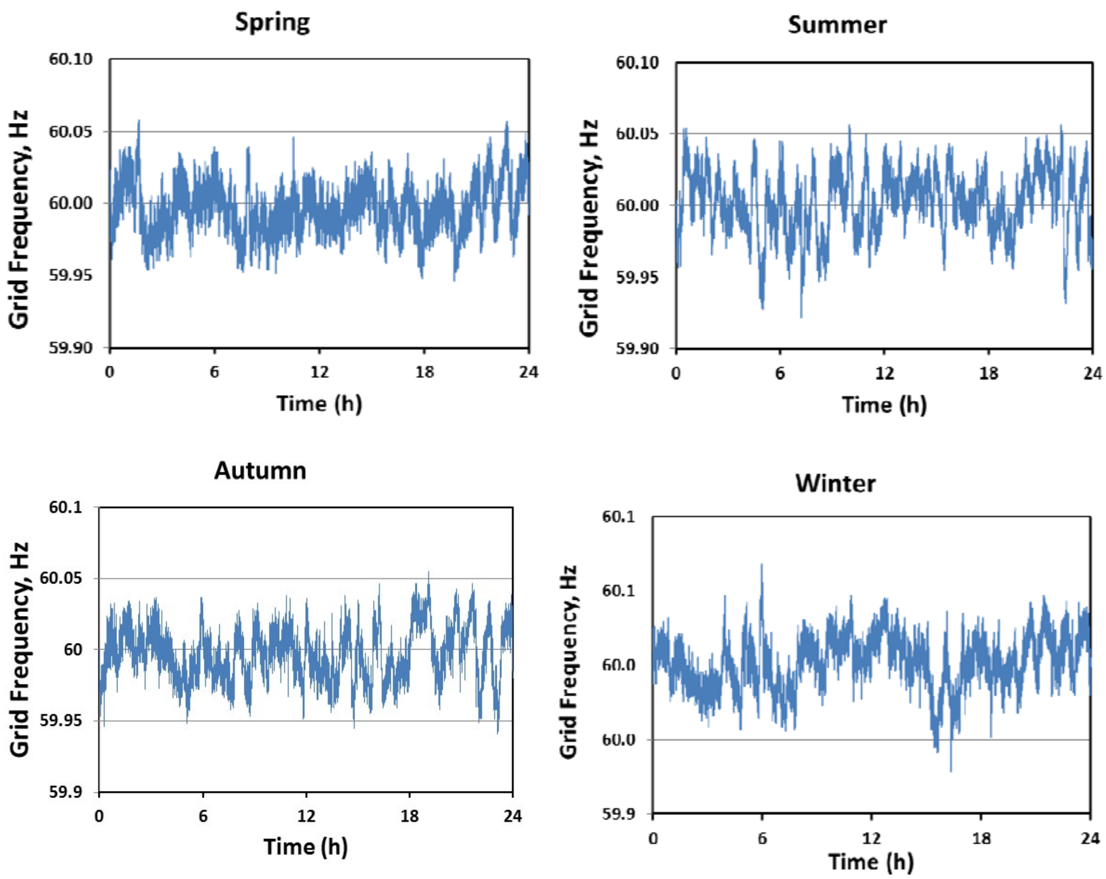

Figure H.2. Distribution Grid Frequency Data for All Four Seasons

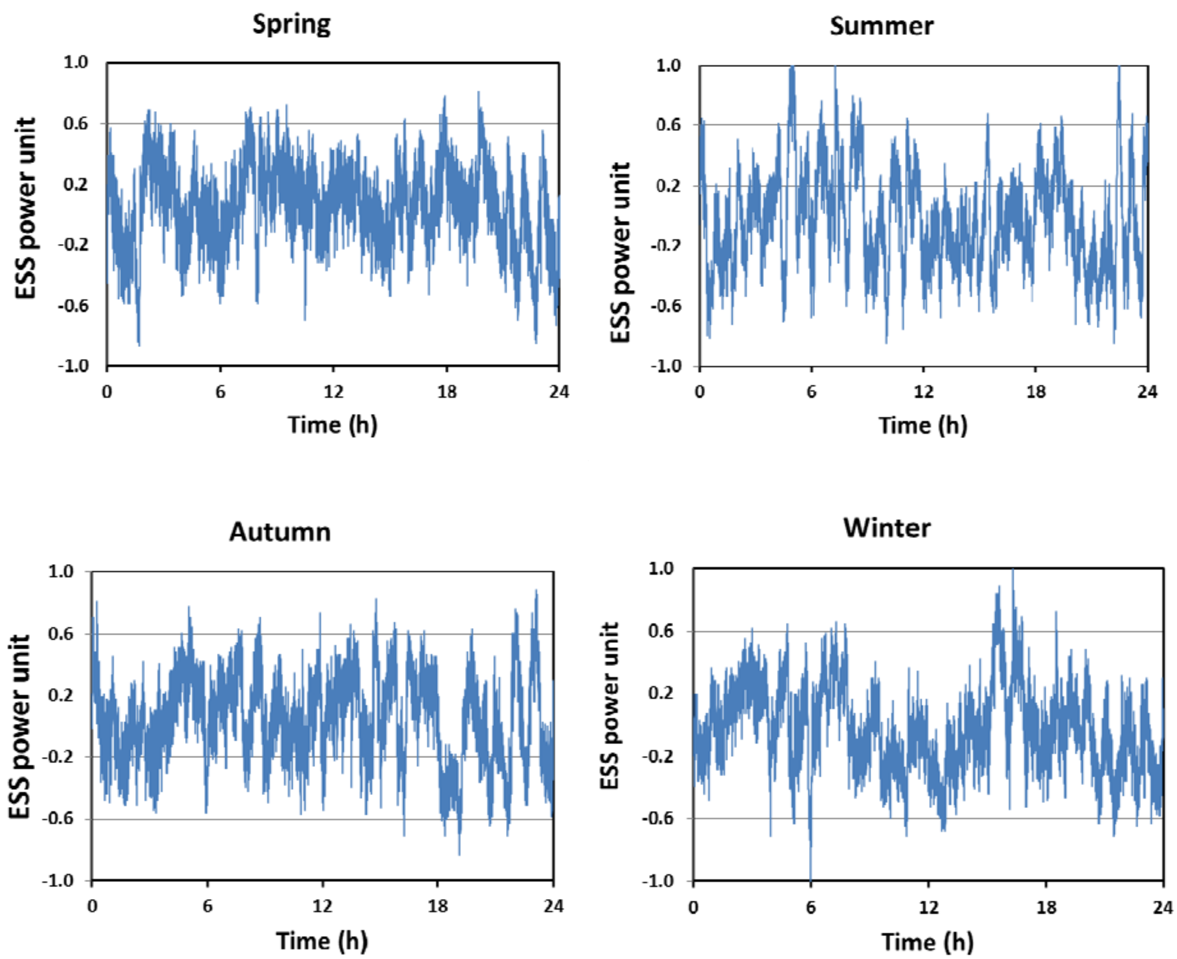

Figure H.3. ESS Duty Cycle for Frequency Control from Grid Frequency Data of Figure H.2.

The duty cycles in Fig. 5.3.8 are embedded in this document as a spreadsheet. Fig. H.3 corresponds to Fig. 5.3.8c in the protocol.