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

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

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Abstract

The U.S. Department of Energy's Energy Storage Systems (ESS) Program, through the support of Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL), facilitated the development of the protocol provided in this report. The focus of the protocol is to provide a uniform way of measuring, quantifying, and reporting the performance of ESSs in various applications; something that does not exist today and, as such, is hampering the consideration and use of this technology in the market. The availability of an application-specific protocol for use in measuring and expressing performance-related metrics of ESSs will allow technology developers, power-grid operators and other end-users to evaluate the performance of energy storage technologies on a uniform and comparable basis. This will help differentiate technologies and products for specific application(s) and provide transparency in how performance is measured. It also will assist utilities and other consumers of ESSs to make more informed decisions as they consider the potential application and use of ESSs, as well as form the basis for documentation that might be required to justify utility investment in such technologies.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Dr. Imre Gyuk, program manager for the DOE Energy Storage Systems Program. The authors would also like to express their appreciation to all the stakeholders who participated as members of the Working Group and its subgroups. Without their thoughtful input and recommendations, the protocol provided in this report would not have been possible. Complete listings of members of the Working Group and subgroups are provided in the Foreword to the protocol included in this report. Special recognition should go to the staffs at Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) in collaborating on this effort. This was clearly a joint effort between PNNL and SNL. Also, special recognition should go to Ryan Franks of the National Electrical Manufacturers Association and Chet Sandberg of the Institute of Electrical and Electronics Engineers, who led working groups on metrics and definitions, respectively.

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FIGURES

TABLES

NOMENCLATURE

AC	Alternating Current
DOE	Department of Energy
ESS	Energy Storage Systems
GE	General Electric
HVAC	Heating, Ventilation, and Air Conditioning
IEEE	Institute of Electrical and Electronics Engineers
PJM	PJM Interconnection
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratories

EXECUTIVE SUMMARY

The U.S. Department of Energy's Energy Storage Systems (ESS) Program, through the support of Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL), facilitated the development of the protocol provided in this report. The focus of the protocol is to provide a uniform way of measuring, quantifying, and reporting the performance of EESs in various applications; something that does not exist today and, as such, is hampering the consideration and use of this technology in the market. The availability of an application-specific protocol for use in measuring and expressing performance-related metrics of ESSs will allow technology developers, power-grid operators and other end-users to evaluate the performance of energy storage technologies on a uniform and comparable basis. This will help differentiate technologies and products for specific application(s) and provide transparency in how performance is measured. It also will assist utilities and other consumers of ESSs make more informed decisions as they consider the potential application and use of ESSs, as well as form the basis for documentation that might be required to justify utility investment in such technologies.

The Department of Energy launched this protocol development activity in early 2012 through public-private collaboration and with a sense of urgency. This effort was intended to empower a working group of industry leaders in the grid-connected energy storage field, assisted by staff of PNNL and SNL, to craft a written document that addresses the most urgent needs in the industry related to measuring and expressing performance characteristics for energy storage technologies in various applications. The goal of this effort was to produce a document by September 2012 that addresses the most pressing needs associated with the measuring and expressing the performance of ESSs as determined by those participating in the development of the protocol.

The protocol development process has been open and widely representative of ESS industry leaders, developers, users, government, research, and other interested stakeholders. This process included a project introduction and invitation letter in early February 2012 to many and varied stakeholders, the involvement of any stakeholders who responded on the project Working Group, five meetings (four web-based and one face-to-face) of the Working Group over a period of 8 months and numerous additional meetings of four subgroups working on specific details associated with the protocol (peak shaving and frequency regulation applications, metrics, and definitions). Through those efforts and numerous correspondence, drafts, re-drafts, etc., the protocol presented in this document was developed.

The protocol presented in this document is intended to be used initially to foster the uniform measurement and expression of performance of ESS used for peak shaving and frequency regulation applications. For each of those applications, a specific duty cycle is presented and relevant metrics to be measured and reported for each application provided. Use of the protocol by manufacturers of ESSs on a voluntary basis or as required by customers of ESS will result in each ESS, via a permanent label and/or specification document providing relevant data about the performance of the ESS, that is uniform in nature and comparable amongst ESS technologies intended for the same application. It is recognized that in addressing only two applications, and a limited set of metrics for each, there are other applications and metrics that need to be addressed. The intent with this initial protocol was to address the most pressing needs in a short period of time and, in doing so, establish a process to identify further work on other applications and/or metrics and build on the protocol in the future.

Protocol development and enhancement is intended to be a dynamic process that will occur over time through a phased approach to address enhancement and consideration of all applications and relevant performance metrics. Through application and use of this protocol, it is hoped that the resultant information will serve short-term needs and that needed refinements can be identified and addressed in a more formal standards development process by a voluntary sector standards development organization. This would then result in a future consensus standard to replace this protocol. Concurrent with any such efforts to develop a consensus standard, the Working Group, protocol, and process for its development are expected to continue, focusing on additional applications and metrics for those new applications as well as additional metrics for the two applications addressed in the initial protocol. In like manner, the next version of the protocol could feed into updates and revisions to any consensus standard whose provisions are based on those in this protocol. This process, compared to going immediately into formal standards development, saves time and money and most importantly provides a document that, while not having an official consensus designation, is available for application and use in a timely manner to fill the immediate need noted above. The success of this collaborative process and 8 month effort to develop this protocol will be realized through the voluntary application and use of the protocol by ESS manufacturers, or the request for its use by ESS customers as they consider adoption and use of the technology. It is hoped that the effort undertaken to develop this protocol proves to be a good investment in technology acceptance by realizing such a successful adoption and use of the protocol.

FOREWARD

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

(The information presented in this foreword is not part of the protocol. It is merely informative and does not contain requirements necessary for conformance to or use of the protocol.)

The Energy Storage Systems (ESS) Program of the U.S. Department of Energy, through the support of the Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) facilitated the development of this protocol to support the uniform measurement and reporting of the performance of ESSs in various applications. The availability of a suite of uniform, application-specific protocols will allow technology developers, power grid operators and other end-users to evaluate the performance of energy storage technologies. This will help differentiate technologies and products for specific application(s) and provide transparency and uniformity in how performance is measured. It will also assist utilities and other consumers of ESSs make more informed decisions as they consider the potential application and use of ESSs.

The protocol is intended to assist the energy storage industry more effectively communicate to all interested parties and ESS customers and users about energy-storage applications in terms of the technical performance associated with providing a service or services that employ ESSs. This in turn will foster the ability of the ESS industry to showcase applicable options for increasing the reliability and energy management capabilities of the electricity delivery system, whether it is connected to the grid or through onsite stand-alone systems.

The Department of Energy launched this protocol development activity officially on February 3, 2012, with a sense of urgency to establish and empower a working group of industry leaders in the grid-connected energy storage field to craft a written document that addresses the most urgent needs in the industry related to measuring and reporting performance characteristics for ESSs in various applications. The goal of this effort was to produce a document by September 30, 2012, that addresses the most pressing needs related to measuring and reporting the performance of ESSs as determined by those participating in the development of the protocol. The protocol development process has been open and widely representative of ESS industry leaders, developers, users, government, research, and other interested stakeholders.

The protocol is intended to be used initially as a resource for uniform test methods for measuring the performance of commercially available ESS for stationary applications with or without all electric inputs and outputs and as a foundation for future work. Protocol development and enhancement is intended to be dynamic and occur over time through a phased approach to address all storage technologies, applications, and relevant performance metrics as deemed appropriate by ESS stakeholders. It is intended that the ESS manufacturer identify the application(s) intended for the system based on the application requirement for the system and desired output characteristics. This allows an orderly delineation of systems in a manner that will meet customer needs. Based on the intended application, the manufacturers of systems intended for a particular application have a uniform way to measure and report performance and customers have a common metric and basis for comparison within a specific application universe. If a system has multiple applications then it would be evaluated under each of the applicable but separate “application tracks” and be accompanied by a separate performance report for each application. The protocol addresses what were determined to be short-term needs associated with the covered topic and capable of being addressed given the timeframe available and availability of the working group members to recommend specific criteria for consideration. Further enhancements are envisioned in the future, as discussed below, to address technologies, applications and associated metrics that are not covered in this initial protocol.

This initial protocol provides methods to address specific metrics associated with the performance of electric ESSs being applied for peak-shaving and frequency-regulation applications. This protocol can also accommodate thermal-storage systems through identification of appropriate metrics and test procedures, some of which may overlap with those presented in the initial protocol. Additional methods to address the performance of ESSs that are intended for other applications are clearly within the title, purpose, scope, and general criteria currently in the protocol and will be developed as subsequent enhancements to and be included in future versions of the protocol. For instance future applications could be identified based on Energy Storage Proceeding R10-12-007 of the California Public Utilities Commission, which identifies 26 uses for energy storage. Additional applications can be included in Table 1 of the protocol, presented in Section 4.3 as new subsections 4.3.3, 4.3.4, etc., and then subsequently addressed as applicable by current or future provisions in Sections 5 through 9. The time frame for addressing additional applications in the protocol would be dependent on market demand for performance information on those systems and the degree to which proponents of those applications are willing to contribute to the development of the language for the protocol to address those applications. This phased approach to develop appropriate standards criteria saves time and better serves critical needs of the industry both in the short and long term.

The protocol is intended to help the industry more effectively communicate about the technical performance associated with providing a service or services that employ ESSs. This in turn will showcase applicable options for increasing the reliability and energy management capabilities of the electricity delivery system, whether it is connected to the grid or through onsite stand-alone systems.

This protocol represents the collective wisdom of over 100 individuals representing over 60 entities involved in ESS or ESS component development, sales and installation, utilities and energy service providers, research and academia, testing agencies, government, and other relevant stakeholders. Those participating in the Working Group, and on subgroups developing the criteria for the two applications, the metrics, and the definitions contained in the protocol, are shown below (subgroup members in bold).

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Deichert, Jim	Steffes Corporation
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Murphy, Kelly	Steffes Corporation
Navid, Nivad	MISO Energy

From February 2012 to September 2012, the Working Group exchanged materials for development, comment and revision and conducted one face-to-face and five web-based meetings. In addition, the four subgroups (peak shaving, frequency regulation, metrics, and definitions) also exchanged materials associated with their portions of the document and had numerous web-based meetings. Collectively the Working Group developed a title, purpose, scope for the protocol and then a general section to provide an overview of how the protocol would be organized. An initial draft of the protocol was provided as a foundation for additional work and refinement on definitions, identification of performance metrics, duty cycles, and test procedures to determine the metrics for each application. Each of the four subgroups (peak shaving, frequency regulation, metrics, and definitions) proceeded to address these items in more detail within their area of responsibility. The input from those four subgroups was then assembled as an initial draft of the complete protocol and subsequently refined by the subgroup leads to create a final draft.

Once a final draft of the integrated material from all four subgroups (including the PNNL and SNL technical staff that led or participated in the subgroups) was completed, it was sent to all Working Group members for review and comment. The Working Group members were encouraged to provide “specific text” changes to the protocol and the rationale for those suggested text changes, as opposed to “general comments” that did not detail suggested text changes, additions or deletions.

Prior to sending out the protocol for review/comment via e-mail, a webinar was conducted by PNNL and SNL with the Working Group to walk through the protocol. The purpose of this webinar was to help foster an understanding of the review process and expectations for input that could be used in preparing the final version of the protocol before its publication. Ten responses replied with suggested text changes and/or broad, general comments.

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Greisen, Leanne	HDR Engineering
Holt, John	NRECA
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Murphy, Kelly	Steffes Corporation
Nourai, Ali	KEMA
Sandberg, Chet	IEEE
Sember, James	S&C Electric Company
Willard, Steve	PNM Resources

These responses were compiled into an integrated document and reviewed and considered by the subgroup leads with assistance from PNNL and SNL. The protocol contained in this report represents the results of these efforts over the above mentioned 8 month period. In most cases, where specific language was provided, it was included in the protocol. When comments were general in nature, they were addressed when possible. If the comments received would have required a major rewrite of the protocol, they were not considered at this time but may be considered in future enhancements to the protocol. Comments received during the review of the final protocol as well as areas for future work identified during development of the protocol are discussed below.

In completing this protocol, it was recognized that the scope of the work to be accomplished to satisfy the stated purpose of the protocol was much larger than could be covered in the short period of time after organizing the Working Group. It was also recognized that the level of detail and specificity provided might need additional refinement in the future. During the development of the protocol, the following items were identified and are documented for future consideration as potential enhancements to the protocol through future work on the protocol and for any standards development organizations that develop standards associated with ESS performance or others that use the protocol as a basis for specifications or other documents covering the purpose and scope addressed by the protocol.

- *Structuring of the protocol*. There was considerable discussion by the Working Group on the approach to be taken in structuring the protocol following the completion of the purpose and scope of the protocol. An agreed upon approach early on was critical in providing a foundation for the applications and metrics to be initially addressed as well as being able to be built upon long term as additional applications, metrics and enhancements to the protocol were considered. The decision was made to focus on specific applications for ESSs and then for those applications to identify relevant metrics and the methods to be used in determining and reporting those metrics for each ESS intended to be used in that application. Figure 1 in the protocol provides that foundation for applications covered in the initial protocol and provides the dynamics needed to visualize future enhancement of the protocol. During final review of the protocol, a member of the Working Group suggested an alternative figure that suggested a series approach consisting of steps to define the ESS boundary, then needed functional testing, identification of applications, integration of the ESS with other systems both onsite and offsite, modeling, and then location. Application of the approach suggested would have had a significant impact on the format and content of the protocol and was not capable of being implemented. That said, there are a myriad of ways to describe ESSs their interactions on the utility and customer sides of the system, all of which could be included in an informative appendix, separate commentary or other document intended to address ESSs. For the purpose of the protocol, the Working Group felt that Section 4 provides the most appropriate layout for short-term use and long-term enhancement.

- *System life*. When a system's performance degrades to the point where it is no longer usable in its intended application, it has reached End of Life. When a system is new, at Beginning of Life, it is a complex task to predict time to End of Life that must be based on and incorporate environmental conditions, maintenance schedules, component cycle life, component calendar life, and many specifics about how the system will be used during its life. It is for these reasons that system life is not included as a performance metric in the protocol. Any metric that could be agreed on would either be too simplistic and misleading (such as battery cycle life) or too expensive and time intensive (such as mean time to End of Life of 10,000 systems tested under various profiles). Even with the complexity of this task, it is still possible to get a reasonable handle on how long a system should last. Conducting component cycle life testing, fully integrated storage system testing, and third-party testing of both varieties will yield reliable data for how long the different elements of a full system should last and how system performance should change over time and use. An analysis of these data can produce a system component replacement/refurbishment schedule, an estimated design life in a given application, and a description of system life sensitivities to operational choices. Life calculations often use complex system models that combine the collected data in nonlinear and technology specific ways to obtain these values. When presented as a package, these data and analyses convey a confidence in design life. While the protocol does not specifically address the issue of system life, it does not preclude anyone from addressing that issue, or any other issue not currently covered by the protocol.

- *Definition of performance testing.* Some feel the concept of reference performance testing needs a more clear definition and the development of more robust procedures should be addressed in the future. The protocol, as discussed above, is an initial effort to provide something in the short term that establishes a firm foundation for future work but concurrently fills a present void that if left unfilled could have an impact on the acceptance of ESSs in the market.

- *Aging.* The concepts of power capability and power requirement, available energy versus total energy versus required energy need to be distinguished and the issue of aging needs to be addressed (e.g., application of the protocol using a power requirement of X on an ESS that has a power capability of X+Y). It was noted that testing to a requirement in the protocol and not the capability of the ESS will not produce meaningful information on real aging. It was suggested that the protocol provide for the availability of these data for the ESS purchaser. At the present time, the protocol does not attempt to define a specific rated power for all applications, only the application being considered (of which there are currently two addressed in the protocol). It is noted that the protocol does reference another test (reference performance test) that users could use to assess battery degradation over time if they so choose. The issue of aging and impacts on performance (degradation) is duly noted, could not be addressed in detail in the timeframe available, and should be the subject of further work and enhancements to the protocol.

- *Where and how to do testing of ESSs?* For large systems (rated at hundreds of kW to MW and beyond), most testing will likely be done in the field at an installation due to the challenges of setting up the system in a test facility (itself a challenge for large systems) and then disassembling it for shipment. For example, the new test site at SNL is physically limited in space and its ability to handle flow battery electrolytes. Scaled-down systems are possible, but many key aspects of a scaled-down system would have to be changed. In this situation (e.g. scale down), it becomes difficult to know if the test results are really representative. The protocol does not address where the testing is to be performed, only that certain data be secured. If in the application of the protocol, it is determined that more specifics as to where testing is to be performed, for the entire ESS and/or ESS components, are needed those can be added in the future. It is hoped in applying the protocol in the short-term users will secure meaningful information that can inform future decisions on this issue.

- *Duty cycle.* The duty cycle provided for each application generated discussion as to the specific choice of the duty cycle (as opposed to others) and then the application of the duty cycle with respect to a full or partial state of charge. The protocol contains a singular duty cycle for each application, which could be enhanced in the future with one or more duty cycles that would represent other conditions imposed on ESS applications. In addition, the duty cycles provide for a number of repeats over 7 days. Future enhancements to the protocol should suggest ways to shorten the number of repeats and time frames associated with the duty cycles in a manner that does not adversely compromise the validity of the resultant reported ESS performance.

- *Inclusion of ESS other than batteries.* Future efforts should include provisions that ensure the applicability of the protocol to storage systems that are not battery oriented.

- *Power test.* A power test should be added in the future as well as metrics to measure and express power factor and harmonics and when added refer to appropriate published consensus standards such as IEEE 1547 or UL 1741.

- *Minimum system size.* Consider establishing a minimum system size for use with the protocol and reinforce that this is a system-level test. The protocol is intended to be applied to the entire system, noting that there are provisions in the protocol directing how the system boundaries are to be defined and described for the ESS being tested. It is also noted that the scope of the protocol specifically excludes the testing of a battery cell or single battery pack, which one might want to conduct and then scale up to represent the performance of a system comprised of those tested cells or battery packs.

- *Common reporting format.* There is a need for a common format or information model for reporting measured parameters to enable further analysis and the incorporation of data obtained from one test into another.

- *Inclusion of operational transition time.* It is not clear where time is measured for systems that have a "sleep" or "dormant state" below "active standby;" it seems that the transition time from dormant to active standby should be counted and included in the measurement of response time as an additional measurement to the total response time measured otherwise.

- *Customer side thermal storage.* A number of participants who manufacture or want to apply "customer side" thermal storage applications, such as the use of residential electric water heaters in the aggregate for peak-shaving control by the serving utility, stressed the important of covering such applications in the protocol. As noted above, those drafting the protocol could not cover all possible situations in this initial effort and in the end were further limited by what those participating were willing to author and contribute as specific text (criteria) for inclusion in the protocol. The initial protocol only provides specific details for all electric ESSs being applied for peak-shaving and frequency applications. The scope and purpose of the protocol, however, are written to cover all ESS technologies. Additional methods addressing systems that are other than all electric should immediately be developed as an enhancement to a future version of the protocol. The development of specific revisions and enhancements to the protocol that would foster its application and use with such systems are encouraged.

- *Use of PJM data for duty cycle.* The Dynamic Regulation Signal from PJM for April 2011 to March 2012 has been made publicly available so it was used as a reference in developing the duty cycle in Section 5.2.3. In a future version of the protocol, it will be important to look at other regional transmission organizations and areas of the country for differences in representative regulation data.

- *Additional metrics.* There are additional metrics that can be considered for future enhancement to the protocol. For frequency regulation, these include the correlation or relationship between control signal and the regulating unit's response, the time delay between the control signal and point of highest correlation, and the difference between the areas under the curve for the control signal and the regulating unit's response.

- *Use of the term application.* There was some concern about the use of the term "application" to describe a single service that storage (or alternative resource) can provide the grid and also to mean a bundle of multiple services or use case. The need to distinguish these was felt to be important to make because the grid service requirements need to be defined by those who will decide to use it (e.g., distribution planners, capacity planning proceedings, etc.). It was further suggested that applications be defined as energy intensive or power intensive. To address this, the terms grid service (i.e., an avoided cost or revenue opportunity with defined technical requirements that can be accomplished through the use of energy storage or an alternative resource) and use case (i.e., a combination or “bundle” of grid services that has established operational hierarchy and control to prioritize services with long-term commitments over short-term commitments were suggested for inclusion in the protocol. It was also suggested that the tests to be performed be guided by grid service requirements including system performance (e.g., capacity, duration, efficiency, ramp, etc.), life (e.g., cycle, calendar, etc.), safety, communications, etc. A list of 13 grid services and associated value metrics were also suggested for inclusion. These suggestions came very late in the development phase and were not able to be addressed during finalization of the protocol.

The collective wisdom of the individuals representing the organizations identified above has produced this document as a starting point to facilitate uniform communication about and assessment of ESS performance. As a starting point it is hoped its use will foster enhancements to the protocol in scope as well as the depth and competency which it brings to addressing the need for reliable and robust performance information on ESS that can foster acceptance and appropriate use of ESS in the market.

1. PURPOSE

This protocol provides a set of “best practices” for characterizing energy storage systems (ESSs) and measuring and reporting on their performance. It serves as a basis for assessing how individual ESSs 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. SCOPE

The protocol defines a set of test, measurement and evaluation criteria with which to express the performance of and applies to energy storage systems (ESS) that are intended for energy intensive stationary applications and/or power intensive stationary applications. The energy storage system includes the storage device and any power conversion systems installed with the storage device and may include battery management systems. The protocol is agnostic with respect to the storage technology and the size and rating of the energy storage system. 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, nor does it provide any pass/fail criteria.

3. 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.

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.

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

Duty Cycle. A charge/discharge profile that represents the demands associated with a specific application that are placed on an energy storage system (ESS).

Energy Efficiency. The useful energy output divided by the energy input to the ESS expressed as a percentage [1], including all parasitic energies needed to run the system, such as heating or cooling.

Energy Performance. The energy supplied to a load at a given discharge rate [1].

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

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

Power Performance. The maximum rate of discharge sustainable for a given duration of discharge.

Ramp Rate. The rate of change of power delivered to or absorbed by an ESS or device expressed as a percentage change in capacity over time (MW/minute).

Reference Performance Test. A set of tests performed at periodic intervals during life testing to establish the condition and rate of performance degradation of devices under test that are generally performed prior to the start of life testing, at defined periodic intervals, and at end of testing, for all devices undergoing either cycle life testing or calendar life testing.

Roundtrip Energy Efficiency. The useful energy output from an ESS divided by the energy input into the system, and expressed as a percentage, and including all system losses as well as any electrochemical, electromechanical, or electrical inefficiency involved in the storage of the energy under normal operating conditions.

Response Time. The time in seconds it takes an ESS to respond to a specific change in output or input plus the time to reach or discharge to 100 percent of rated capacity from an initial measurement taken when the system is at rest.

Stored Energy Capacity. The amount of energy capable of being stored by an ESS expressed in terms of electric power or heat.

4. GENERAL

4.1 Intent

The intent of this section is to provide an overview of the protocol and how it is intended to be used to determine the performance of an energy storage system (ESS). The first step in using the protocol is to identify the ESS and its intended application. These activities shall be performed in accordance with Sections 4.2 and 4.3. Based on the intended application of the ESS, Section 4.4 shall be used in identifying the duty cycle to be applied and data to be collected at the ESS boundary as defined by the manufacturer of the ESS. Section 4.5 shall be used in defining the collected data that are to be used to determine the performance metrics applicable to the selected application(s). The reporting and presentation of the ESS performance based on the application and use of the collected data shall be in accordance with Section 4.6 (see Figure 1).

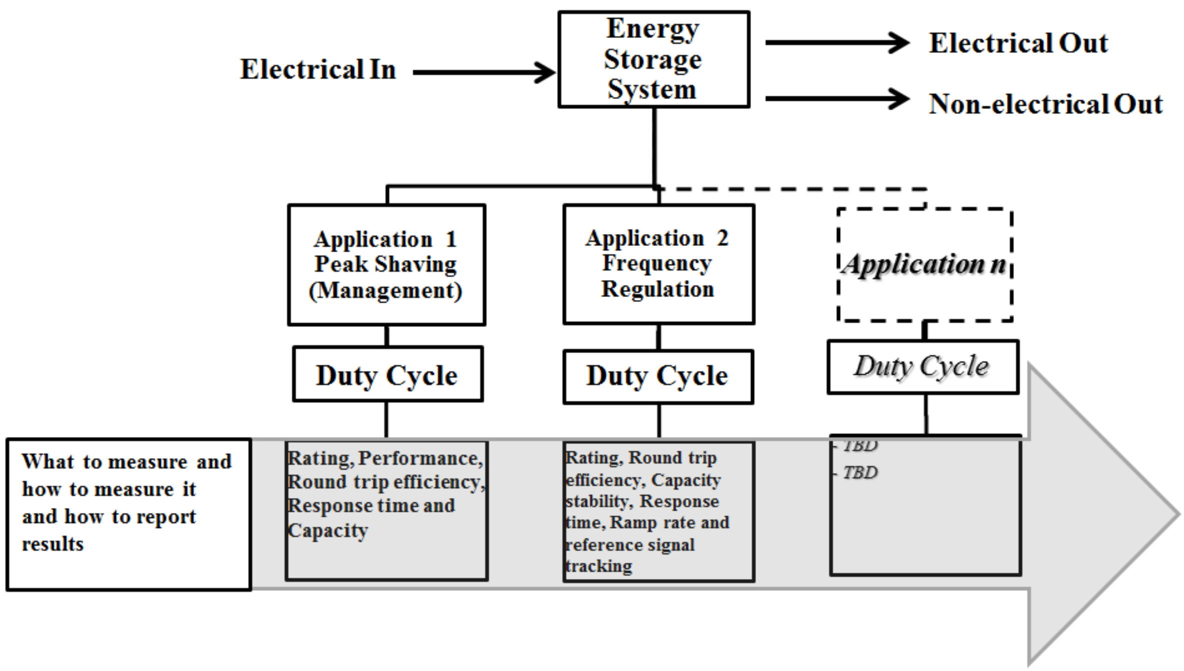

Figure 1. Protocol Overview.

4.2 Identification of the energy storage system

The ESS shall be described by the system manufacturer via a system inventory, which shall include the devices, components, controls, and other components associated with the system. The boundary within which the ESS resides shall be identified and all the inputs and outputs that cross the ESS boundary shall be identified as to type of input or output and the purpose of each (See Figure 1). 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 required tests and data collection.

4.3 Identification of the ESS application

The intended application(s) of the ESS shall be identified by the manufacturer in accordance with Table 1.

Table 1. Energy Storage System Applications

Intended Application of the System
Peak Shaving (Management) (See Section 4.3.1)
Frequency Regulation (See Section 4.3.2)

4.3.1 Peak Shaving (Management)

ESSs that are intended to be applied to manage energy use associated with peak load/generation shall be identified by the system manufacturer as to their application classification, discharge duration and power range in accordance with Section 5.1.1. All required testing, calculations, and/or simulations to determine the performance of ESSs intended for peak-shaving (management) applications shall be conducted in accordance with the duty cycle in Section 5.1.3.

4.3.1.1 System rating

The rating of the ESS shall be determined by the manufacturer as outlined in Section 5.1.2.

4.3.1.2 Performance

The power and energy performance of the ESS shall be determined in accordance with the provisions in Section 5.1.4.1.

4.3.1.3 Roundtrip efficiency

The roundtrip efficiency of the ESS shall be determined in accordance with the provisions in Section 5.1.4.2.

4.3.1.4 Response time

The response time of the ESS shall be determined in accordance with the provisions in Section 5.1.4.3.

4.3.1.5 Stored energy capacity

The capacity of the ESS shall be determined in accordance with the provisions in Section 5.1.4.4.

4.3.2 Frequency regulation

ESSs that are intended to be applied for frequency regulation shall have their performance determined in accordance with Section 5.2.1. All required testing, calculations and/or simulations to determine the performance of these applications shall be conducted in accordance with the duty cycle provided in Section 5.2.3.

4.3.2.1 System rating

The rating of the ESS shall be determined in accordance with the provisions in Section 5.2.2.

4.3.2.2 Round-trip efficiency

The roundtrip efficiency of the ESS shall be determined in accordance with the provisions in Section 5.2.4.1.

4.3.2.3 Capacity stability

The capacity stability of the ESS shall be determined in accordance with the provisions in Section 5.2.4.2.

4.3.2.4 Response time

The response of the ESS shall be determined in accordance with the provisions in Section 5.2.4.3.

4.3.2.5 Ramp rate

The ramp rate of the ESS shall be determined in accordance with the provisions in Section 5.2.4.4.

4.3.2.6 Reference signal tracking

The ability of the ESS to respond to a reference signal shall be determined in accordance with the provisions in Section 5.2.4.5.

4.4 Measurement Procedure

Measurements shall be conducted in accordance with the test conditions, data acquisition conditions, and test procedures in Section 6.0, the use of which is intended to produce accurate and repeatable data necessary to calculate the performance metrics relevant to the application.

4.4.1 Input

The data associated with input(s) to the ESS across the designated system boundary shall be determined in accordance with Section 6.2.

4.4.2 Output

The data associated with outputs(s) from the ESS across the designated system boundary shall be determined in accordance with Section 6.3.

4.5 Determining relevant performance metrics

The performance of the ESS shall be determined using the data collected pursuant to Section 6.0 and used in accordance with Section 7.0. The application will define what metrics are to be used and the measurement procedure and collected data will provide the information necessary to derive these metrics. In some situations calculations can be performed to determine energy and/or power before a metric is determined such as but not limited to a thermal ESS that does not have an electrical output but does have an effect on the electrical efficiency of the building as well as potentially affecting the efficiency and stability of the power grid. In such cases, any reported value of the metric pursuant to the provisions in Section 8.0 must clearly state how values for the energy or power were obtained or derived.

4.6 Reporting and displaying performance

The performance of the ESS for each intended application shall be reported in accordance with Section 8.0 and included in a permanent label affixed to the system or included with the system specifications. Where the system has multiple applications, the determination and reporting of performance shall be conducted separately for each application.

5. APPLICATIONS

5.1 Peak shaving (management)

Energy storage systems (ESS) intended for use in peak-shaving (management) applications shall have their performance determined in accordance with this section.

5.1.1 Classification

ESSs intended for peak-shaving (management) applications shall be classified as to use in accordance with the provisions of this section.

Sections 5.1.1.1 through 5.1.1.11 shall be used to determine the applicable application classification(s).

5.1.1.1 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 either the storage system owner pays wholesale market energy rates plus a delivery charge or pays time of day retail rates.

5.1.1.2 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 which 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.

5.1.1.3 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.

5.1.1.4 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 5.1.1.1 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 in low price periods when the system is not congested and discharged during high price time periods when prices have increased due to congestion.

5.1.1.5 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 where 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 current distribution system equipment to remain on line longer until other conditions necessitate that the distribution system equipment be upgraded.

5.1.1.6 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 5.1.1.5 except that it applies on higher voltages and higher power conditions found on the electric transmission system.

5.1.1.7 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.

5.1.1.8 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 price periods is stored and then delivered during high wholesale price periods.

5.1.1.9 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 photovoltaic technology that typically correlates more closely with system load is stored and then delivered to the system when needed.

5.1.1.10 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 the ability of the renewable generation to participate in the capacity market.

5.1.1.11 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.

5.1.2 System ratings

Ratings for ESSs shall be based on and stated by the manufacturer of the system for specific set operating conditions. The performance of the system shall be based on the actual, measured operational effectiveness of the system at those operating conditions at the beginning of the life of the system. In addition the manufacturer shall provide an indication of how the performance of the system is expected to change over time to account for time and use of the system.

The determination and reporting of ratings for ESSs applied in a peak-shaving (management) application shall be in accordance with Institute of Electrical and Electronics Engineers (IEEE) Standard 1679 as expanded herein to provide more specific test procedures applying to peak-shaving (management) applications. Such expansion shall include application of the duty cycle in Section 5.1.3 and metrics in Section 5.1.4 in determining and expressing the performance of systems for peak-shaving (management) applications.

5.1.3. 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 thereby allowing the duty-cycle profile to be applied the same 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 2 and Sections 5.1.3.1 through 5.1.3.3. When cycling under any of these profiles the system shall be operated to maximize its performance with respect to the metrics in Section 5.1.4 while not exceeding an operational envelope that compromises the design life of the system.

Each cycle must have a 12-hour charge window, a variable duration discharge window and two equal float windows that bring the total cycle duration to one 24- hour period. While Figure 2 displays these profiles for a midnight to midnight day with an evening peak, for the purposes of testing any 24-hour window shall be permitted to be selected. When conducting performance tests using these profiles, the baseline point selected from which to start the test and representing the beginning of each duty cycle shall be the same point the system is returned to after the 24-hour duration of the test. This baseline point shall be at either the start of the charge widow or the start of the discharge window as applicable to the storage technology being tested.

5.1.3.1 Charge window

During the charge window, the system shall be permitted to charge or float and shall be permitted to supply power to any load external to the system.

5.1.3.2 Float window

During the float windows the storage system shall not charge or discharge but shall be permitted to sustain any necessary balance of plant operation. The operation of any internal support loads for the system such as, but not limited to. HVAC systems shall continue to operate as normal during the float window. Charging of the system shall be permitted when it does not change the state of charge of the system, such as but not limited to trickle charging to maintain a state-of-charge set point. Discharging of the system that does not serve a load external to the system shall be permitted during the float window.

5.1.3.3 Discharge window

During the discharge window the system shall be set to discharge at a rate that the system can sustain for the full duration of the duty cycle. During the test the system shall ramp up to and reach its power set point before the start of the discharge window.

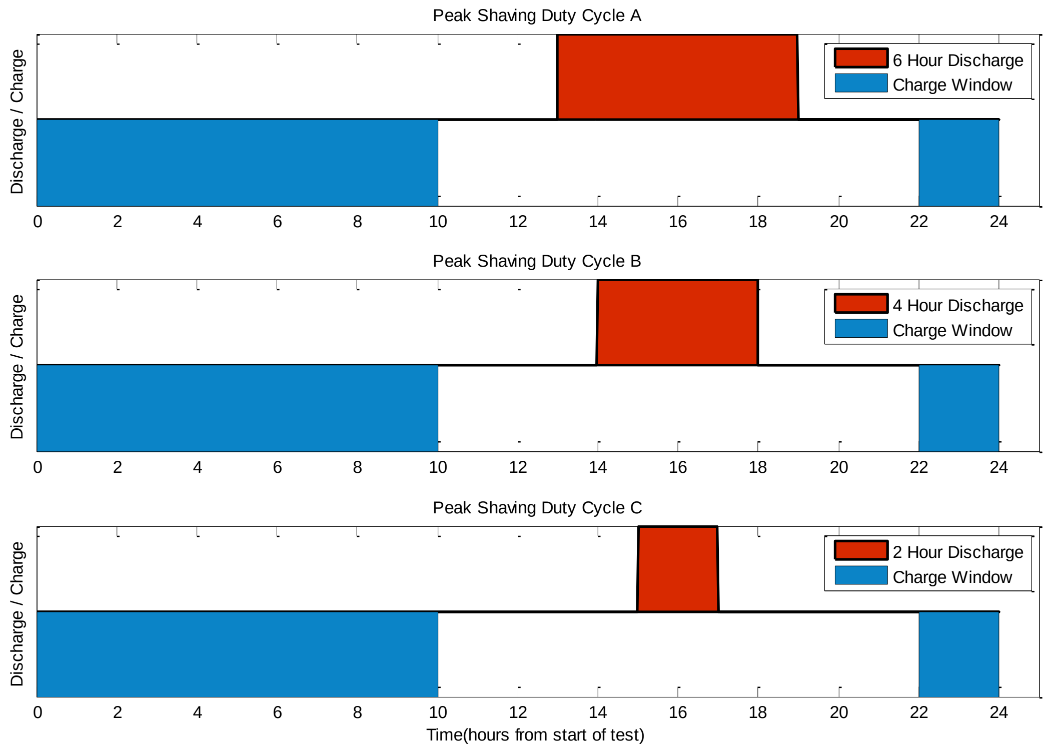

Figure 2. Peak-Shaving Duty Cycles.

5.1.3.4 Application of the duty cycles

In conducting performance testing each separate test shall be run over a 24-hour period and consist of the performance of duty-cycle B at least five times consecutively followed immediately by one application of duty-cycle A and then one application of duty-cycle C. At least seven such tests shall be performed in sequence over a total of at least seven consecutive days as shown in Figure 3.

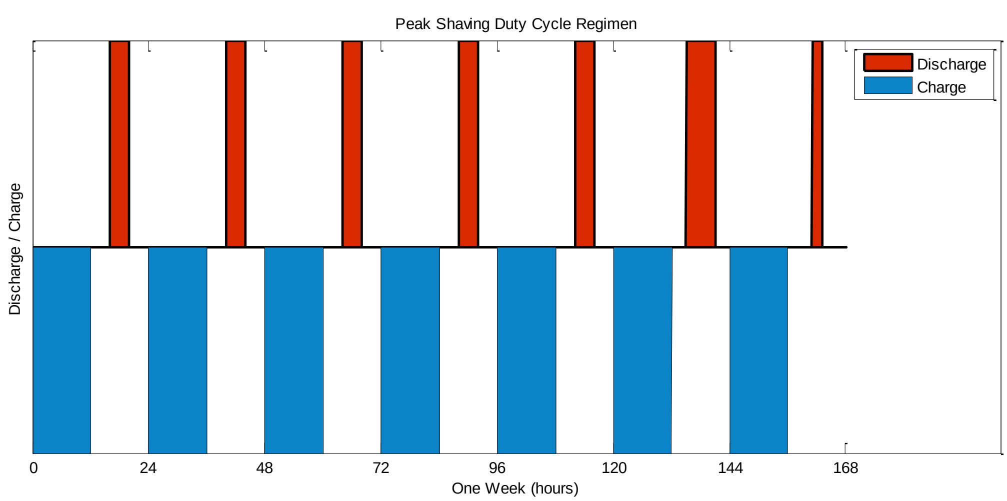

Figure 3. Peak Shaving (Management) Duty-Cycle Regimen.

These duty cycles shall be used to calculate the metrics covered in Section 5.1.4 that are to be used as a basis for determining and reporting the operational effectiveness of an ESS in peak-shaving (management) applications.

5.1.4 Performance

The performance of the ESS shall be expressed in terms of power and energy performance, efficiency, and response rate as outlined in Sections 5.1.4.1 through 5.1.4.3 based on the application of the duty-cycle regimen provided in Section 5.1.3.

5.1.4.1 Duty-cycle roundtrip efficiency

The duty-cycle roundtrip efficiency shall be determined in accordance with Section 7.4.2.

5.1.4.2 Roundtrip energy efficiency

The roundtrip energy efficiency of ESS shall be calculated in accordance with Section 7.4.

5.1.4.3 Response time

The response time associated with an ESS does not regulate power or frequency but does respond to energy prices that will vary over the course of several minutes or hours. This includes peak-shaving (management) applications that require the ESS to respond to and capitalize on sudden peaks in energy generation from renewable or waste energy resources or energy prices when improved use of the stored energy in the order of minutes is to be assessed. Where the response time of an ESS is to be reported, it shall be determined in accordance with Section 7.6.

5.1.4.4 Capacity

The capacity of ESS shall be determined in accordance with Section 7.3.

5.2 Frequency Regulation

5.2.1 Frequency regulation performance assessment

Energy storage systems (ESS) intended for use in frequency regulation shall have all required testing, calculations and/or simulations to determine their performance in accordance with this section using the duty cycle provided in Section 5.2.3. The performance of such ESSs shall be evaluated on the basis of roundtrip efficiency, response time as the time for storage to respond and the ramp rate, ramp rate, reference performance and the ability to respond to signal.

Frequency regulation shall be permitted to represent area regulation as used by a balancing authority to meet NERC Balancing Authority Performance Control Standards.

5.2.2 System Rating

Ratings for ESSs shall be based on and stated by the manufacturer of the system for specific set operating conditions. The performance of the system shall be based on the actual, measured operational effectiveness of the system at those operating conditions at the beginning of the life of the system. In addition the manufacturer shall provide an indication of how the performance of the system is expected to change over time to account for time and use of the system.

The determination and reporting of ratings for systems to be applied for frequency regulation shall be in accordance with the provisions of this section using the duty cycle in Section 5.2.3 and metrics in Section 5.2.4.

5.2.3 Duty cycle

The duty cycle to be applied in determining the performance of an ESS for a frequency regulation application is shown in Figure 4 as power normalized with respect to the system rated power over a 24-hour time period, where positive represents charge into the ESS and negative represents discharge from the ESS as a function of time in hours. The raw data upon which Figure 4 is based are included in Appendix A.

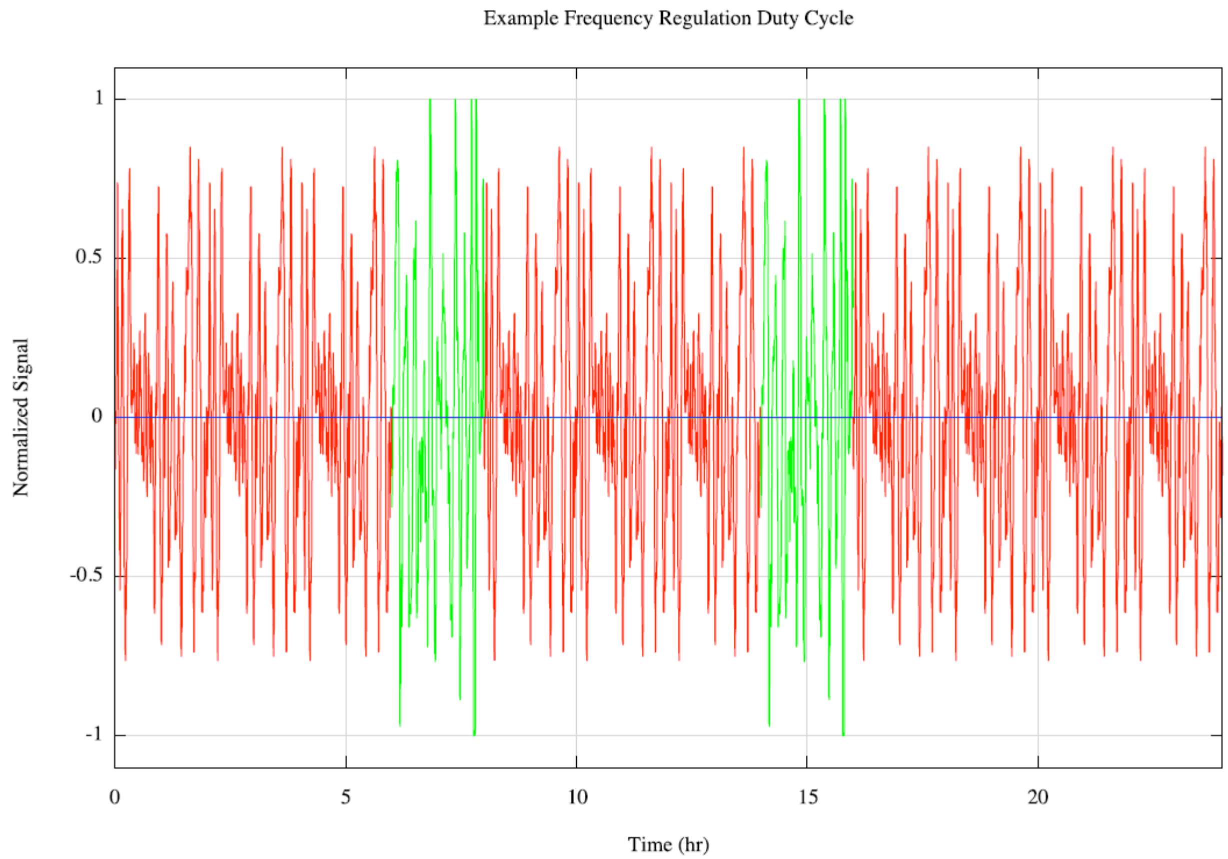

Figure 4. Frequency Regulation Duty Cycle.

5.2.4 Performance

The performance of the ESS shall be expressed in terms of key metrics such as roundtrip energy efficiency, reference performance, response time, ramp rate, and the ability for the system to respond to signal as outlined in Sections 5.2.4.1 through 5.2.4.5 based on the application of the duty-cycle regimen provided in Section 5.2.3 to the applicable provisions of Section 7.

5.2.4.1 Roundtrip energy efficiency

The roundtrip energy efficiency of an ESS serving a frequency regulation application shall be determined in accordance with Section 7.4.

5.2.4.2 Capacity stability

The energy capacity stability of an ESS serving a frequency regulation application shall be measured over a 24-hour duty cycle and reported as a percent of initial performance. The ambient temperature and pressure shall be recorded during the test and also reported. The baseline ESS capacity shall be measured in accordance with Section 7.2. After the 24-hour duty cycle is completed the ESS shall be brought back to 100 percent state of charge and then the energy capacity at rated power shall be determined in accordance with Section 7.3.

5.2.4.3 Response time

The response time of the ESS shall be measured in accordance with Section 7.6 as the time for the system to reach the rated power level from rest to full charge or discharge after receiving the balancing signal. Response time shall include the time for the ESS to respond to the signal after the signal is received and the time taken to ramp up or down to rated power level as a function of its ramp rate. The time taken to reach rated power from rest shall be measured for the extreme state-of-charge ranges specified by the system manufacturer and reported by the manufacturer. Response time shall include measuring the time taken for the system to respond to signal and the ramp rate. The time to respond to signal shall be determined by subjecting the system to a signal at open circuit voltage and measuring the time it takes for the system to reach 2 percent of rated power.

5.2.4.4 Ramp rate

The ramp rate of the ESS shall be determined by measuring the time it takes for the system to reach rated power from 2 percent of rated power in accordance with Section 7.5.

The ramp rates to full rated power during charge and discharge shall be measured and reported at the extreme states-o- charge specified by the system manufacturer. The system shall respond faster than the lower limit of the ramp rate, such that its response time is always less than the upper limit of response time measured.

5.2.4.5 Reference signal tracking

The ability of the ESS to respond to signal for the 24-hour duty cycle and that reflects the ability of the system to track the signal shall be defined and determined by the manufacturer of the system in accordance with Section 7.4.3. The balancing signal shall be changed every 4 seconds during the duty cycle.

In addition, the manufacturer of the system shall also determine and report separately the total percentage tracking and the times when the system stops tracking and restarts tracking as an indication of whether the system is capable of tracking high peaks and/or high energy half cycles. The manufacturer shall also determine if the system can go through a 24-hour period without reaching the lower or upper state-of-charge limits. This shall be performed during the 24-hour duty cycle as provided in Section 5.2.3, and any time during that period when the system indicates 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 4-second duration and cannot deliver or absorb the required signal energy during the duration when the signal remains above or below the x-axis. The total time the system cannot follow the signal and percentage tracked shall be determined in accordance with Section 7.4.3.

6. ENERGY STORAGE SYSTEMS

6.1 Subsystems and components

The manufacturer shall identify all subsystems and major components that comprise the energy storage system (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 Sections 6.2 and 6.3.

6.2 Input characteristics

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 reported in conjunction with the data reported in Section 8.

6.3 Output characteristics

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 reported in conjunction with the data reported in Section 8.

7. TEST METHODS AND PROCEDURES

7.1 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 system application and system metrics to which they are being applied and in accordance with recognized standards applicable to the measurements being taken. All parameters measured and recorded shall be reported by the manufacturer in the system information model that must be used for further analysis and determination and reporting of system performance. All tests shall be conducted on the entire energy storage system (ESS) as defined by the manufacturer of the system in accordance with Section 4.2.

7.2 Reference performance test

A reference performance test shall be conducted in accordance with this section and used to determine baseline system performance that can be subsequently used as a baseline to assess any changes in the condition of the system and rate of performance fade over time and use. This test 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 system and shall be in units of time, number of cycles, or energy throughput. Unless specified otherwise, reference performance testing shall include the tests listed in Table 2.

Table 2. Reference Performance Tests

Peak Shaving (Management)	Frequency Regulation
Capacity test (Section 7.3)	Capacity test (Section 7.3)
Round trip energy efficiency test (Section 7.4)	Round trip energy efficiency test (Section 7.4)
Response time test (Section 7.6)	Ramp rate test (Section 7.5)
Duty-cycle roundtrip efficiency (Section 7.4.2)	Response time test (Section 7.6)
	Duty-cycle roundtrip efficiency (Section 7.4.2)
	Reference signal tracking test (Section 7.4.3)

7.3 Capacity Test

A capacity test shall be performed in accordance with this section and is intended to be used to determine energy performance at the rated power for the intended application as specified by the manufacturer.

7.3.1 Test overview

After the initial charge to the ESS, the system shall be discharged to the minimum storage level specified by the manufacturer. Recorded values of energy input to the system shall be obtained by recording them at regular intervals of time or at step or percentage variances at a rate that is documented by the manufacturer to provide adequate resolution.

In conducting the capacity test, the manufacturer shall describe a detailed and documented charging procedure within the specifications of the ESS for charging the system in less than 12 hours to full state-of-charge. In addition, the manufacturer shall select a discharge time at constant power output based on the intended application of the system. For devices intended for peak-shaving (management) application, the discharge time shall be selected between 2 and 12 hours or as recommended by the system manufacturer. For devices intended for frequency regulation, the minimum discharge time shall be selected between 15 minutes and 1 hour or as recommended by the system manufacturer. This choice is constrained by the system limitations. Once this discharge time is selected, all capacity tests conducted on the same system should remain consistent to properly track performance degradation.

7.3.2 Energy Capacity and roundtrip efficiency test routine

The ESS shall be tested for its stored energy capability at selected power in accordance with the procedure listed below. The measurements shall be collected in accordance with Section 7.3.1 throughout the test.

1. The ESS shall be discharged to its minimum state of charge level in accordance with the system manufacturer's specifications and operating instructions.
2. The ESS shall be charged in accordance with the system manufacturer's specifications to full state of charge. The energy input $\mathbf{Wh_{Ii}}$, into the system during system charging, including all parasitic losses, shall be measured and recorded.
3. The system shall be left at rest in an active standby state for 30 minutes.
4. The system shall be discharged in accordance with the system manufacturer's specifications and operating instructions to the minimum state of charge associated with the practical state-of-charge range as defined by the system manufacturer and provided in the system manufacturer's specifications. The energy output from the system $\mathbf{Wh_{Di}}$ shall be measured and recorded during discharge.

5. The system shall be left at rest in an active standby state for 30 minutes.

6. Steps 1 to 5 above shall be repeated at least eight times, 1 through the number of test repeats X. The reference performance test value shall be calculated as the mean of the second through $\mathbf{X^{th}}$ values of $\mathbf{Wh_{Di}}$ as measured in item 2 above, with the standard deviation also calculated and reported.

7. The system shall be recharged in accordance with step 2 and the system left in a fully charged state. The energy input for this step will not be used for calculation of roundtrip energy efficiency.

7.4 Roundtrip energy efficiency test

A roundtrip energy efficiency test shall be conducted to determine the amount of energy that an ESS can deliver relative to the amount of energy injected into the system during the preceding charge. This test shall be performed as part of the reference performance test outlined in Section 7.2. This test shall be performed using the energy test routine and the applicable duty cycle for the intended application of the system. The ESS shall be tested for its roundtrip energy efficiency in accordance with the test covered in Section 7.3.2.

7.4.1 Roundtrip energy efficiency from energy capacity test routine

The roundtrip energy efficiency of the ESS shall be determined in accordance with Equation 7-1 based on the data secured in accordance with measurements in accordance with Section 7.3.2.

$$Round\ trip\ efficiency = \left(\left(\frac{\sum_2^X (Wh_{DX})}{\sum_2^{X_1} (Wh_{IX})}\right)\right) \quad (7\text{-}1)$$

Where:

X = number of test repeats

Wh_{Di} = the Watt hour rated power (AC) or thermal energy equivalent watt hours delivered (output) by the system measured and recorded as $\mathbf{Wh_{Di}}$, where I is the cycle number

Wh_{Ii} = the Watt hour input (AC) into the system during system charging, including all parasitic losses, where I is the cycle number

Wh_I = the Watt hour input $\mathbf{Wh_{I1}}$, into the system during system charging, including all parasitic losses.

7.4.2 Duty-cycle roundtrip efficiency measurement

The manufacturer shall select an intended application and relevant duty cycle as provided in Section 5.1.3 for peak shaving (management) applications and Section 5.2.3 for frequency regulation applications. In conducting the tests required in Sections 5.1 and 5.2, the charge and discharge of the ESS shall be in accordance with the section using the duty cycle in Section 5.1.3 or 5.2.2 depending on the intended application of the system.

1. The ESS shall be fully charged in accordance with the manufacturer's specifications. The system shall be brought to the initial desired state-of-charge in accordance with the applicable duty cycle by removing the necessary amount of energy at the rate provided in the system specifications provided by the manufacturer or alternatively brought to the desired starting state-of-charge in accordance with a vendor specified procedure.
2. The ESS shall then be subjected to the applicable duty cycle.
3. At the end of the duty cycle, the system shall be returned to the initial state-of-charge just prior to the application of the duty cycle.
4. The roundtrip efficiency shall be determined in accordance as the total energy output divided by the total energy input measured between the same state-of-charge end points associated with the application of the duty cycle during the test.

7.4.3 Reference signal tracking test (frequency regulation)

The ability of the ESS to respond to a reference signal shall be recorded during a roundtrip efficiency test. The sum of the square of errors between the balancing signal Psignal and the power delivered or absorbed by the ESS Pess shall be calculated in accordance with Equation 7-2 and used to estimate the inability of the system to track the signal.

$$\Sigma(\text{Psignal-Pess})^2 \qquad (7\text{-}2)$$

Where:

Psignal = balancing signal

Pess = energy storage system power (watts).

The sum of the absolute magnitude of the difference between the balancing signal and ESS power shall be calculated in accordance with Equation 7-3.

$$\Sigma|\text{Psignal-Pess}| \qquad (7\text{-}3)$$

Where:

Psignal = balancing signal

Pess = ESS power (watts).

The sum of the absolute magnitude of the difference between the balancing signal and ESS energy shall be calculated in accordance with Equation 7-4 and reported by the manufacturer of the system to account for the inability for the system to meet high energy half cycles due to the system reaching the state-of-charge limits.

$$\Sigma|\text{Esignal-Eess} \qquad (7\text{-}4)$$

Where:

Esignal = signal energy for a half cycle, with half cycle being the signal of the same sign (above or below the x-axis)

Eess = ESS supplied or absorbed energy for each half cycle.

The total time the system cannot follow the signal and percentage tracked shall be determined in accordance with Equation 7-5.

$$(1 - \text{time signal cannot be followed (hours)}/24) * 100 \qquad (7\text{-}5)$$

7.5 Ramp rate test

A ramp rate test to determine the rate at which power output can be changed due to the system charging or discharging or whether it is beginning at a low or high state-of-charge initially shall be conducted in accordance with this section.

7.5.1 Test overview

The method for measuring ramp rate shall be the same for all systems regardless of application. The manufacturer shall provide information on rated power as required by Section 5.1 or 5.2.

7.5.2 Charge test routine

The ESS charge test shall be performed once at the 50 percent state-of-charge as specified by the manufacturer. The test shall be initiated with the system in a state of active standby. The system shall then be subjected to a constant power charge equal to its rated power and the voltage (or voltage and thermal output equivalent) across the system and the current (or current and thermal output equivalent) measured at the external system terminals and the time taken to reach the rated power recorded. The ramp rate shall be determined in accordance with Equation 7-6 and expressed ratio of rated power in MW and the time in minutes to reach the rated power.

$$\text{Ramp Rate} = RP/T \qquad (7\text{-}6)$$

Where:

RP = Rated power (MW)

T = Time (minutes).

7.5.3 Discharge test routine

The ESS shall have a discharge test performed once at the 50 percect state-of-charge as specified by the manufacturer. The test shall be initiated with the system in a state of active standby. The system shall then be subjected to a constant power load equal to its rated power and the voltage (or voltage and thermal output equivalent) across the system and the current (or current and thermal output equivalent) measured at the external system terminals and the time taken to reach the rated power recorded. The ramp shall be determined in accordance with Equation 7-6 and expressed as ratio of rated power in MW and the time in minutes to reach the rated power.

7.6 Response time test

The ESS shall have a response time test performed in accordance with this section to determine the amount of time required for the system output to transition from no discharge to full discharge rate and from no charge to full charge.

7.6.1 Test overview

The response time shall be measured in accordance with Figure 5 starting when the signal is received at the system boundary as established in Section 4.2 to when the system begins to discharge within 2 percent of the rated power of the system.

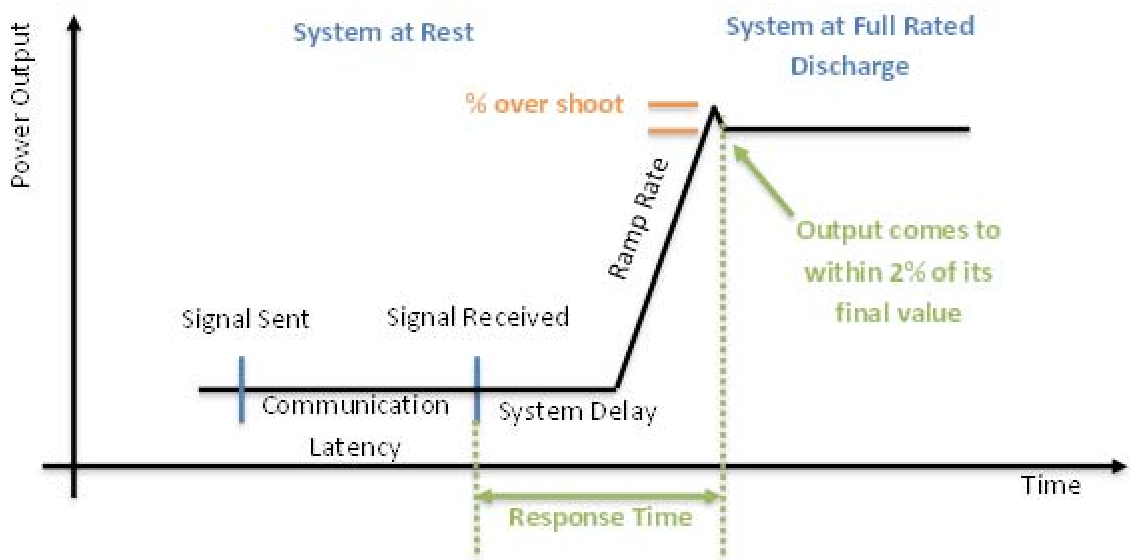

Figure 5. Response Time Test.

7.6.2 Charge test routine

The response time test shall be conducted in accordance with the following procedure and the response time calculated in accordance with Equation 7-7.

1. The system shall be at the maximum state-of-charge as specified by the manufacturer for the applications and in an active standby state.
2. The data acquisition system shall be configured to record a time stamp $\mathbf{T_1}$ when a change in set point from rest to a discharge output is sent to the system.

3. The data acquisition system shall be configured to record a time stamp $\mathbf{T_2}$ when the output of the system maintains a value within 2 percent of its rated power. The acquisition rate of data shall be at least twice as fast as the full rated power divided by the ramp rate of the system, as determined in Section 7.5, and at least one intermediate data point shall be acquired as the system transitions from rest to full discharge.
4. The system shall be configured to respond to a step change in power set point according to the system specifications provided by the manufacturer.
5. The data acquisition system shall be started and shall the command to change the power output of the system to full rated discharge power and $\mathbf{T_1}$ and $\mathbf{T_2}$ measured and recorded
6. The data acquisition system shall be reset to a state to begin taking data and the system placed in a state of active standby.

RT as $\mathbf{RT_Y = T_2 - T_1}$ (7-7)

Where:

RT = response time in seconds

$\mathbf{T_1}$ = the initial time beginning when a change in set point of output is sent to the system, in seconds

$\mathbf{T_2}$ = the end time stamp when the output of the system maintains a value within 2 percent of its rated power, in seconds.

The test shall be repeated starting at the minimum state-of-charge as specified by the manufacturer based on the intended application of the system.

7.6.3. Discharge test routine

The tests in Section 7.6.2 shall be repeated at the maximum and minimum state of charge levels, with a charge input signal sent to the ESS.

8. REPORTING PERFORMANCE RESULTS

8.1 Peak shaving (management) applications

The performance of an energy storage system (ESS) intended for a peak-shaving (management) application shall be reported by the manufacturer of the system in accordance with Sections 8.1.1 through 8.1.4 as determined in accordance with Sections 7.3, 7.4, 7.4.2 and 7.6 along with the specific application as determined in accordance with Section 5.1.1.

8.1.1 System capacity

The capacity (size) of the ESS shall be reported for the selected power as determined in accordance with Section 7.3.

8.1.2 Duty-cycle roundtrip efficiency

The duty-cycle roundtrip efficiency shall be reported together with respect to each other and to the discharge duration based on the data collected in accordance with Section 7.4.2. Table 3 shall be used to report the measured power and energy performance of the ESS.

Table 3. Reporting Peak-Shaving (Management) Duty-Cycle Roundtrip Efficiency

	Discharge Duration	Power Performance	Energy Performance
Cycle 1	4 hours	______ kW	______ kWh
Cycle 2	4 hours	______ kW	______ kWh
Cycle 3	4 hours	______ kW	______ kWh
Cycle 4	4 hours	______ kW	______ kWh
Cycle 5	4 hours	______ kW	______ kWh
Cycle 6	6 hours	______ kW	______ kWh
Cycle 7	2 hours	______ kW	______ kWh

8.1.3 Roundtrip efficiency

The roundtrip efficiency of the ESS shall be reported based on calculations in accordance with Section 7.4. Table 4 shall be used to report the efficiency of the ESS, and Table 5 shall be used to report the recorded performance metrics.

Table 4. Reporting Peak-Shaving (Management) Efficiency

	Discharge Duration	Efficiency
Cycle 1	4 hours	______ %
Cycle 2	4 hours	______ %
Cycle 3	4 hours	______ %
Cycle 4	4 hours	______ %
Cycle 5	4 hours	______ %
Cycle 6	6 hours	______ %
Cycle 7	2 hours	______ %

Table 5. Reporting Peak-Shaving (Management) Metric Statistics

	Min	Mean	Max	σ
Power Performance	______ kW	______ kW	______ kW	
Energy Performance	______ kWh	______ kWh	______ kWh	
Efficiency	______%	______ %	______ %	

8.1.4 Response time

The response time in minutes of the ESS shall be reported as determined in accordance with Section 7.6.

8.2 Frequency regulating applications

The performance of an ESS intended for a frequency-regulation application shall be reported by the manufacturer in accordance with Sections 8.2.1 through 8.2.5 as determined in accordance with Sections 7.3, 7.4, 7.4.2, 7.4.3, 7.5 and 7.6.

8.2.1 System capacity

The capacity (size) of the ESS shall be reported for the selected power as determined in accordance with Section 7.3.

8.2.2 Roundtrip energy efficiency

The roundtrip energy efficiency of the ESS shall be reported in accordance with Section 8.1.3.

8.2.3 Reference signal tracking

The reference signal tracking of the ESS shall be reported in accordance with Section 7.4.3.

8.2.4 Duty-cycle roundtrip efficiency

The duty-cycle roundtrip energy efficiency of the ESS shall be reported in accordance with Section 8.1.2.

8.2.5 Ramp rate

The ramp rate of the ESS in watts per minute shall be reported as determined in accordance with Section 7.5.

8.2.6 Response time

The response time in seconds of the energy storage shall be reported as determined in accordance with Section 7.6.

9. REFERENCED STANDARDS

9.1 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.

10. REFERENCES

1. IEEE Standard 1679-2010 "Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications."

2. Eyer J, J Iannucci, and G Corey. 2004. *Energy Storage Benefits and Market Analysis Handbook*. SAND2004-6177, Sandia National Laboratories, Albuquerque, New Mexico.

3. 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.

APPENDIX A: DUTY-CYCLE SIGNAL FOR FREQUENCY REGULATION APPLICATIONS OF ESSs

In determining the duty cycle, the PJM balancing signal for the year 2011 was analyzed. The standard deviation over a 24-hour period was used as a metric for 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 nominal standard deviation as the average and high deviation signal days the representative segment was taken from. The duty cycle consisted of three 2-hour average signals, followed by one 2-hour high deviation signals, three 2-hour average signals, one 2-hour high deviation signals and four 2-hour average signals to make up the 24 hour signal.

Data and statistics provided in Table A.1 are the bases for a duty-cycle graphic presented in Section 5.2.3.

Table A.1. Example Data and Statistics for Frequency Regulation

Example Statistics	**Standard Deviation**	**Sum of signal**	**Time at 1 (sec)**	**Time at -1 (sec)**	**% Time at 1**	**% Time at -1**
Average Profile	0.361	-0.00065	0	0	0	0
Aggressive Signal	0.460	0.00175	164	132	2.28	1.83
Reference Statistics	**Lowest Day**	**Avg Day #1**	**Avg Day #2**	**Avg Day #3**	**Highest Day**	
Standard Deviation	0.132	0.334	0.332	0.333	0.451	

Duty Cycle
3 Average
1 Aggressive
3 Average
1 Aggressive
4 Average

Time	Average Signal	Aggressive Signal
0:00:00	-0.144251049	-0.282695264
0:00:04	-0.129648238	-0.273952544

0:00:08	-0.136013523	-0.265209794
0:00:12	-0.142378807	-0.256467074
0:00:16	-0.148744106	-0.247724339
0:00:20	-0.155109391	-0.2383544
0:00:24	-0.161474675	-0.228357255
0:00:28	-0.150013253	-0.218360111
0:00:32	-0.138551846	-0.208362967
0:00:36	-0.113525704	-0.198365822
0:00:40	-0.08397799	-0.18872872
0:00:44	-0.054430272	-0.179451689
0:00:48	-0.032121196	-0.170174643
0:00:52	-0.009812118	-0.164905593
0:00:56	0.00501351	-0.159636542
0:01:00	0.012355687	-0.139434874
0:01:04	0.019697864	-0.104300603
0:01:08	0.005642735	-0.069166332
0:01:12	-0.008412393	-0.025457811
0:01:16	-0.016135313	0.018250709
0:01:20	-0.017526021	0.050382435
0:01:24	-0.018916732	0.070937358
0:01:28	-0.007483151	0.091492288
0:01:32	0.003950429	0.096228711
0:01:36	0.016937084	0.100965127
0:01:40	0.030441433	0.101237461
0:01:44	0.043945782	0.097045712
0:01:48	0.065859124	0.092853956
0:01:52	0.087772466	0.087061487
0:01:56	0.102681331	0.081269011
0:02:00	0.115255378	0.077279635
0:02:04	0.127829418	0.075093359
0:02:08	0.136286065	0.072907083

0:02:12	0.144742712	0.071547456
0:02:16	0.168096304	0.070187822
0:02:20	0.206346855	0.065275341
0:02:24	0.24459739	0.056809999
0:02:28	0.286141574	0.048344657
0:02:32	0.327685773	0.04501012
0:02:36	0.371769905	0.041675579
0:02:40	0.41839397	0.041155186
0:02:44	0.464600265	0.043448932
0:02:48	0.509553194	0.045742679
0:02:52	0.554506123	0.053398695
0:02:56	0.602924347	0.06105471
0:03:00	0.654807866	0.070469923
0:03:04	0.706691384	0.081644334
0:03:08	0.720910609	0.092818744
0:03:12	0.735129833	0.1054141
0:03:16	0.737693191	0.118009456
0:03:20	0.728600562	0.129463658
0:03:24	0.719507933	0.139776722
0:03:28	0.697333694	0.150089785
0:03:32	0.662077785	0.155796483
0:03:36	0.616101444	0.161503181
0:03:40	0.559404731	0.166243717
0:03:44	0.502707958	0.170018077
0:03:48	0.434835255	0.173792437
0:03:52	0.366962582	0.259592712
0:03:56	0.299703628	0.345392972
0:04:00	0.233058423	0.409059495
0:04:04	0.166413218	0.450592279
0:04:08	0.126902997	0.492125064
0:04:12	0.087392792	0.492103755

0:04:16	0.062752046	0.492082447
0:04:20	0.052980773	0.490190148
0:04:24	0.043209501	0.48642692
0:04:28	0.031373527	0.482663661
0:04:32	0.019537557	0.480816096
0:04:36	0.001462346	0.478968501
0:04:40	-0.022852104	0.480422795
0:04:44	-0.047166552	0.485178918
0:04:48	-0.057434734	0.48993507
0:04:52	-0.067702919	0.500819147
0:04:56	-0.080728419	0.511703193
0:05:00	-0.09651123	0.524471402
0:05:04	-0.112294048	0.539123714
0:05:08	-0.141811341	0.553776085
0:05:12	-0.171328619	0.570581317
0:05:16	-0.19213371	0.587386549
0:05:20	-0.210034728	0.60419178
0:05:24	-0.227935746	0.620996952
0:05:28	-0.252165616	0.63694191
0:05:32	-0.27639544	0.650305927
0:05:36	-0.296143562	0.663669944
0:05:40	-0.31140995	0.677338839
0:05:44	-0.326676309	0.691312611
0:05:48	-0.336338639	0.705286384
0:05:52	-0.346000969	0.719260216
0:05:56	-0.354167581	0.733233988
0:06:00	-0.361835599	0.745755792
0:06:04	-0.369503617	0.756825626
0:06:08	-0.382226527	0.767895401
0:06:12	-0.394949466	0.770347893
0:06:16	-0.413662046	0.772800386

0:06:20	-0.438364327	0.771793187
0:06:24	-0.463066578	0.767326355
0:06:28	-0.491415203	0.762859464
0:06:32	-0.519763827	0.758392572
0:06:36	-0.535574436	0.753925741
0:06:40	-0.53884691	0.74991554
0:06:44	-0.542119443	0.74636209
0:06:48	-0.525878966	0.74280864
0:06:52	-0.509638429	0.772468626
0:06:56	-0.485117942	0.802128613
0:07:00	-0.452317476	0.808736086
0:07:04	-0.41951701	0.792291105
0:07:08	-0.398959488	0.775846064
0:07:12	-0.378401995	0.776005566
0:07:16	-0.360686213	0.776165128
0:07:20	-0.345812142	0.778602719
0:07:24	-0.330938071	0.78331846
0:07:28	-0.311509281	0.788034201
0:07:32	-0.292080462	0.792749882
0:07:36	-0.264012247	0.797465622
0:07:40	-0.227304593	0.800635874
0:07:44	-0.190596953	0.802260756
0:07:48	-0.151647434	0.803885579
0:07:52	-0.112697922	0.802513361
0:07:56	-0.07070902	0.801141083
0:08:00	-0.02568073	0.796761096
0:08:04	0.019347558	0.789373279
0:08:08	0.066808105	0.781985462
0:08:12	0.114268646	0.768378317
0:08:16	0.149056494	0.754771113
0:08:20	0.179620102	0.737595737

0:08:24	0.21018371	0.716852129
0:08:28	0.226593435	0.69610852
0:08:32	0.243003175	0.673140526
0:08:36	0.260151565	0.650172532
0:08:40	0.278038591	0.625315309
0:08:44	0.295925617	0.598568857
0:08:48	0.345791727	0.571822405
0:08:52	0.395657867	0.540236712
0:08:56	0.416477412	0.508651018
0:09:00	0.427614808	0.475282341
0:09:04	0.438752174	0.440130711
0:09:08	0.484879583	0.40497905
0:09:12	0.531006992	0.368054479
0:09:16	0.564311445	0.331129909
0:09:20	0.584792912	0.294205308
0:09:24	0.605274379	0.257280737
0:09:28	0.625755847	0.220356166
0:09:32	0.646237314	0.184814364
0:09:36	0.653857112	0.149272561
0:09:40	0.648615301	0.115076534
0:09:44	0.643373489	0.082226284
0:09:48	0.618583143	0.049376033
0:09:52	0.593792737	-0.037982456
0:09:56	0.579453528	-0.125340939
0:10:00	0.568597972	-0.255351096
0:10:04	0.557742417	-0.428012878
0:10:08	0.534055412	-0.600674689
0:10:12	0.510368407	-0.702175319
0:10:16	0.484838426	-0.80367589
0:10:20	0.45746544	-0.875576496
0:10:24	0.430092424	-0.917877018

0:10:28	0.406610578	-0.9601776
0:10:32	0.383128703	-0.965281844
0:10:36	0.355775058	-0.970386088
0:10:40	0.324549615	-0.967141032
0:10:44	0.293324172	-0.955546677
0:10:48	0.249806523	-0.943952382
0:10:52	0.206288859	-0.924059927
0:10:56	0.163547352	-0.904167473
0:11:00	0.121064566	-0.882113814
0:11:04	0.078581773	-0.85789907
0:11:08	0.03163211	-0.833684206
0:11:12	-0.015317554	-0.809469461
0:11:16	-0.035845049	-0.785254598
0:11:20	-0.047565155	-0.761400461
0:11:24	-0.059285261	-0.737906992
0:11:28	-0.081598312	-0.714413524
0:11:32	-0.103911363	-0.690919995
0:11:36	-0.133230746	-0.667426527
0:11:40	-0.169556454	-0.644908607
0:11:44	-0.205882162	-0.623366296
0:11:48	-0.249970943	-0.601823986
0:11:52	-0.294059724	-0.585796714
0:11:56	-0.332335889	-0.569769442
0:12:00	-0.36479944	-0.555796027
0:12:04	-0.39726299	-0.54387635
0:12:08	-0.423568636	-0.531956732
0:12:12	-0.449874282	-0.5225811
0:12:16	-0.468467623	-0.513205469
0:12:20	-0.4793486	-0.503829837
0:12:24	-0.490229607	-0.494454175
0:12:28	-0.50880307	-0.485078543

0:12:32	-0.527376473	-0.479038358
0:12:36	-0.545949936	-0.472998172
0:12:40	-0.564523339	-0.46839875
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