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Standard for Uniformly Measuring and Expressing the Performance of Electrical Energy Storage Systems

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Foreword

The National Electrical Manufacturers Association has adapted the Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage (herein referred to as the Protocol) into a NEMA Standard. The Protocol was developed by the U.S. Department of Energy's Energy Storage Systems (ESS) Program, with the support from the Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL), facilitated the development of this protocol. The National Electrical Manufacturers Association has taken this protocol and developed a NEMA Standard.). This Standard leverages the work of several revisions of the Protocol.

Recognition

NEMA would like to recognize the following for their work in developing the Protocol.

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Feedback

In the preparation of this Standards Publication, the input of users and other interested parties has been sought and evaluated. Inquiries, comments, interpretation requests, and proposed or recommended revisions should be submitted to the concerned NEMA product section by contacting the:

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At the time of NEMA Codes and Standards Committee approval of this Standard, the companies forming the sponsoring NEMA section were as shown below.

ABB Inc.	S&C Electric Company
Delta Electronics	Schneider Electric
Delta Products Corporation	Siemens Industry, Inc.
East Penn Manufacturing Co. Inc.	TESLA Motors, Inc.
Eaton	Toshiba International Corporation
GE Energy Storage	

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 Standard must continue to evolve to more fully address the wide scope and purpose stated in Sections 1 and 2 of the Standard.

As formal Standards are completed and available from and updated by SDOs, ongoing Standard 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 Standard based on a process open to all stakeholders on an equitable basis that provides them an opportunity to participate and provide input.

Organization of Content

Section 1 provides the purpose of the Standard, Section 2 is the scope, and Section 3 contains definitions. Section 4 provides an overview of the Standard 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 Standard.

Applications

There are eight ESS applications covered in this Standard including peak shaving, frequency regulation, islanded microgrids, PV smoothing, volt/VAR, renewables firming, power quality and frequency control. Each of these applications 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 applications is provided in the following descriptions.

Peak Shaving

Peak shaving (management) applications shall be designated by several classifications listed below.

a. Energy time shift (arbitrage)
b. Electric supply capacity
c. Load following
d. Transmission congestion relief
e. Distribution system upgrade deferral
f. Transmission system upgrade deferral
g. Retail demand charge management
h. Wind energy time shift (arbitrage)
i. Photovoltaic energy time shift (arbitrage)

j. Renewable capacity firming
k. Baseload generation time shift

Frequency Regulation

Frequency regulation is mainly provided by ramping (up and/or down) of generation assets. This typically takes minutes rather than seconds. ESS has the capability to do this in milliseconds. 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.

Islanded Microgrid

A typical microgrid is connected to the main grid and should have the flexibility to operate in an islanded mode. Since the applications associated with a microgrid, while connected to the grid are quite large in number, the focus of this application is on operation of an ESS in an islanded mode. The metrics for an islanded microgrid application are the same as those for frequency regulation applications. The following use cases for an islanded microgrid application are included in the Standard:

a. Microgrid with Renewables (where renewables consisted of a mix of solar and wind generation)
b. Microgrid with Renewables but no frequency regulation
c. Microgrid with no renewables and no frequency regulation

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 ESS 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

a. system rating

b. round-trip energy efficiency

c. response time

d. ramp rate

e. energy

f. energy stability

Duty-cycle–specific metrics

a. reference signal tracking

b. SOC excursion

c. duty-cycle round-trip efficiency

d. 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

a. round-trip efficiency

b. response time and ramp rate

c. energy

d. energy stability

Duty-cycle–specific metrics

a. reactive power ramp rate at 50% SOC (This is a new metric and uses the same procedure as real power ramp rate.)
b. round-trip efficiency
c. reference signal tracking
d. ∆SOC_volt/var, which is the difference between the final and initial SOC
e. ∆SOC_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
f. Wh_discharge, which is the real energy injected (with and without the volt/var duty cycle)
g. Wh_charge, which is the real energy absorbed (with and without the volt/var duty cycle)
h. 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:

a. system rating
b. round-trip energy efficiency
c. response time
d. ramp rate
e. energy
f. energy stability

Duty-cycle–specific metrics:

a. reference signal tracking
b. SOC excursion
c. duty-cycle round-trip efficiency
d. 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

a. round-trip efficiency
b. response time and ramp rate
c. energy
d. energy stability

Duty-cycle–specific metrics

a. peak discharge power for durations of 1, 5, and 10 minutes
b. duty-cycle round-trip efficiency
c. reference signal tracking
d. 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 Standard, 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.

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

a. round-trip efficiency
b. response time and ramp rate
c. energy
d. energy stability

Duty-cycle–specific metrics

a. peak power for 1 minute during charge and discharge
b. peak power for 20 minutes during charge and discharge
c. duty-cycle round-trip efficiency
d. reference signal tracking

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 i
Acronyms and Abbreviations ix
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. 4
4.3 Identification of the ESS Application. 5
4.3.1 Peak Shaving (Management). 5
4.3.2 Frequency Regulation. 6
4.4 ESS Specifications and Performance Metrics. 6
4.4.1 Subsystems and Components. 6
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. 12
5.2.1 Stored Energy 12
5.2.2 Round-Trip Energy Efficiency 14
5.2.3 Response Time and Ramp Rate. 15
5.2.4. Standby Energy Loss Rate 17
5.2.5. Self-Discharge Rate. 18
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 21
5.3.4 PV Smoothing Duty Cycle. 23
5.3.5 Volt/Var Support Duty Cycle 24
5.3.6 Renewables (Solar) Firming Duty Cycle. 27
5.3.7 Power Quality Duty Cycle 27
5.3.8 Frequency Control Duty Cycle. 30
5.4 Duty-Cycle Performance. 33
5.4.1 Duty-Cycle Round-Trip Efficiency. 34
5.4.2 Reference Signal Tracking. 35
5.4.3 State-of-Charge Excursions. 36

5.4.4 Energy Stability. 36
5.4.5 Additional Metrics. 37
6.0 Reporting ESS General Information, Specifications, and Performance Results 38
6.1 Energy Storage System Description, General Information, and Technical Specifications. 38
6.2 Energy Storage System Reference Performance. 39
6.3 Energy Storage System Duty-cycle Performance. 41
7.0 Referenced Standards 43
8.0 References 43
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 Signals for Renewable (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

1.0 Purpose

This Standard 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 Standard will enable more informed decision-making in the selection of ESSs for various stationary applications.

2.0 Scope

The Standard 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 electrical 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 Standard is agnostic with respect to the storage technology and the size and rating of the ESS.

The Standard 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. It also does not apply to thermal energy storage systems.