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Determination of Duty Cycles for Energy Storage Systems Providing Frequency Regulation and Peak Shaving Services with var Support

February 2018

JE Alam
AJ Crawford
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability (OE)
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

This report supplements the report, *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems*, PNNL-22010 Rev. 2/SAND2016-3078 (2016 Protocol). It provides the background and documentation associated with the development of a duty cycle to be applied to an energy storage system for either of the two applications (frequency regulation with var support or peak shaving with var support) in the report title.

To date, the Protocol has addressed either real or reactive power flow. The work reported here addresses situations that have both real and reactive power flow. Frequency Regulation (FR), with its energy neutral and volatile signal, and peak shaving (PS), with constant power charge and discharge, were chosen as two extremes in the real power duty cycle. The available vars were used in one case for both FR and PS, while keeping the power factor fixed for the second case. The impact on the grid of combining real and reactive power is discussed relative to storage sourcing reactive power during discharge and sinking reactive power during charge. Performance metrics were identified for both applications and new metrics were developed and are described herein.

Acknowledgments

The author team gratefully acknowledges the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability (OE)—in particular, Dr. Imre Gyuk—for funding the efforts of the working group that addressed the development of standard duty cycles for assessment of energy storage system (ESS) performance when an ESS is engaged in providing var support while also providing frequency regulation and peak shaving services. This document represents the work of all members of the working group; we thank you for your contributions.

Acronyms and Abbreviations

CAISO	California Independent System Operator
ESS	energy storage system
IEEE	Institute of Electrical and Electronics Engineers
PCC	Point of Common Coupling
PF	power factor
PJM	PJM Interconnection
PV	photovoltaic
PNNL	Pacific Northwest National Laboratory
RST	reference signal tracking
RTE	round trip efficiency
SOC	state of charge
var	Volt-Ampere Reactive

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1.0 Introduction

This report supplements the report, *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems*, PNNL-22010 Rev. 2/SAND2016-3078 R, 2016 (2016 Protocol). It provides the background and documentation associated with the development of a duty cycle to be applied to an energy storage system (ESS) for the purpose of determining its anticipated performance in the following applications:

- frequency regulation with the ESS providing available reactive power (vars) as needed (combine power-intensive real power application and var based on power factor regulation), and
- peak shaving with the ESS providing available vars as needed (combine energy-intensive real power application and var based on power factor regulation).

Each of these duty cycles is applied to an ESS for the purpose of gathering data on the performance of the ESS, which is then used to determine the value of various metrics associated with ESS performance covered in the 2016 Protocol. The duty cycles are appended as spreadsheets to this document.

2.0 Background

Energy storage systems[1] with four-quadrant inverters can provide reactive power (var) sourcing or sinking support simultaneously while performing active power charging/discharging duty as long as the rated apparent power capacity in kilo-volt-amperes or mega volt amps of the inverter is not exceeded. Because power systems are undergoing increasingly stressful operations to accommodate different types of load and generation in a competitive market setting, the right type of var support at the right time, along with active power support, could be beneficial for system operation. The two specific use cases this document covers are frequency regulation and peak shaving. A period of frequency disturbance, being associated with under- and over-generation events, is likely to be accompanied by under- and over-voltage events in a stressed system. As discussed in a General Electric document on load shedding and restoration [1], a normal under-frequency condition in the system would usually be accompanied by a lower than normal voltage. Low voltage and lack of adequate var supply during a stressed condition after incidents such as tripping of transmission lines have been observed before, and utilities recognize the importance of implementing under-voltage load shedding schemes to complement their under-frequency load shedding programs [2]. Similarly, a period of peak shaving, being associated with under-generation or excess loads in a feeder or a part of the network, is likely to be accompanied by an under-voltage situation, and the reverse would be true for over-generation (or low load) periods. Voltage and power have a high correlation when reactive power is not charging. The North American Electric Reliability Council 1999 Review of Selected North American Electric System Disturbances [3] identified some low-voltage incidents caused by heavy loads due to hot weather and lack of adequate var supply to support voltage during a peak load condition. While low voltage during a heavy load period is a concern for system operators, so is high voltage during a low load period. In a forum of Independent System Operators (ISOs), ISO New England [4] suggested high voltage could well be a concern during a light load period with capacitor banks that cannot be switched out. Therefore, sourcing or sinking of var, as appropriate based on the grid condition, could be beneficial by allowing the maintenance of voltage alongside achieving a regulated frequency or a shaved peak. However, before engaging an ESS to provide

[1] Note that going forward, thermal energy storage systems will not be considered in this work. This work assumes electricity in and electricity out of the energy storage system.

this type of support in a real-world situation, it is necessary to understand the performance of an ESS by subjecting it to a similar type of active and reactive power sourcing and sinking duty cycle.

This document describes the development of standard duty cycles for assessment of ESS performance when the ESS is engaged in providing var support while also providing frequency regulation or peak shaving services. As with duty cycles provided for other ESS applications covered in the 2016 Protocol, these new duty cycles provide a basis for the uniform measurement and reporting of relevant metrics, which facilitates the comparison of different ESSs being considered by ESS customers and users.

3.0 Sign Conventions and Notations

For single cell testing, discharge current is assigned a negative sign and charge current is assigned a positive sign. For grid-scale testing, the opposite is the case. This is because when the ESS charges, the grid is providing power. Hence, from the grid perspective, the power is assigned a negative sign. Similarly, when the ESS discharges, the grid receives this power. Hence, from the grid perspective, the sign is positive. The same logic applies when ESS sources reactive power (positive sign), and sinks reactive power (negative sign).

This work addresses instances when both real and reactive power are flowing through the ESS. The ESS discharge of real power and sourcing of reactive power have similar effects on the grid voltage—both result in raising the grid voltage. Hence in this work, it is assumed that when the ESS discharges, it also sources reactive power and vice versa. In this work, the following sign conventions were followed:

- Discharge corresponds to real power discharge, and has a positive sign.
- Charge corresponds to real power charge, and has a negative sign.
- Sourcing of reactive power is the same as generation of reactive power, which is the same as capacitive vars, and has a positive sign.
- Sinking of reactive power is the same as consumption of reactive power, which is the same as inductive vars, and has a negative sign.
- During discharge, the ESS sources capacitive vars.
- During charge, the ESS sinks inductive vars.
- Reactive power is denoted by the Institute of Electrical and Electronics Engineers (IEEE) convention var.

4.0 Discussion of Various Issues

The work reported here is a continuation of work started in 2012 related to duty cycles and performance metrics developed for multiple applications. This work enhances the 2016 Protocol by covering two new applications. Our practice has been to include in the working group anyone interested in participating. In fiscal year 2017 (FY17), emails were sent out to the stakeholders that participated in past efforts associated with the development of the Protocol and to newly identified stakeholders. Those who chose to participate in this working group are listed below:

Name	Organization
Lorraine Akiba	Hawaii State Government
Md Jan E Alam	Pacific Northwest National Laboratory
Gabriel Andaya	Southern California Edison
Jorge Araiza	Southern California Edison
Md Arifujjaman	Southern California Edison
Demy Bucaneg	Hawaiian Electric
David Chambers	California Energy Commission
Mohit Chhabra	ABB
Larry Conrad	Conrad Technical Services
Alasdair J Crawford	Pacific Northwest National Laboratory
Robert Favela	El Paso Electric
Ryan Franks	CSA Group
Mike Gravely	California Energy Commission
Prajwal Gautam	Southern California Edison
Jay Holman	Venture to Market
Paul Leufkens	Consultant
Roger Lin	NEC Energy Systems
Brian Marchionini	National Electrical Manufacturers Association
Jim Reilly	Consultant
Dave Schoenwald	Sandia National Laboratories
Joe Steiber	Consultant
Bert Taube	Southern Research
Vilayanur V Viswanathan	Pacific Northwest National Laboratory
Brittany Westlake	Electric Power Research Institute
Gina Yi	Hawaii State Government

Biweekly hourly webinars (a total of about 15) were held to discuss pertinent issues and develop duty cycles and metrics. Meeting notes were provided in a constantly updated document that included action items. The host started each meeting by presenting a summary of work done to date and checking on the status of action items. The host also described the path forward and encouraged participants to have an interactive discussion. The last 20 minutes were allocated for questions, suggestions, and input from working group members. Various issues were discussed during the biweekly meetings. Some of the issues/items discussed, along with their resolution, are listed below.

1. The duty cycle for frequency regulation varies with location. For example, the California Independent System Operator (CAISO) may have a different duty cycle than the PJM duty cycle. It was decided that for this work, the duty cycle for frequency regulation developed in the initial release of the U.S. Department of Energy (DOE), Office of Energy-sponsored ESS Performance Protocol and retained in the 2016 Protocol [5] will continue to be used.

2. Regarding the var related duty cycle, a recent CAISO straw proposal [6] provides some minimum power factor values for synchronous and asynchronous assets. Hence, it was proposed that the ESS power factor has to be within the range proposed in the CAISO straw proposal. The working group agreed that this restriction did not apply to the ESS for the purpose of this document, because it is simply responding to commands from the system operator for real and reactive power input/output based on system needs.

3. Concerns were expressed about how the duty cycles will affect the grid frequency and voltage in a non-stiff grid such as the ones in Hawaii. Hence, it is important to know how this duty cycle will affect the grid parameters such as frequency and voltage. The working group agreed that was out of the scope of this work. The duty cycles described here are generic; they are simply intended to obtain relevant metrics from the ESS subject to these duty cycles. Of course, with multiple storage assets participating, the grid frequency and voltage will be affected. In fact, that is the purpose—to respond to signals from the system operator who sends signals to the ESS in order to keep the grid parameters within an acceptable range.

4. It was proposed that instead of limiting the maximum apparent power to 0.8 times the ESS rated power, the ESS be exercised at its rated power during operation. The working group agreed that it is not very realistic for an ESS to be at 100% of rated apparent power continuously. Hence, limiting the maximum apparent power to 0.8 times rated power was a good compromise. Those who want to use higher multiples of rated power may do so in addition to what is required in this duty cycle, and simply report this multiple in the test results (e.g., the result from this duty cycle and then the result from the alternative duty cycle along with the higher rated power used).

5. It was pointed out that there are some instances when the ESS vars should be capacitive during over-generation by solar photovoltaic (PV) located downstream of a substation. The voltage at the PV Point of Common Coupling (PCC) with the grid has to be higher than the substation voltage for power to flow toward the substation. Hence the PV power factor needs to be less than 1 so that capacitive vars are sourced at the PV PCC. This is an example of capacitive vars needed when there is over-generation. The working group agreed this could be a specific case where the PV is significantly downstream of the substation, thus requiring capacitive vars to boost its voltage. If the PV has storage integrated with it, this situation would probably be mitigated, because the storage can be used to absorb excess generation. It is only when the storage is fully charged that the voltage at the PCC needs to be higher, thus requiring capacitive vars. It was decided that the direction of vars can be reversed and recorded accordingly if appropriate for the specific user/location. However, when there is over-generation, the voltage at the point of over-generation automatically is expected to rise, and power flow is directed toward loads that are connected to the grid at lower voltage. Hence, this discussion appears to be moot.

6. It was pointed out that there have been instances when grid voltage collapsed while grid frequency increased. The increase in frequency would have required a charge of the ESS, while voltage collapse would have necessitated sourcing capacitive vars. Hence, it may not be appropriate to assume that charging the ESS is always accompanied by sinking vars. The group agreed that this is a special case. It was hypothesized that when the voltage collapsed, there was load shedding to counter the collapse by removing inductive vars to boost voltage. An unintended effect was to decrease the load. This could have had a cascading effect as more load was shed, resulting in a spike in frequency. Based on this, it appears that if sufficient capacitive vars was available, the grid voltage collapse could have been prevented. This would prevent the need for load shedding, ensuring that grid frequency did not spike. Had this approach been taken, the voltage collapse could possibly have been avoided. Hence, it was decided that the ESS would source vars while discharging and sink vars while charging.

7. Additional discussions took place on denying connections for storage on the distribution side if the storage sources vars while discharging. Hawaii Electric, for example, requires rooftop solar PV to consume vars while providing watts. Effective as of 2016, all new connections must have vars go in the opposite direction of watts at all times. The working group agreed that while this is applicable to

PVs, once storage is integrated with PV, it absorbs excess generation, thereby avoiding frequency excursions on the high side. Also, storage is used in isolation (not always next to PV) for a myriad of use cases of applications. For example, when there is excess load in the grid, it is likely that the local voltage will be low. Hence, providing real power (discharge) to the grid while also sourcing vars (capacitive) would make sense.

8. There was some discussion about including vars with frequency response. The team felt this is simply a special case of vars with peak shaving, so this was not pursued.

5.0 Definition of Each Use Case

Use cases for which duty cycles are developed in this document are defined and explained below.

5.1 Frequency Regulation with var Support

This use case intends to deploy the available var capacity of an ESS to source or sink var as necessary at the same time it is discharging or charging to provide frequency regulation service. During a frequency regulation duty cycle, when an ESS discharges to counter under-generation, the ESS also sources vars, and when the ESS charges to counter excess generation, it also sinks var. This enables maintaining the grid frequency within the required frequency range, while providing voltage support in the required direction.

5.2 Peak Shaving with var Support

This use case intends to deploy available var capacity of an ESS to meet the reactive power demand at a specific location in the circuit, at the same time it provides peak shaving services by discharging stored energy. Depending on the application, the peak that will be shaved by the ESS could be load peak or generation peak. During periods when the ESS is required to discharge to shave load peaks, the ESS simultaneously sources vars, and during periods of charging when there is excess generation, the ESS simultaneously sinks vars. This enables aiding the grid voltage in the direction necessary (e.g., increasing voltage during peak load and reducing voltage during excess generation). This application could also provide congestion relief by alleviating the requirement to import vars from an upstream network during a peak load period, thereby releasing capacity and reducing congestion of the upstream transmission system by avoiding vars generation.

The above definitions and the duty cycles that follow are simply representative duty cycles. They are not intended to represent all situations that may occur in the grid. As previously covered, the purpose of establishing representative duty cycles is to facilitate the comparison of different ESSs on a uniform basis.

6.0 Duty Cycles Development

This section describes the methodologies used for developing representative duty cycles for each application. The duty cycles developed will not cover all cases in the real world, but they are expected to cover the type of signals an ESS would be subjected to while being used to provide the services under consideration.

6.1 Duty-Cycle Development for Frequency Regulation with var Support

The duty cycles are developed by varying the var output of the inverters according to a given constraint. Duty-cycle values are determined using a per unit (p.u.) system, where +/-1 p.u. is simply +/- the rated or maximum power of the ESS. Hence, the duty cycles can be used for different sizes of ESSs. Two scenarios were considered as outlined below.

1. In the first scenario, reactive power was controlled to be equal to real power. Therefore, the power factor remains fixed at 0.707. The apparent power was limited to 0.8 p.u., to prevent the ESS being at rated power continuously for the 24-hour duration of the duty cycle. Per unit, as stated above, is simply the normalized rated power of the ESS. Hence, if the ESS rated power is 10 MW, one p.u. is 10 MW. Note that for the frequency regulation duty cycle, the duty-cycle power varies between +/- 1 p.u. In this duty cycle, the apparent power is constant, because the power factor is fixed at 0.707. Active power of the ESS, denoted by P_{ESS}, is controlled according to a predefined frequency regulation signal developed by the Frequency Regulation Working Group of the DOE-sponsored effort, leveraging work previously done by Sandia National Laboratories, that varies from +1 to -1 and is denoted using P_{FRS} in this document. To impose the apparent power limit, P_{ESS} is determined by multiplying P_{FRS} by 0.8 and the fixed power factor (0.707). ESS var output, Q_{ESS}, is equal to the active power as shown in Equation (1). It is assumed that when the ESS is discharged, it also sources reactive power, and when it is being charged, it sinks reactive power. Discharge power and sourcing of reactive power are assigned a positive sign, while charge power and sinking of reactive power are assigned a negative sign in this document. Hence, the sign of var is the same as the sign of real power throughout this document.

$$Q_{ESS} = P_{ESS} = (0.8 \times P_{FRS}) \times 0.707 \tag{1}$$

2. In the second scenario, Q_{ESS} is fixed at 0.3 p.u. and, similar to scenario 1 above, the apparent power is not allowed to exceed 0.8 p.u. P_{ESS} is determined from the frequency regulation signal P_{FRS} in such a manner that the 0.8 p.u. apparent power limit is not violated. This is expressed in Equation (2) below.

$$\begin{aligned} Q_{ESS} &= 0.3 \\ P_{ESS} &= P_{FRS} \times \sqrt{0.8^2 - Q_{ESS}{}^2} \end{aligned} \tag{2}$$

The duty cycles for frequency regulation with var based on these two scenarios are shown in Figure 1 and Figure 2 below.

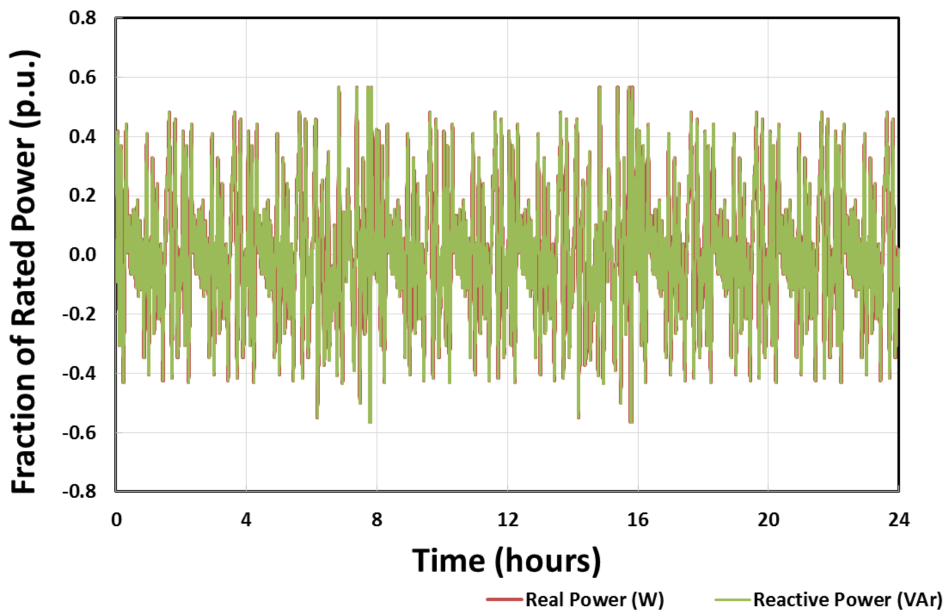


Figure 1. Frequency regulation with var support duty cycle 1; fixed PF of 0.707 (real = reactive), maximum apparent power 0.8 p.u.

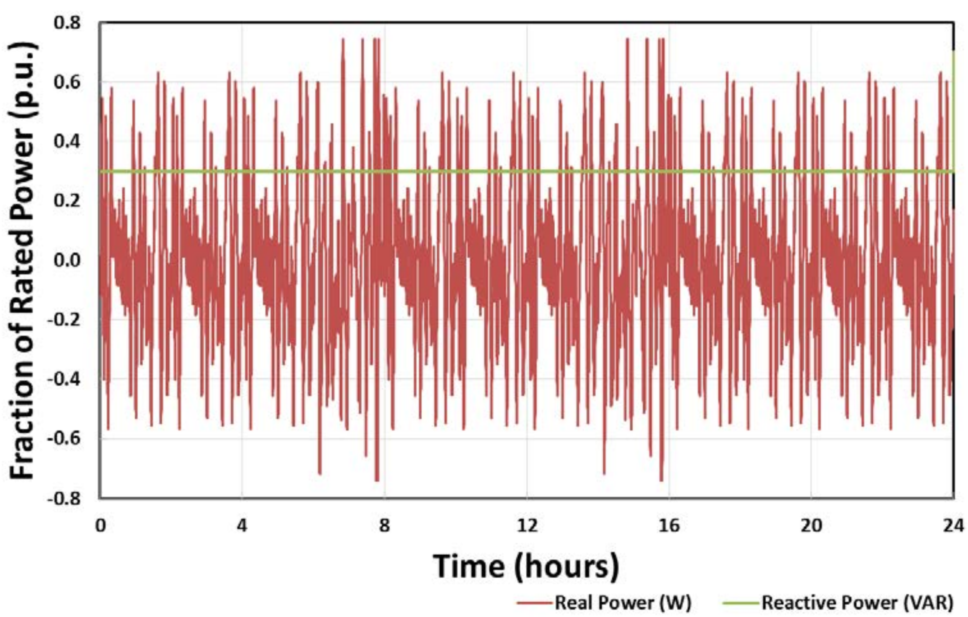


Figure 2. Frequency regulation with var support duty cycle 2; vars = 0.3 times rated apparent power, maximum apparent power for this duty cycle = 0.8 times rated apparent power.

6.2 Duty-Cycle Development for Peak Shaving with var Support

These duty cycles are developed by constraining var output using a limit on the apparent power and setting the charging and discharging rates at a given value. Two cases were considered[1] as outlined below. The resulting duty cycles are shown in Figure 3 and Figure 4.

3. In the first scenario, discharging (denoted using $P_{ESS\text{-}D}$) is performed at the $P_R/2$ rate for 2 hours and charging (denoted using $P_{ESS\text{-}C}$) is performed at the $P_R/4$ rate for 5 hours (to account for round trip efficiency <1), where P_R is the ESS rated power. Apparent power is limited to 0.8 p.u. The var outputs of the ESS during discharge and charge operation, denoted using $Q_{ESS\text{-}D}$ and $Q_{ESS\text{-}C}$, respectively, are determined using Equation (3) below.

$$Q_{ESS-D} = \sqrt{0.8^2 - P_{ESS-D}{}^2}$$
$$Q_{ESS-C} = \sqrt{0.8^2 - P_{ESS-C}{}^2} \quad . \tag{3}$$

4. In this scenario, discharging and charging power/duration are the same as the first scenario (C/2 rate discharge, C/4 rate charge), apparent power is limited to 0.8 p.u. during discharge operation only, and the power factor during charging operation is assumed to be equal to the power factor during discharge operation. This is expressed in Equation (4) below.

$$Q_{ESS-D} = \sqrt{0.8^2 - P_{ESS-D}{}^2}$$
$$Q_{ESS-C} = \sqrt{\left(\frac{0.8P_{ESS-C}}{P_{ESS-D}}\right)^2 - P_{ESS-C}{}^2} \tag{4}$$

The derivation for Equation (4) for $Q_{ESS\text{-}C}$ is given below.

During discharge, the power factor PF_D is given by Equation (5).

$$PF_D = \frac{P_{ESS-D}}{0.8} \tag{5}$$

During charge, the power factor PF_C, is given by Equation (6).

$$PF_C = \frac{P_{ESS-C}}{S} \tag{6}$$

where S is apparent power.

Because the power factor for charge and discharge are equal, setting Equation (5) equal to Equation (6), S can be expressed as shown in Equation (7).

[1] Duty cycles presented in this document source var when active power is discharged from the ESS and sink var when active power is used to charge the ESS. During Working Group 2 meetings, special cases were discussed when it may be necessary to perform the opposite action (e.g., sinking vars when discharging from ESS). These duty cycles could be produced by slight modifying the duty cycles presented in this document. For example, changing the sign of var in the presented duty cycles can meet the requirement of a duty cycle that sinks var during active power discharge.

$$S = \frac{0.8 \times P_{ESS-C}}{P_{ESS-D}} \quad (7)$$

It should be noted that the duty cycles shown in Figure 3 (top) and Figure 4 (top) correspond to an ESS energy-to-power ratio (E/P) of 1. When E/P > 1, the discharge duration has to be increased to fully exercise the ESS across its state of charge (SOC) range. For example, at E/P = 2, the discharge duration is doubled relative to the duration for E/P = 1, as shown in Figure 3 and Figure 4 (bottom).

When E/P < 1, the rated power is set equal to the rated energy to avoid over-discharging or over-charging the ESS. Subsequent calculations are done in the same manner as for the E/P = 1 case. The duty cycle looks the same as for E/P = 1 once the power is derated to be equal in magnitude to the rated energy. Hence, this duty cycle is not shown separately.

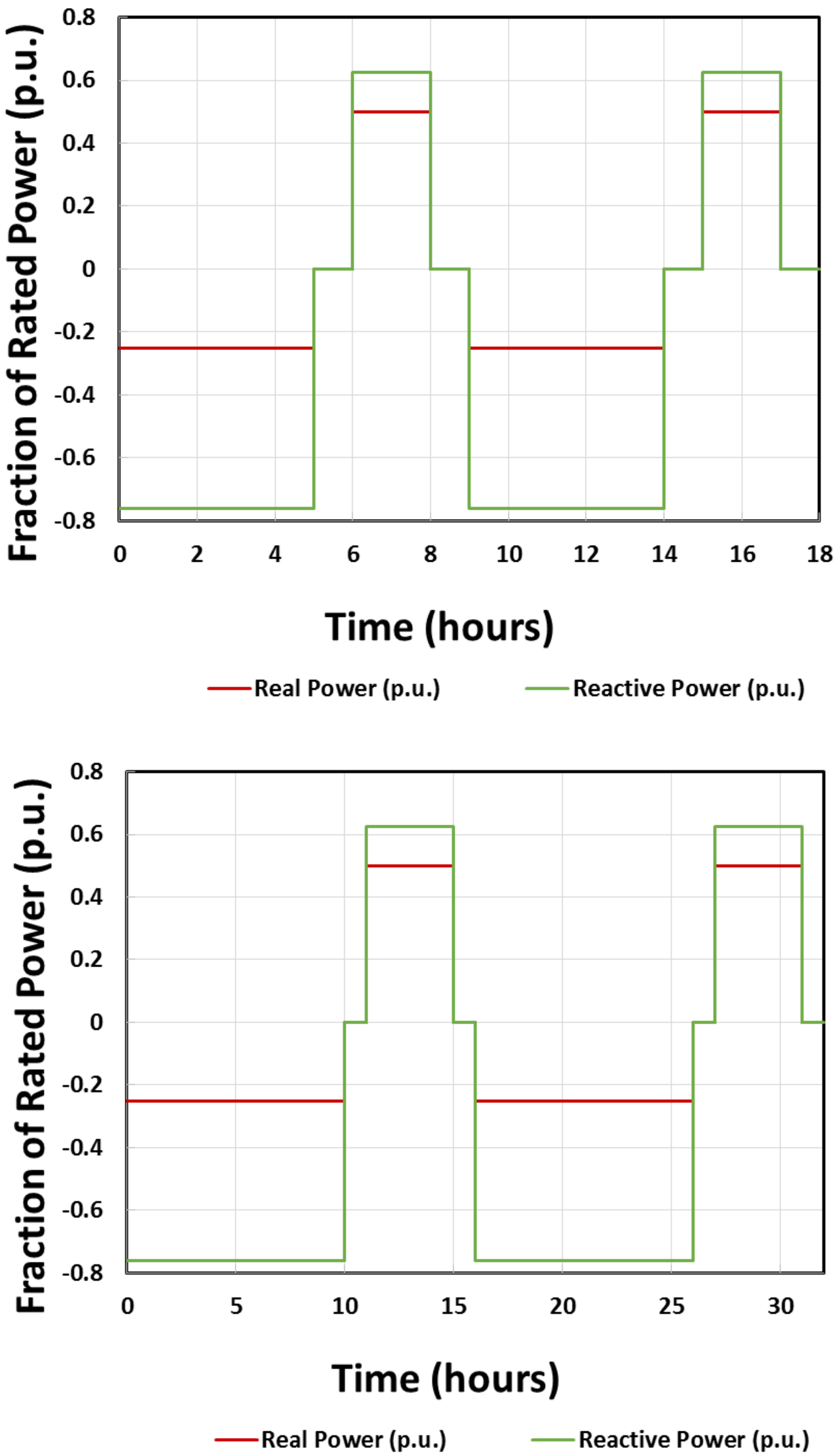
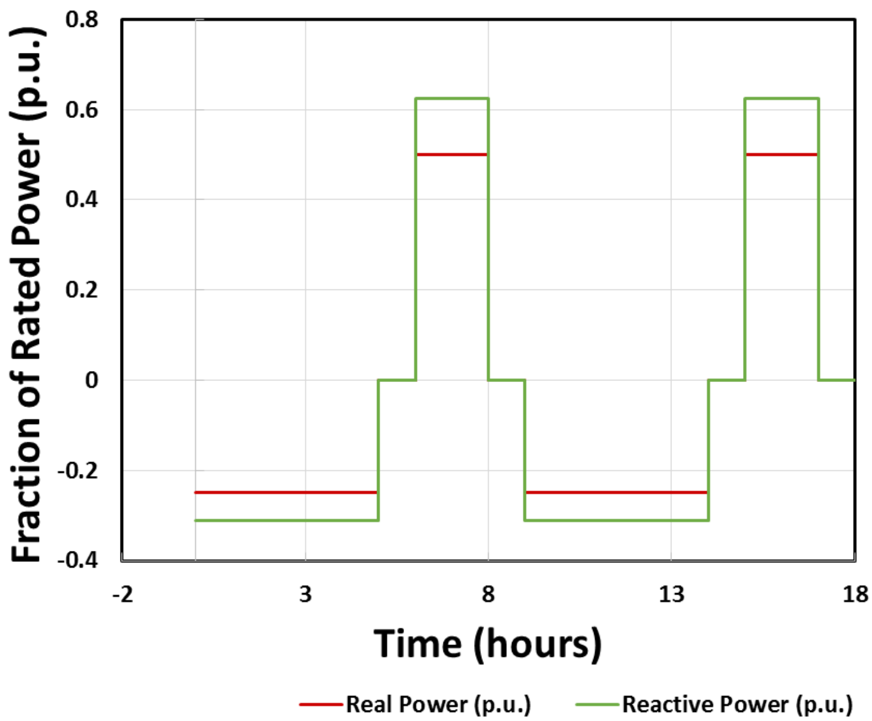


Figure 3. Peak shaving with var duty cycle 1; C/2 rate discharge, C/4 rate charge, maximum apparent power 0.8 p.u. (top) E/P = 1, (bottom) E/P = 2. For E/P < 1, the duty cycle looks identical to E/P = 1 once the power is derated to be equal in magnitude to the rated energy.



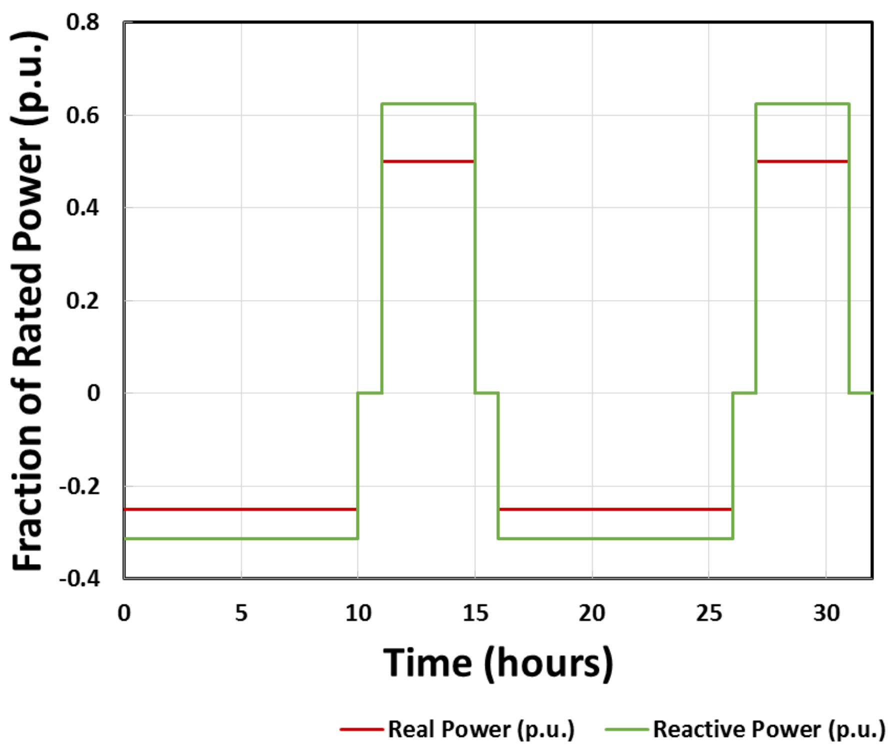


Figure 4. Peak shaving with var support duty cycle 2; C/2 rate discharge, C/4 rate charge, maximum apparent power 0.8 p.u. during discharge, power factor during charge set equal to power factor during discharge (top) E/P = 1, (bottom) E/P = 2. For E/P < 1, the duty cycle looks identical to E/P = 1 once the power is derated to be equal in magnitude to the rated energy.

7.0 Metrics

The metrics used in these applications will be a combination of the ones already developed to date in the 2016 Protocol and any modifications or additions to them as developed by the working group and described in this document.

7.1 Metrics for Frequency Regulation with var Support

The metrics used for performance assessment of ESSs while providing frequency regulation and var support are specified in Table 1 and Table 2. Development of these metrics involve assessment of how different ESS parameters (e.g., efficiency, SOC, energy capacity) are affected when subjected to a duty cycle. Metrics are also defined to assess the ESS capability to track the power commands contained in the imposed duty cycle.

Table 1. Metrics for Frequency Regulation with vars.

Metric	Description
Duty-cycle Round Trip Efficiency AC RTE (Section 5.4.1 [Viswanathan 2016] with and without auxiliary power)	The useful energy output from an ESS divided by the energy input into the ESS over the duty cycle for this specific application expressed as a percentage. The energy to bring the ESS final SOC to the initial SOC is taken into account.
Reference Signal Tracking (RST) (this metric from the 2016 Protocol has been modified and is described in Section 7.2 below)	The ability of the ESS to respond to a reference signal.
State of Charge Excursions (SOCx) (Section 5.4.3 [Viswanathan 2016])	The maximum and minimum SOC attained by the ESS during the execution of the duty cycle.
Energy Capacity Stability (Section 5.4.4 [Viswanathan 2016])	The measured energy capacity at any point in time as a percent of the initial measured energy capacity

7.2 Modified Metrics for Reference Signal Tracking

A set of modified metrics has been established to evaluate the performance of an ESS in tracking the reference signal of the imposed duty cycle. The modified metrics are described in Table 2.

Table 2. Modified metrics for reference signal tracking.

Metric	Mathematical Expression	Example
Root Mean Square Error (RMSE) of the signal (with and without auxiliary power)	$\text{RMSE} = \sqrt{\frac{\sum_{i}^{n}\left(X_{Ri} - X_{Si}\right)^2}{n}}$	Assume RMSE is 20 kW, the rated power is 1000 kW. The RMSE as a percent of rated power = 20 kW/1000 kW = 0.2 or 2%

Table 2. (contd)

Metric	Mathematical Expression	Example
Normalized RMSE (NRMSE) (with and without auxiliary power)	$\text{NRMSE} = \dfrac{\text{RMSE}}{\left(\dfrac{\sum \lvert X_{Si} \rvert}{n}\right)}$	Assume average of the absolute value of the signal is 200 kW. Normalized RMSE = 20 kW/200 kW = 0.1 or 10%
Mean Absolute Error of the Signal (MAE_S), calculated with and without auxiliary power.	$\text{MAE}_\text{S} = \dfrac{\sum_{i=1}^{n} \lvert X_{Ri} - X_{Si} \rvert}{n}$	
Mean Absolute Error in the Energy (MAE_E) under the signal curve, calculated with and without auxiliary power.	$\text{MAE}_\text{E} = \dfrac{\sum_{j=1}^{n_X} \lvert E_{Rj} - E_{Sj} \rvert}{n_X}$	
Percentage Signal Tracked (PST) is the percentage of responses whose deviation from signal satisfy the following criteria: a) <1% of signal b) <10% of signal c) <2% of rated power PST will be calculated with and without auxiliary power.	$\text{PST}_{1\%\text{S}} = \dfrac{n_{1\%\text{S}}}{n}$ $\text{PST}_{10\%\text{S}} = \dfrac{n_{10\%\text{S}}}{n}$ $\text{PST}_{2\%\text{P}} = \dfrac{n_{2\%\text{P}}}{n}$	

where,

- X_{Si} = the *i*-th data point in the signal;
- X_{Ri} = the *i*-th data point in the response;
- n = the number of data points in the signal;
- E_{Sj} = the energy under the *j*-th segment of the signal curve;
- E_{Rj} = the energy under the *j*-th segment of the response curve;
- n_X = the number of X axis crossings of the power signal; and,
- $n_{<1\%\text{S}}$, $n_{<10\%\text{S}}$, and $n_{<2\%\text{P}}$ = number of data points in the signal satisfying the criteria of less than 1% of signal, less than10 % of signal, and less than 2% of rated power, respectively.

The "less than 1% of signal" criterion for the Percentage Signal Tracked metric in Table 2 might be too aggressive. Therefore, the "less than 10% criterion" was proposed. In the context of a signal tracking metric based on rated power, it is noteworthy that a draft revision of IEEE 1547 (April 2017) allowed an accuracy level of ± 5% of rated power for both active and reactive power. Tighter accuracy measurement requirements are needed to fully gain the benefit for the fast responding ESS.

The same metrics described above apply to reference signal tracking for vars, except there is no need to do the calculations without auxiliary power.

7.3 Metrics for Peak Shaving with var Support

The metrics used for performance assessment of the ESS while providing peak shaving and var support are specified in Table 3.

Table 3. Metrics for peak shaving with var support.

Metric	Description
Duty-cycle Round Trip Efficiency AC RTE (Section 5.4.1 [6]) (with and without auxiliary power)	The useful energy output from an ESS divided by the energy input into the ESS over the duty cycle for this specific application expressed as a percentage. The energy to bring the ESS final SOC to the initial SOC is taken into account.
Reference Signal Tracking (RST) for vars (this metric from the 2016 Protocol has been modified and is described in Section 7.2 above)	The ability of the ESS to respond to a reference signal.
State of Charge Excursions (SOCx) (Section 5.4.3 [6])	The maximum and minimum SOC attained by the ESS during the execution of the duty cycle.
Energy Capacity Stability (Section 5.4.4 [6])	The energy capacity at any point in time as a percent of the initial energy capacity.

8.0 References

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