Development of a Frequency Regulation Duty-Cycle for Standardized Energy Storage Performance Testing

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Abstract

The US DOE protocol for uniformly measuring and expressing the performance of energy storage systems, first developed in 2012 through inclusive working group activities, provides standardized methodologies for evaluating an energy storage system's ability to supply specific services to electrical grids. This article elaborates on the data and decisions behind the duty-cycle used for frequency regulation in this protocol. Analysis of a year of publicly available frequency regulation control signal data from a utility was considered in developing the representative signal for this use case. This showed that signal standard deviation can be used as a metric for aggressiveness or rigor. From these data, we select representative two hour long signals that exhibit nearly all of dynamics of actual usage under two distinct regimens, one for average use and the other for highly aggressive use. These results were combined into a 24-hour duty-cycle comprised of average and aggressive segments. The benefits and drawbacks of the selected duty-cycle are discussed along with its potential implications to the energy storage industry.

Keywords: energy storage, performance, frequency regulation, testing, duty-cycle

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Nomenclature

ACE - Area Control Error

AGC - Automated Generation Control

DC - Direct Current

5 DOD - Depth of Discharge

DOE - United States Department of Energy

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

Duty-Cycle - a time-series of system usage or input commands that can be applied to
10 generate performance metrics

EPA - United States Environmental Protection Agency

Frequency Regulation - a service that dampens the momentary fluctuations in grid
frequency caused by the difference between load and supply (see also AGC)

IEC - International Electrotechnical Commission

15 ISO - Independent System Operator

ESS - Energy Storage System

PNNL - Pacific Northwest National Laboratory

Point-to-Point Mileage - positive differences between consecutive commands in a time
series

20 ptp - shorthand notation for point-to-point

Mileage - a rolling sum of the point-to-point mileage for a giving time period (an integer
multiple of average point-to-point mileage)

MW - Megawatt

NERC - North American Electric Reliability Corporation

25 FERC - Federal Energy Regulatory Commission

PJM - (Pennsylvania Jersey Maryland) PJM is an RTO that manages the flow of electric
power across 13 states and the District of Columbia.

PSD - Power Spectral Density

p.u. - shorthand notation for “per-unit,” used here for a unit of power which is normal-
30 ized to the maximum rated power of an energy storage device

RTO - Regional Transmission Operator

σ - standard deviation

SNL - Sandia National Laboratories

SOC - State of Charge

35 1. Introduction

In 2012, the Energy Storage Systems (ESS) Program of the U.S. Department of Energy organized the development of a Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems (DOE Protocol) [1]. This effort, undertaken by Sandia National Laboratories (SNL) and Pacific Northwest National Laboratory (PNNL), brought together over 50 industry stakeholders and organizations with the purpose of developing best practices for analyzing and communicating ESS performance. While ESS are capable of providing many services in support of the electric grid [2], this protocol was focused, at first, on just two: peak shaving, and frequency regulation. The protocol has since undergone three revisions adding Microgrids and PV Smoothing to its list of use cases. The group sought to develop a frequency regulation duty-cycle allowing for performance comparisons based on real-world usage requirements. The process developing this duty-cycle was documented, in brief, in a normative appendix of the DOE Protocol. A more detailed explanation of intermediate findings and motivations that drove selection of the frequency regulation duty-cycle could be beneficial to the ongoing work updating the DOE Protocol and to standards bodies now considering adoption of some or all of the tests it outlines

Frequency regulation is a service that dampens the momentary fluctuations in grid frequency caused by the difference between load and supply [2]. In the US, the North American Electric Reliability Corporation’s (NERC’s) Real Power Balancing Control Performance (BAL001) and Disturbance Control Performance (BAL002) are examples of standards that require balancing authorities to operate such that frequency doesn’t deviate too far from the scheduled set point (nominally 60Hz in the US) [3, 4]. This is done through tracking and placing limits on Area Control Error (ACE). The calculation for ACE is shown in Equation 1. These requirements, common in many countries [5, 6],

60 enable regulators to impose fines on balancing authorities shown to be out of compliance. To avoid fines and properly manage grid frequency, balancing authorities place contracts with generation assets to secure the needed flexibility. Sometimes this is done through an open market [7]. Assets providing frequency regulation are configured to respond to a modified ACE signal, giving balancing authorities the control to maintain
65 ACE compliance.

$$ACE = (NIA - NIS) - 10B(FA - FS) - IME \quad (1)$$

Adapted from [3] Where:

NIA - the algebraic sum of actual power flows on all tie lines.

NIS - the algebraic sum of scheduled power flows on all tie lines.

70 B - the Frequency Bias Setting (MW/0.1 Hz) for the Balancing Authority. The constant factor 10 converts the frequency setting to MW/Hz.

FA - the actual frequency.

FS - the scheduled frequency. FS is normally 60 Hz (in the US) but may be offset to effect manual time error corrections.

75 IME - the meter error correction factor typically estimated from the difference between the integrated hourly average of the net tie line flows and the hourly net interchange demand measurement (megawatt-hour). This term should normally be very small or zero.

Fast responding assets, such as many types of ESS, are able to provide more effective
80 frequency regulation (per MW) than slow responding assets by following changes in the control signal more accurately. In an extensive study of California frequency regulation resources, Makarov et al reported that 1 MW of an ideal fast responding regulation asset, with instantaneous response and infinite energy, provides roughly the same impact as 1.7 MW of regulation supplied by hydro power, 2.7 MW of regulation supplied by
85 combustion turbines, or 29 MW of regulation supplied by steam turbine or combined-cycle units [8]. Findings such as these contributed to the US Federal Energy Regulatory Commission's (FERCs) decision to issue order 755 "Pay for Performance." This requires Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs), two types of balancing authorities, within FERC jurisdiction to pay assets for

90 frequency regulation based on capacity they provide for flexible operation (in MW) and
their performance [9]. Performance in this context is composed of the mileage (the ab-
solute change in the control signal) and the accuracy of the asset’s response. Response
delays, finite energy, and other non-ideal operational limits generate errors in how closely
the asset follows the control signal. Inaccuracy reduces the mileage payment and hence
95 the asset’s economic performance. This presents a challenge in predicting the accuracy of
an undeployed ESS as the effects of non-ideal operational limits are difficult to reproduce
in a laboratory setting. A representative duty-cycle is one way to overcome this challenge
and make accurate performance predictions based on representative laboratory data.

The goal of selecting a duty-cycle was to enable testing labs to expose an ESS to
100 the demands of providing frequency regulation in order to predict ESS economic perfor-
mance, and compare different ESS designs using service relevant factors. At any given
time ESS are limited in their available power and energy on both charge and discharge.
These limits, as well as those imposed by response delay and thermal management, may
prevent a real-world design from following a command signal with perfect accuracy. Ad-
105 ditionally, as the storage medium (e.g. batteries) can be subject to self-discharge and
round trip efficiency losses, the commanded signal is often modified to maintain long term
State of Charge (SOC). An effective duty-cycle would need to expose how these factors
affect tracking error performance. This paper presents the analysis of publicly available
frequency regulation control signal data and its subsequent use in the development of a
110 duty-cycle that was created for the DOE Protocol.

2. Methods

This section is broken into two parts: the methods used to analyze available frequency
regulation data and the methods used in the development of the duty-cycle.

2.1. Methods for Frequency Regulation Data Analysis

115 There are a number of metrics that can be used to sort and process frequency reg-
ulation control signal data. Statistical metrics, minimum; mean (μ); maximum; and
standard deviation (σ), were obtained by processing data from each day in a sample
year. Statistical metrics were also obtained for the signal’s point-to-point mileage which

is a time record of the positive differences between consecutive commands. Mileage,
 120 which is used in some balancing authority's performance/payment calculation, represents the rolling sum of the point-to-point mileage for a given time record [10]. A time record's μ and σ can be calculated according to Equation 2. From the statistical metrics calculated for all of the available days, the year's lowest metrics, average metrics, highest metrics, and the standard deviation of these metrics were identified.

125 The frequency spectrum of the time record can be determined using the discrete Fourier transform. The relevant formulation of this transform is shown in Equation 3. Also, the Power Spectral Density (PSD) can be obtained through Equation 4. The PSD is a series of real numbers that represent the power at each frequency [11]. The PSD is obtained for all available days and then averaged to obtain a mean PSD. This process
 130 attenuates the effects of signal noise clarifying subtle patterns in the data.

$$\mu = \frac{1}{N} \sum_{n=1}^N x(n) \quad \sigma = \sqrt{\frac{1}{N} \sum_{n=1}^N |x(n) - \mu|^2} \quad (2)$$

$$X(k) = \frac{1}{N} \sum_{n=1}^N x(n) e^{\frac{-j2\pi(k-1)(n-1)}{N}}$$

$$f(k) = \frac{nf_s}{2} \quad \forall n \in 1 \leq \mathbb{Z} \leq N \quad (3)$$

$$T(k) = \frac{1 \text{ hour}}{(3600 \text{ seconds})} \frac{1}{f(k)} \quad \forall k \in 1 \leq \mathbb{Z} \leq N$$

$$PSD(k) = |X(k)|^2 \quad \forall k \in 1 \leq \mathbb{Z} \leq N \quad (4)$$

Where:

μ - mean

σ - standard deviation

135 X - frequency spectrum (p.u. complex power)

x - time record control signal (p.u. power)

N - number of samples in the time record

n - independent discrete time domain variable

k - independent discrete frequency domain variable

140 $\mathbb{Z}$ - set of all integers

f - frequency (Hz)
 f_s - sample frequency (Hz)
 T - period (hours)
 PSD - Power Spectral Density (p.u. power²)

145 2.2. Methods for Duty-Cycle Development

To derive an energy storage device's round-trip-efficiency it must start and end a test at the same SOC. This requirement, to charge and discharge the device in equal measure, imposes a requirement for the duty-cycle to be "energy neutral." Equation 5 shows the optimization statement for finding the most energy neutral segment of length M , starting
 150 at point I , in an N length time record of frequency regulation control signal data. This statement can be read as follows: choose I , out of the set of integer values between 1 and N inclusive, such that the objective function is minimized. This optimization is used in Section 4 to find the most energy neutral 2-hour segment within a number of days which exemplify average and aggressive control signal requirements.

$$\underset{I \in \{1 \leq \mathbb{Z} \leq (N-M)\}}{\text{minimize}} \quad \left| \sum_{n=I}^{I+M} x(n) \right| \quad (5)$$

155

Where:

x - time record control signal (p.u. power)
 N - number of samples in the time record
 n - independent discrete time domain variable
 160 I - discrete time domain variable which denotes the start of the period
 $\mathbb{Z}$ - set of all integers
 M - number of samples in the period

3. Frequency Regulation Data Analysis

At the time of the DOE Protocol's development, one source of publicly available data
 165 on frequency regulation, and the most comprehensive we found, was PJM. Short for "Pennsylvania, New Jersey, Maryland," the three states where it is most prevalent; PJM is an US RTO that manages the flow of electric power across 13 states and the District

of Columbia. PJM makes historical ACE based frequency regulation signals, for both fast and slow response assets, available on its website (www.pjm.com). Figure 1 shows the signal for fast responding assets between April 1, 2011 and March 31, 2012. Each vertical slice shows 24 hours of the historical frequency regulation control signal. The 5 days from Dec 15, to Dec 19 were unavailable in this data set and are hence shown as a gap in this and subsequent plots. The signal is normalized to the dynamic range (in MW) provided for frequency regulation resulting in a magnitude between -1.0 and 1.0 p.u. (per unit). Green represents values close to zero, meaning little to no regulation service is being requested. Blue denotes negative values or requested down regulation while red denotes positive values or requested up regulation. Though it takes close inspection, several trends can be observed. Note that these observations are intended only to provide an intuitive sense of the signal’s characteristics and inform the statistical analyses to follow. The summer months, June through August, are lighter (illustrated as a higher concentration of green) than the winter months, December through February, especially in the morning between midnight and 5:00am. Horizontal purple (combined red and blue) lines, examples of which are identified at 5:00am; 6:00am; and 7:00am, indicate predictable demands for frequency regulation at the same time each day. The presence of these lines might indicate that regional load and/or market patterns influence the properties of the frequency regulation control signal. Because of this, we might predict that the frequency regulation control signal in different areas will have very different characteristics. Despite this potential for regional variance, PJM provides a rich data set by which to start characterizing the patterns of use for this service.

The results of a statistical analysis of the sample year is shown in Table 1 listing metrics for both the raw signal and the point-to-point (ptp) mileage. It can be observed that the year’s average mean signal is close to zero; meaning that the signal is energy neutral. The signal’s lowest daily σ of 0.132 is roughly 30% of signal’s highest daily σ of 0.451, which could represent a useful metric in characterizing the range of operation that an ESS may expect when providing this service in this area. Accumulated mileage shows a similar trend. Figure 2 shows the relationship between these metrics with each day’s total mileage plotted against its control signal σ . While it should be recognized that the day with the highest signal σ was not the day with the highest total mileage,

the two metrics are closely correlated.

200 The power spectrum of the PJM frequency regulation control signal can illuminate several useful statistical properties. Figure 3 shows the mean PSD of the full year of data; derived by first computing the PSD of each day according to Equations 3 and 4 and then averaging the resultant spectra. The magnitude of the PSD represents the power of the signal at each period. Periods close to zero hours represent high frequency signal
205 components (up to half the sample frequency of 0.25 Hz). 24 hours is the period which corresponds to the lowest measurable frequency (not including DC) for each day of data. The plot shows the full spectrum (above) while the magnifier window (below) shows only those components with periods shorter than two hours (a.k.a. with frequencies higher than 0.000277 Hz). While a signal's PSD is more often plotted as a function of
210 frequency, it is plotted here as a function of period (which is the reciprocal of frequency) to better illustrate the proportion of the signal's component frequencies which would be represented in a two hour long test. By calculating the area under the power spectrum below two hours and dividing it by the area under the full power spectrum, it can be shown that, on average, 99.9% of the power in each day's signal is composed of
215 components whose periods are shorter than two hours. Distinct peaks in the magnitude of the power spectrum can be observed at periods of 5, 7.5, 10, 12, 15, 19.45, and 30 minutes (shown in the magnified window). These modes of oscillation in the grid's requirements for frequency regulation services likely represent a combination of electromechanical and market forces. This phenomenon, also observable in Figure 1 as horizontal lines, could
220 result from large load or supply changes at specific times such as from timed industrial heating or cooling or the operations of an hourly generation supply market. Note that these factors would be different in areas not served by PJM, and hence the trend may differ or not be observed elsewhere.

To investigate seasonal changes in the PJM frequency regulation signal, an investiga-
225 tion was performed on how σ changed over the year surveyed. Figure 4 shows the daily calculated σ of the signal over the sample year. The lowest value occurs on July 22, and the highest value occurs on December 1. As expected, this metric supports the summer to winter trend observed qualitatively in Figure 1. The histogram of these data, shown in Figure 5, illustrates that its median σ is greater than its average. If it can be inferred

230 that days with a higher σ are more strenuous on non-ideal frequency regulation assets, a skewed histogram such as this means that an asset will more often be following a signal which is closer to its hardest day than to its easiest. The validity of this inference can be tested through a closer look at what low, medium and high σ days look like and what requirements they impose on an ESS.

235 A more detailed analysis was performed on the year’s lowest (July 22, 2011), three closest to the average (June 30, October 18, and February 5, 2012), and highest (December 1, 2011) signal σ days. Figure 6 shows the raw data from these 5 days, and Table 2 shows some of the calculated performance specification metrics. Several observations can be made about the requirements of frequency regulation in PJM from an analysis
240 of these metrics. The total energy required, to be provided (discharged) and consumed (charged) by an asset over a single day, varies by a factor of four between the lowest σ day and the highest. To illustrate this difference an example system is considered. A 10MW, 5MWh ESS providing frequency regulation, assuming the signal is tracked with no error, would need to supply 11 MWh of energy on the lowest σ day, 2.2 full Depth of Discharge
245 (DOD) cycles, and 44 MWh on the highest σ day, 8.8 full DOD cycles. These data support the inference that days with low control signal σ have lower requirements, are less taxing or less aggressive, and days with high control signal σ have higher requirements, are more taxing or more aggressive. These findings are used to inform development of a representative duty-cycle.

250 4. Duty-Cycle Development

A duty-cycle is a time-series control signal that can be applied to a system to generate performance metrics predictive of the system’s future, real-world operation. Unlike characterization, which can be useful for inter-sample comparison but is often removed from any specific use-case, testing using a duty-cycle allows for the measurement of the emer-
255 gent system behaviors that are vital to predicting economic performance. Perhaps the most widely used example of duty-cycle testing is for gas-mileage in automobiles. The US Environmental Protection Agency (EPA) has standardized the time-series driving profile to be used in calculation of “in-city” and “highway” efficiency [12]. In 2012, working groups attempting to develop standardized methods for testing ESS recognized the need

260 for a similar set of use-case specific duty-cycles for performance testing. A duty-cycle for frequency regulation would need to adequately represent this service's requirements while also producing data sufficient to predict the full range of operational performance.

Except for the time that it would take to apply, an ideal duty-cycle would be actual use. The full year of frequency regulation data discussed in Section 3 could be viewed
265 as an ideal baseline. In discussions with various stakeholders, 24 hours was selected as a reasonable maximum period for the duty-cycle that could be applied without greatly increasing the cost of product development and evaluation. The problem then became how to reduce the ideal baseline to a representative day. The most average (mean signal σ day) could be used in its entirety, but this would not provide any predictive metrics
270 on expected performance during aggressive (high signal σ) days. The most aggressive day could be used in its entirety, but this would not allow for accurate measurement of efficiency during average (average signal σ) days. A combination of average and aggressive days was selected to achieve the benefits of each. It is helpful to note that a full day would not be needed for accurate representation as it was calculated in Section
275 3 that 99.9% of the power in the frequency regulation control signal occurs in the range of periods less than two hours. Therefore, two distinct 2-hour segments were selected representing average and aggressive regimens.

The average 2-hour control signal was selected by first identifying the three days with σ closest to the yearly mean σ (0.333). These are denoted as Average Day # 1, # 2, and
280 # 3, shown in Figure 6 (June 30, October 18, and February 5 respectively). Then, the most energy neutral 2-hour section was identified from the 72 hours of available signal, according to the algorithm described in Section 2.2. The σ for this 2-hour section was then compared to the σ for the day it came from to confirm that it did not vary significantly and was not less aggressive than the trend for the day. Similarly, the aggressive 2-hour
285 data set was taken by identifying the day with the highest σ for the year, December 1, also shown in Figure 6. Then, the most energy neutral 2-hour section from that day was selected, according to the algorithm described in Section 2.2. The σ from this section was compared to the σ for the day to confirm it did not vary significantly and was not less aggressive. Table 3 shows some selected statistical metrics for the representative
290 control signals. It can be observed that the aggressive signal has 28% higher energy

throughput but only 12% higher mileage than the average signal. Also note, the average signal spends 40% more time near 0 p.u. (in the range of ± 0.1 p.u.) than does the aggressive signal. A further illustrative comparison between the average and aggressive signal can be seen in Figure 7, where their histograms are overlaid.

295 With these two signals as building blocks the combined duty-cycle was designed by assembling three repetitions of the average signal, followed by a single aggressive signal, three more average signals, one more aggressive signal, and finally four repetitions of the average signal as shown in Table 4. Once assembled, the combined 24-hour duty-cycle is shown in Figure 8. Other combinations were considered (e.g. 2 average signals, 1 aggressive signal, 2 average signals, 1 aggressive signal, 2 average signals, 1 aggressive signal, and 3 average signals) which possess similar merit. A balance was struck by the working group between the number of aggressive signals used in the duty-cycle and the difficulty of the overall duty-cycle. More aggressive signals would generate more data on how an ESS performed under the most difficult conditions but could produce metrics
305 such as efficiency which would not predict average performance.

The full duty-cycle image, shown in Figure 8, is color coded by average and aggressive signals, in which average signal sections are shown in red, and aggressive signal sections are shown in green. The required pre/post-conditioning steps that ensure the ESS starts and ends the test at a designated SOC are not shown. An example of this procedure
310 would be to fully charge the system (known 100% SOC), then discharge the system to prepare for the duty-cycle (e.g. estimated 50% SOC), and then after the duty-cycle is completed, fully recharge the system (known 100% SOC). These additional steps enable the calculation of operational energy efficiency. It is also anticipated the signal will need to be modified to compensate for self-discharge and efficiency losses. Many solutions
315 exist to compensate for system inefficiency, and the ideal method may differ by design. The working group decided not to standardize what schema should be used for this compensation. Figure 8 constitutes the final duty-cycle selected for the DOE Protocol.

5. Discussion

The selected duty-cycle adequately represents expected use and enables the calculation of predictive performance metrics, while not adding substantively to the cost of
320

system development. The 2-hour representative control signals were shown to have periods sufficient to exhibit 99.9% of the frequency components present in each day's control signal. Repeating the same signal several times improves performance measurement accuracy. This practice also allows for calculation of consistency metrics showing if/how a
325 system's performance varies over time. As both the average and aggressive control signal are used, this duty-cycle enables the estimation of average performance metrics as well as the assessment of a system's ability to maintain performance under the most difficult usage conditions.

The utility of this duty-cycle comes with salient critiques. The use of 2-hour representative control signals limits the data collected to only those dynamics at periods shorter
330 than two hours. This may provide an advantage to systems with a low energy to power ratios as they might have lower accuracy when supporting very low frequency signal dynamics which the 2-hour control signals would not include. The unfiltered succession of representative signals may also introduce additional frequency components not seen during
335 real usage. This may make some predictions of real-world performance less accurate as the full 24-hour duty-cycle includes 11 transitions between segments. One method to adjust for this may be to apply the average and aggressive control signals separately, each with pre/post-conditioning. Additionally, using control signal σ as a fully representative metric for aggressiveness may not adequately capture what aspects of real-world
340 operation impose requirements on ESS design. For example, a hypothetical system could be designed to reject sufficient heat to not reach its thermal limits during the application of this duty-cycle, where 20/24 hours are spent in average usage, while not rejecting sufficient heat for nearly six months of sustained above average usage. While there would be some indication of this deficiency during the aggressive control signal portions of the
345 duty-cycle, a detailed analysis and comparison to thermal models would be required to make a determination of adequacy. Environmental conditions and altitude also play a significant role in heat rejection adequacy, both of which would further complicate the thermal models to be validated.

Despite these criticisms, this duty-cycle shows great potential to simplify between
350 sample performance comparisons. Metrics such as tracking accuracy and round-trip efficiency can be calculated and used to directly compare systems and predict economic

performance. It is anticipated that this duty-cycle will be changed over time to incorporate feedback on how well it accomplishes these tasks. Adjustments can be made to identify salient differences between systems and improve performance forecasting. Finally, as markets change and new markets open for energy storage to provide frequency regulation, new duty-cycles may need to be developed if the performance specifications are substantively different than those derived from the 2011/2012 PJM data set used here.

6. Conclusion

Frequency regulation, as an ancillary service, enables grid operators to balance the moment to moment differences between electric load and supply. Energy storage technologies have the potential to provide frequency regulation more effectively than many forms of conventional generation. This is enabled by fast responding power conversion systems and limited by finite energy. To support the appropriate utilization of energy storage providing frequency regulation and other services to the electric grid the US DOE instigated a consensus based process to develop the Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems. It was recognized that a standard frequency regulation duty-cycle would be needed to enable performance comparisons between energy storage systems and technologies (e.g. flywheel to battery).

Development of a standard duty-cycle started with a detailed analysis of publicly available PJM frequency regulation control signal data from April 1, 2011 to March 31, 2012. This analysis determined that signal σ could be used and a metric for aggressiveness or rigor of operation, and that 99.9% of the power in the daily signal is represented in periods shorter than two hours. This enabled the development of a 24 hour duty-cycle from a series of 2-hour representative “average” and representative “aggressive” signals. The representative average signal was selected by finding the most energy neutral two hours within the three days determined to have σ ’s closest to the yearly average signal σ . The representative aggressive control signal was selected by finding the most energy neutral two hours within the day with the highest σ . Both signals were checked to ensure their properties adequately represented the days from which they were selected. The final duty-cycle was composed of the representative control signals performed in the

following order: preconditioning, 3 average signals, 1 aggressive signal, 3 average signals, 1 aggressive signal, 4 average signals, and post-conditioning.

The derivation of this duty-cycle from PJM frequency regulation data was to enable
385 laboratory testing analogous to real-world use and it accomplishes this goal. However,
the performance specifications for frequency regulation will differ in different regions, and
will likely change over time. These PJM data were selected because of their availability,
and because they represented a market in which grid storage had an existing incentive
to participate. The selected duty-cycle will be easy to replicate in a laboratory setting,
390 provides data for the side to side comparison of energy storage technologies, and can help
predict the potential economic performance of undeployed ESS. Future work will apply
this duty-cycle to batteries and energy storage systems.

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Table 1: Statistical Metrics for PJM Frequency Regulation Control Signal

	Daily Signal Min	Daily Signal Mean	Daily Signal Max	Daily Signal σ	Daily ptp Mileage Min	Daily ptp Mileage Mean	Daily ptp Mileage Max	Daily ptp Mileage σ
Years Low- est	-1.000	-0.015	0.607	0.132	0.000	0.009	0.057	0.008
Years Aver- age	-0.994	0.000	0.993	0.333	0.000	0.017	0.193	0.015
Years High- est	-0.578	0.007	1.000	0.451	0.000	0.022	0.800	0.023
Years σ	0.034	0.002	0.038	0.057	0.000	0.002	0.101	0.003

Table 2: Performance Specification Metrics for PJM Frequency Regulation Control Signal

Metric	Units	Lowest σ Day	Most Aver- age σ Day 1	Most Aver- age σ Day 2	Most Aver- age σ Day 3	Highest σ Day
Signal σ	p.u. power	0.132	0.334	0.332	0.333	0.451
Mileage	p.u. power	185.872	388.964	378.752	386.552	426.359
Energy Dis- charged	p.u. en- ergy (ESS Cycles)	1.163	3.064	3.023	3.126	4.408
Energy Charged	p.u. en- ergy	1.169	3.068	3.061	3.169	4.248
Energy Through- put (Charge + Discharge)	p.u. en- ergy	2.331	6.132	6.083	6.295	8.656
Time Oper- ated Below 0.1 p.u. Power	Hours	15.074	6.462	6.838	5.257	4.107
Time Oper- ated Above 0.9 p.u. Power	Hours	0.000	0.459	0.340	0.393	1.491

Table 3: Performance Specification Metrics for Representative Control Signals

Metric	Units	Average Control Signal	Aggressive Control Signal
Signal σ	p.u. power	0.361	0.460
Mileage	p.u. power	31.424	35.325
Energy Dis- charged	p.u. en- ergy (ESS Cycles)	3.429	4.400
Energy Charged	p.u. en- ergy	3.429	4.400
Energy Throughput (Charge + Discharge)	p.u. en- ergy	6.858	8.800
Time Operated Within ± 0.1 p.u. Power	Hours	0.540	0.387
Time Operated Outside ± 0.9 p.u. Power	Hours	0.000	0.124

Table 4: Structure of 24 hour duty-cycle

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

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Figure 1: PJM Frequency Regulation Control Signal 04/01/2011 to 03/31/2012

Figure 2: Correlation of Frequency Regulation Control Signal Mileage and Signal σ

Figure 3: Average PSD of the PJM Frequency Regulation Control Signal

Figure 4: Trend of PJM Frequency Regulation Control Signal σ , 04/01/2011 to 03/31/2012

Figure 5: Histogram of Daily Regulation Signal σ , 04/01/2011 to 03/31/2012

Figure 6: Exemplar Days of Raw PJM Frequency Regulation Control Signal

Figure 7: Representative Control Signal Histogram Comparison

Figure 8: Frequency Regulation Duty-Cycle

Figure1_update