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Development of a frequency regulation duty-cycle for standardized energy storage performance testing

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A R T I C L E I N F O

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A B S T R A C T

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 2 h 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-h 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.

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 (NERCs) Real Power Balancing Control Performance (BAL001) and Disturbance Control Performance (BAL002) are examples of standards that require balancing authorities to operate such that frequency does not deviate too far from the scheduled set point (nominally 60 Hz 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 Eq. (1). These requirements, common in many countries [5,6], 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 ACE compliance.

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

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Nomenclature

ACE	area control error
AGC	automated generation control
DC	direct current
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 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
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
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
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 normalized 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

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.
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.
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 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 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 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 absolute 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 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 the demands of providing frequency regulation in order to predict ESS economic performance, 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. Additionally, 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 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

There are a number of metrics that can be used to sort and process frequency regulation 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, 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 Eq. (2). From the