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Determination of Duty Cycle for Energy Storage Systems in a PV Smoothing Application

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Abstract

This report supplements the document, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems," issued in a revised version in April 2016 (see [4]), which will include the photovoltaic (PV) smoothing application for an energy storage system (ESS). This report provides the background and documentation associated with the determination of a duty cycle for an ESS operated in a PV smoothing application for the purpose of measuring and expressing ESS performance in accordance with the ESS performance protocol.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Dr. Imre Gyuk, program manager for the DOE Energy Storage Systems Program. The authors would also like to express their appreciation to all the stakeholders who participated as members of the PV Smoothing Subgroup. Without their thoughtful input and recommendations, the definitions, metrics, and duty cycle provided in this report would not have been possible. A complete listing of members of the PV Smoothing Subgroup appears in the first chapter of this report. Special recognition should go to the staffs at Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) in collaborating on this effort. In particular, Mr. David Conover and Dr. Vish Viswanathan of PNNL and Dr. Summer Ferreira of SNL were especially helpful in their suggestions for the determination of a duty cycle for the PV Smoothing application.

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NOMENCLATURE

AC	Alternating Current
ARRA	American Reinvestment and Recovery Act of 2009
AUX	Auxiliary input
BAT	Battery
BESS	Battery Energy Storage System
CABs	Container of Advanced carbon Battery cells
CSV	Comma Separated Values
CDF	Cumulative Density Function
CI	Daily Clearness Index
DC	Direct Current
DOE	Department of Energy
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems
IEEE	Institute of Electrical and Electronics Engineers
kW	kilo-Watts
kWh	kilo-Watt hours
MA	Moving Average
MW	Mega-Watts
MWh	Mega-Watt hours
NNMC	Northern New Mexico College
PJM	PJM Interconnection
PMF	Probability Mass Function
PNM	Public Service Company of New Mexico
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
SNL	Sandia National Laboratories
SoC	State of Charge
UNM	University of New Mexico
V	Volts
VAC	Volts Alternating Current
VDC	Volts Direct Current
VI	Daily Variability Index
VRLA	Valve Regulated Lead Acid

1. BACKGROUND

When the initial effort was undertaken to develop a protocol for measuring and expressing the performance of energy storage systems ("ESS") in early 2012, it was recognized that, due to the range of ESS applications, not all ESS applications could be addressed at the same time. As a result, it was determined to focus on those applications considered to have the highest priority (i.e., peak shaving and frequency regulation), and after completion of an initial protocol the application of the protocol to additional ESS applications would be pursued. After publication of the initial protocol (see [1] and updated version [2]), the protocol working group was polled to determine which applications they felt should be addressed by the next edition of the protocol. The application of ESS for microgrids and photovoltaic ("PV") smoothing received the highest level of support. The working group was polled to identify members who were interested in participating in subgroups to develop criteria for each of these new applications. The names and affiliations of those who participated in the PV Smoothing Subgroup appear in Table 1. The document describing the duty cycle determination for the Microgrids Subgroup appears in [3].

From the formation of the PV smoothing subgroup (February 28, 2014) until the completion of their work (April 14, 2015) there were 8 webinar meetings, many e-mail exchanges among subgroup members, and a number of drafts and redrafts of criteria leading up to the proposed enhancements to the Protocol to cover the PV smoothing application. These enhancements focused on needed terms and definitions, metrics applicable to ESS performance in a PV smoothing application, the applicable duty cycle for the ESS, and the manner in which operational data is to be captured; from this data, performance of the ESS would be reported.

There were several factors discussed within the subgroup that needed to be decided upon as either within or outside the scope of the protocol. Modeling, while considered important, was not considered a use case, and hence was considered to be outside the scope of the work associated with the protocol enhancements. It was also agreed that the effort would not include determining failure mechanisms for the ESS because those were not considered to be within the scope of the protocol. Periodic capacity tests were considered to be a good proxy for the state of health of the ESS. In addition, safety related issues were not considered, as they are also outside the scope of the protocol.

The PV smoothing subgroup spent considerable time discussing and developing an appropriate duty cycle for assessing the performance of an ESS in a PV smoothing application. Data used in developing the PV smoothing duty cycle was obtained from the PNM Prosperity Project, with permission from PNM (see Section 4). The PV smoothing subgroup discussed which metrics are applicable to measuring and expressing the performance of an ESS in a PV smoothing application. It was determined that all of the metrics applicable to frequency regulation, included in the 2013 Protocol and in the June 2014 revision of the Protocol, were relevant. After finalizing the duty cycle, the PV smoothing subgroup discussed the characteristics of the duty cycle that should be reported in this document (see Section 7). Most of these characteristics relate to the variability of the ESS tracking signal as well as some of the duty cycle statistical properties. The revised version of the Protocol, which incorporates the PV smoothing application was published in April 2016 and appears in [4].

Table 1. Participants in PV Smoothing Subgroup

Name	Affiliation
Schoenwald, David	**Sandia National Laboratories**
Borneo, Dan	Sandia National Laboratories
Bouchard, Philippe	EOS Energy Storage
Bray, Kathy	Pacific Northwest National Laboratory
Byrne, Ray	Sandia National Laboratories
Chen, Kevin	DNV GL
Conover, David	Pacific Northwest National Laboratory
Ferreira, Summer	Sandia National Laboratories
Franks, Ryan	National Electric Manufacturers' Association
Fribush, David	Pacific Gas & Electric
Hone, Matt	Los Angeles Department of Water and Power
Khare, Neeta	EOS Energy Storage
McLellan, Nick	Johnson Controls Inc.
Miller, Troy	S&C Electric
Mosso, Ron	Enervault
Nichols, David	DKN Consulting
Nourai, Ali	DNV Kema Energy & Sustainability
Rosewater, David	Sandia National Laboratories
Ruiz, John	Johnson Controls Inc.
Sankar, Narayanan	Tri-Technic
Sathrum, Aaron	General Atomics
Startari, Joseph	Anapole Technologies Inc.
Strauch, Jason	General Atomics
Vassallo, Anthony	University of Sydney
Viswanathan, Vish	Pacific Northwest National Laboratory

2. DEFINITION OF PV SMOOTHING

From an energy storage systems performance standpoint, the following sentence shall serve as our operating definition of PV smoothing.

The application of an energy storage system (ESS) to mitigate rapid fluctuations in photovoltaic (PV) power output that occur during periods with transient cloud shadows on the PV array by adding power to or subtracting power from the output of a PV system in order to smooth out the high frequency components of the PV power.

Thus, PV smoothing is the use of an ESS to reduce high variability in PV power output. The purpose of PV smoothing is to mitigate frequency variation and stability issues that can arise at both the feeder and transmission level in high penetration PV scenarios to help meet ramp rate requirements. At the feeder level, PV smoothing can mitigate voltage flicker and voltage excursions outside desired or mandated 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 feeder and/or transmission level.

The consequences to the grid, at both the feeder and transmission level, of un-smoothed or poorly smoothed PV output power are described in more detail in Trueblood, et al (2013) [5] and Ela, et al (2013) [7].

3. METRICS FOR PV SMOOTHING

The following definitions shall be applied within the context of this protocol for the purposes of performance testing. To be useful, test procedures must include definitions to narrow the margin for interpretation and increase the repeatability of tests. Terms not defined shall have their normal dictionary meaning and be applied as such when using the protocol.

1. System Rating – at ambient conditions
2. Roundtrip Energy Efficiency – for the entire ESS
3. Duty-Cycle Roundtrip Efficiency – for the entire ESS
4. Response Time of ESS in responding to a command signal – does not include communication delay times
5. Ramp Rate
6. Energy Capacity
7. Energy Capacity Stability
8. Reference Signal Tracking – how well does ESS track the reference signal; metric definition is:|reference signal power – ESS power^2
9. State-of-Charge Excursions
10. Power Factor – measure of inverter performance
11. Operating Temperature Range

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

Ramp Rate. The rate of change of power delivered to or absorbed by an ESS expressed as a percentage change in rated power over time (percent per second).

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

Response Time. The time in seconds it takes an ESS to reach 100 percent of rated power during charge or to reach 100 percent of rated power during discharge from an initial power measurement taken when the ESS is at rest.

Stored Energy Capacity. The amount of electric or thermal energy capable of being stored by an ESS expressed as the product of the ESS rated power and the discharge time at rated power.

4. SOURCE OF PV DATA

The data used for this study is from the Public Service Company of New Mexico's Prosperity Electricity Storage Project ("PNM Prosperity").

PNM Prosperity consists of a 500 kW/350 kWh advanced lead-acid battery with integrated supercapacitor (for power smoothing) and a 250 kW/990 kWh advanced lead acid battery (for energy shifting), and is co-located with a 500 kW solar photovoltaic ("PV") resource. The project received American Reinvestment and Recovery Act ("ARRA") funding, and has been operational since 2011. More details and analysis of the project can be found in Roberson, et al (2014) [8] and Willard (2014) [10].

We have received permission from PNM to use both PV and battery power output from PNM Prosperity for this study. This data has a time resolution of one second, and has been archived from 2011 onward. A schematic of the project is depicted in Figure 1.

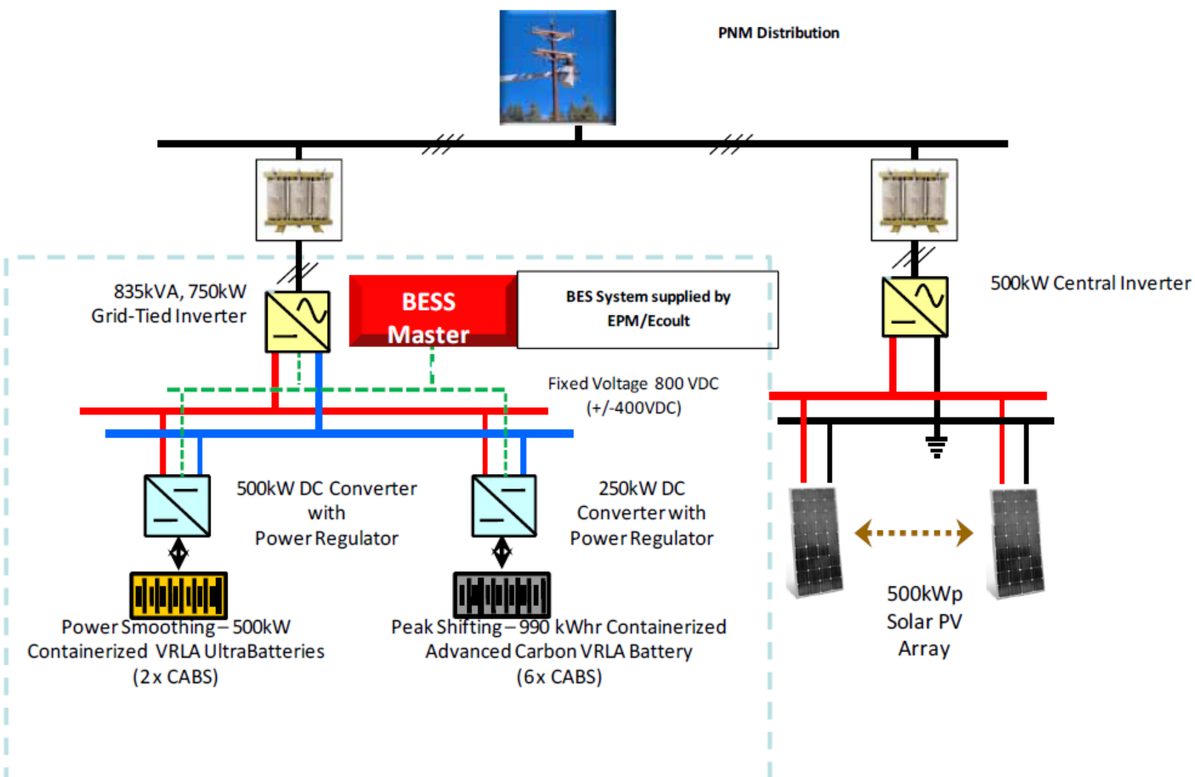

Figure 1. Schematic of the PNM Prosperity Project.

5. PHILOSOPHY OF DUTY CYCLE DEVELOPMENT PROCESS

A duty cycle is a charge/discharge profile that represents the demands placed on an energy storage system (“ESS”) by a specific application. A PV smoothing duty cycle should take into account what an ESS would need to do on a daily basis to smooth PV.

From the start we faced a choice: create many different duty cycle profiles to reflect PV generation variability differences due to differences in regions, weather, and time of year, or create one duty cycle profile that represents a challenging, yet realistic, signal. We chose the latter approach because we believe that it is more straightforward, and that designing an ESS for a challenging yet realistic scenario is most appropriate for this application.

A duty cycle that is not stringent enough would encourage the development of systems that are not robust enough to perform smoothing on challenging days. A duty cycle that is too stringent could specify systems that are more capable (and therefore more expensive) than necessary. Since we are concerned with PV output variability when a significant amount of power can be produced, a 10-hour duty cycle (representing the daylight hours of significant PV generation) should be sufficient.

We sought to create such a duty cycle profile by splicing together one-hour segments of actual PV generation obtained from different days. These segments were chosen to capture different PV generation scenarios, which we grouped into mostly sunny, partly cloudy, and mostly cloudy days. In order to make the profile challenging, we sought segments that were moderate to very high in the level of PV power generation variability.

Given that cloud cover can rapidly change PV output, we determined that having a 1-second PV output time series was necessary. Fortunately, the data being collected at PNM Prosperity was of that resolution.

To create a challenging duty cycle, it is necessary to have a way of judging how variable PV output is. We used the Variability Index (“VI”), described in Stein, et al (2012) [9] (additional measures, not used here, can be found in Hoff and Perez (2010) [6]).

6. PROCESS FOR CONSTRUCTING DUTY CYCLE

We used the following process to construct the PV smoothing duty cycle.

- Step 1: Locate and download files containing time series data for PV power generation daily profiles. (Again, the data should have a temporal resolution of one second at a minimum, and there should be daily generation profiles for different seasons of the year).
- Step 2: Using Excel or Matlab plot the data from these files to observe the range of variability in PV power among the different days and form a "composite" day.
- Step 3: From our composite day, compute its moving average.
- Step 4: Construct the PV power residue = PV power – PV moving average.
- Step 5: Duty Cycle will be the normalized values of this residue, w.r.t. ESS rated power, +/- 500 kW in our case.
- Step 6: Assess several characteristics of this signal to be sure that it meets assumptions and desired variability.

We used a number of assumptions in constructing the PV smoothing duty cycle. Our sign convention was that a positive duty cycle value means that the ESS is discharging power, and a negative value means that the ESS is in charging mode. We used a 30-minute window length to compute the moving average of the constructed PV power profile. All ramp rates were computed using 1-minute intervals.

7. CHARACTERISTICS OF DUTY CYCLE

Following the process outlined in Section 6, a 10-hour time series for the PV smoothing duty cycle was derived. This time series is graphically depicted in Figure 2.

An Excel spreadsheet containing the full 10-hour time series data for the PV smoothing duty cycle can be downloaded from the link given in Schoenwald (2016) [11].

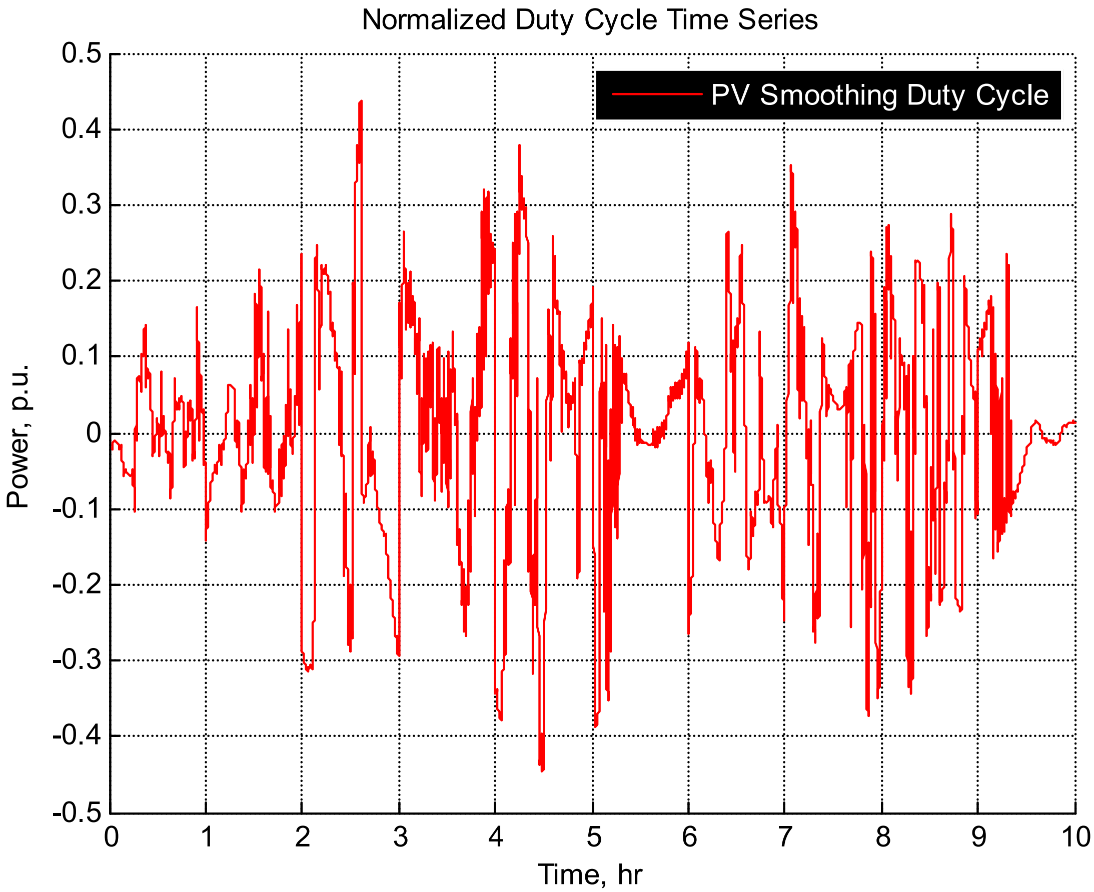

Figure 2: Duty Cycle Signal for PV Smoothing Application.

8. CONCLUSIONS

A duty cycle is a charge/discharge profile that represents the demands placed on an energy storage system ("ESS") by a specific application. A PV smoothing duty cycle should take into account what an ESS would need to do on a daily basis to smooth PV.

In creating a duty cycle for the PV smoothing application, our overall goal was to have a signal that was challenging yet realistic. Through understanding what an energy storage system tasked with smoothing PV would need to be able to do, we can get a better sense of the required capacity and characteristics of such a system.

We believe that one can draw the following conclusions:

1) PV smoothing is a power smoothing application – it requires a relatively large power capacity and a low energy capacity; and
2) The ESS should be designed to perform many charge/discharge cycles per day with little to no degradation in performance.

This methodology of constructing a challenging yet realistic duty cycle can be performed for the particular location and PV system being considered in the PV smoothing application to get precise specifications for the ESS needed. An Excel spreadsheet containing the full 10-hour time series data of the PV smoothing duty cycle can be found from the link given in Schoenwald (2016) [11].

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