Cycle-Life Degradation Assessment of Battery Energy Storage Systems Caused by Solar PV Variability

M J E Alam
UQ Solar, Global Change Institute
The University of Queensland
Brisbane, QLD 4072
m.alam8@uq.edu.au

T K Saha
School of Information Technology and Electrical Engineering
The University of Queensland
Brisbane, QLD 4072
saha@itee.uq.edu.au

***Abstract*—With an ability to manage solar PV variability in one side and high capital investment in the other, Battery Energy Storage System (BESS) is considered as a critical asset in a PV plant. It is therefore essential to meticulously track the use of BESS in day to day operation and the resulting degradation of life. Due to the intermittent nature of BESS operation as an effect of PV variability, determination of the exact number of charge-discharge cycles a BESS undergoes, and hence the amount of cycling capacity loss it encounters, is not a trivial task. This paper investigates the impact of variable PV based operation of BESS on its cycle-life by applying "Rainflow Counting" algorithm – a generic cycle counting technique traditionally used for metal fatigue analysis. Conducted using data from a real PV plant in Australia, the case study presented in this paper provides a realistic idea of cycle-life degradation that may be caused by PV variability.**

***Index Terms*— Solar PV Variability, Battery Energy Storage System, Cycle-Life Degradation, Rainflow Counting.**

I. Introduction

High cost of Battery Energy Storage System (BESS) is one of the key factors affecting its large scale deployment in mitigating intermittency effects of renewable energy resources and eventually facilitating a desired level of penetration into distribution grid. In spite of a decreasing trend of BESS cost [1] and a speculation of less than 1000 USD/kWh by 2020 [2], installation of BESS is still a significant investment for business entities and individual consumers. However, integration of BESS with certain renewable generation resources, e.g. solar PV, is nearly inevitable due to non-coincident load and generation peak, and unacceptable ramp rates caused by weather conditions. Reverse power flow, voltage rise, and fluctuations in PV power and PV system connection point voltage are among the most adverse impacts that could be mitigated with a PV integrated BESS. Therefore, despite the massive scale of investment, many PV system owners have either installed or planning to install BESS.

Similar to any other physical device, BESS cells have rated life which is typically specified by the total number of charge-discharge cycles before reaching 80% of the initial capacity. Given the technical importance, cost, and limited life time, BESS is considered as a key asset for any PV generation business and therefore, its rated life needs to be utilised in the most effective way possible. Hence, its usage and degradations caused by day to day operations need to be closely monitored and assessed to implement an effective asset management regime.

Cycle-life degradation analysis involves determining the total number of cycles spent by a BESS in a given period of time. The difficulty in cycle counting for BESS operation in solar PV applications is the presence of irregular charge-discharge cycles of varying Depth of Discharge (DoD) caused by PV variability. As the cycle-life varies for different DoD ranges, all the micro-cycles (small cycles within a main charge-discharge time history) present in a DoD profile for a given period of time needs to be extracted to estimate the total amount of degradation of the BESS cycle-life. Existence of irregular cycles is also found in stress time series data used for metal fatigue analysis [3]. To identify individual cycles in a given stress history, "Rainflow Counting" method was developed by Matsuishi and Endo in 1968 [4]. In power engineering, recent applications of this algorithm was found in lifetime assessment of power semiconductor switches [5, 6]. Given the similarity of irregular stress cycles for metal with the irregular DoD cycles for BESS, this algorithm has also gained interest for BESS life degradation analysis [7]. Authors in [8] have applied Rainflow Counting technique to evaluate BESS life degradation caused by providing frequency regulation ancillary services. Life degradation as a result of exercising various wind variability smoothing algorithms is compared in [9] using this method. Rainflow Counting algorithm is also used for BESS sizing in a wind-diesel hybrid system for wind power smoothing in the presence of ultra-capacitors [10]. Impact of different charging strategies on EV battery cycle-life is evaluated in

978-1-5090-4168-8/16/$31.00 ©2016 IEEE

[11] using this cycle counting technique. Provided that occurrence of irregular charging-discharging cycles in BESS operation in response to PV variability is obvious, and that BESS as a critical asset needs to be properly managed, it is essential to understand how such intermittency could impact BESS rated cycle-life. Incorporation of cycle-life degradation data in asset management systems would also be useful in avoiding an unexpected failure of a battery.

This paper investigates the impact of PV variability on BESS cycle-life degradation. Rainflow Counting method is applied for extracting range and cycle information from an irregular DoD profile, which is then used for assessment of incurred cycle-life. Data from a real solar PV plant in Australia and a proposed BESS for that plant is used for this investigation. The strategy used for BESS control performs scheduled charging and discharging operation for predefined objectives, and unscheduled short term discharge-charge operation to limit PV output ramp rate. Therefore it creates a number of micro-cycles in the DoD profile. Use of real system data and a multifunctional BESS control strategy provides a realistic indication of BESS cycle-life degradation caused by PV intermittency.

II. Rainflow Counting Method for Estimation of BESS Cycle-Life Degradation

Rainflow Counting method is a generic cycle counting technique that can extract cycle and range information from an irregular time series data. As BESS operation to cope with variable PV creates partial cycles, this method can be applied to determine the frequency and range of cycles that a BESS has gone through within a given DoD history. The Rainflow Counting algorithm and its application for BESS cycle-life degradation analysis is explained below.

A. *The Rainflow Counting Algorithm* [3, 12]

Consider a time series $\mathbf{S}_{\mathbf{DoD}}$ that contains a DoD history resulted from BESS operation in a certain time period. The steps followed to determine micro-cycles are as follows.

- Step-1: $\mathbf{S}_{\mathbf{DoD}}$ is reduced to a time series containing valleys and peaks only by identifying slope reversals and the reduced time series is denoted by $\mathbf{S}_{\mathbf{PkVl}}$.
- Step-2: Two ranges R_X and R_Y are constructed from first three points in $\mathbf{S}_{\mathbf{PkVl}}$.

$$R_X = \left|\mathbf{S}_{\mathbf{PkVl}}(i) - \mathbf{S}_{\mathbf{PkVl}}(i+1)\right|$$
$$R_Y = \left|\mathbf{S}_{\mathbf{PkVl}}(i+1) - \mathbf{S}_{\mathbf{PkVl}}(i+2)\right| \quad (1)$$

- Step-3: A cycle is identified and designated as half (0.5) or full (1.0) cycle using the rules given below.

$$\text{Cycle} = \begin{cases} 0.5, \text{if } R_X \leq R_Y \text{ and } i = 1 \\ 1.0, \text{if } R_X \leq R_Y \end{cases} \quad (2)$$

- Step-4: If a cycle is identified and R_X is the first range in the time series $\mathbf{S}_{\mathbf{PkVl}}$, only the first point of the range R_X is removed and the second point is considered as the beginning of $\mathbf{S}_{\mathbf{PkVl}}$. If R_X is not the first range of $\mathbf{S}_{\mathbf{PkVl}}$, then both points of R_X are removed. Steps 2 to 4 are continued until all the data points are considered.
- Step 5: Once all data points in $\mathbf{S}_{\mathbf{PkVl}}$ are considered, each of the ranges discarded before due to not qualifying as a cycle or half-cycle, is considered as a half cycle.

A simple numerical example is provided below to illustrate the algorithm. A 14-point DoD time series is taken, as shown using a dashed line in Fig. 1(a), which is reduced to $\mathbf{S}_{\mathbf{PkVl}}$ (solid line) by identifying peaks and valleys according to Step-1. Following Step-2, $R_X = 2$ and $R_Y = 4$ is found. According to Step-3, R_X is a half cycle and also the first range in $\mathbf{S}_{\mathbf{PkVl}}$ as observed in Fig. 1(b). Therefore, only the first data point (28) is removed. As Step 2 to 4 continues, R_X formed by points 26 and 27 are identified as full cycle and removed from the $\mathbf{S}_{\mathbf{PkVl}}$. The blue triangle in Fig. 1(c) is the corresponding full cycle. In continuation, R_X between points 24 and 29 are also identified as a full cycle, as shown in Fig. 1(d), and then removed. After all the data points are considered, ranges formed by points 30, 22, and 30 remain unused and identified as half cycles, as found in Fig. 1(e). Therefore, this DoD profile contains 3 half cycles of ranges {2, 8, 8} and 2 full cycles of ranges {1, 5}, as shown in Fig. 1(f). This algorithm was implemented in MATLAB for this investigation and validated using example cases from [12-13].

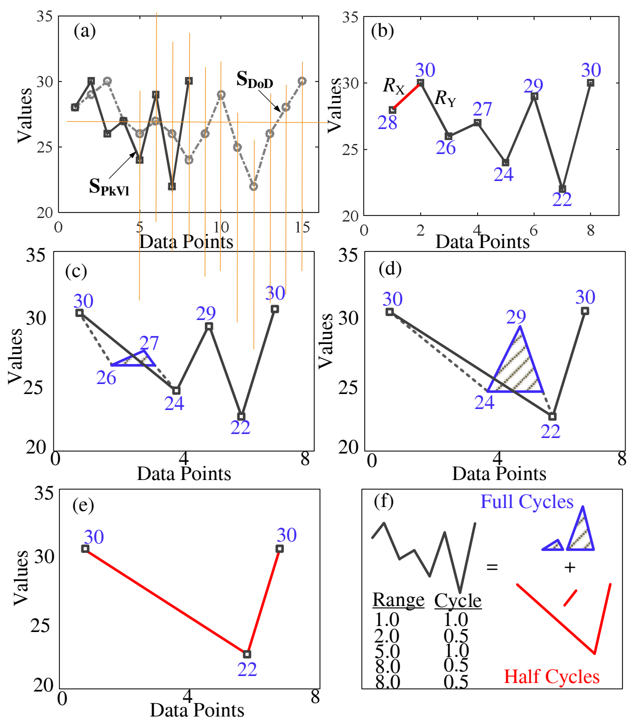

Figure 1. Illustration of Rainflow Counting Algorithm.

B. *Estimation of BESS Cycle Life Degradation*

Once micro-cycles from the DoD profile are identified, degradation of cycle-life can be estimated using the rated cycle-life curve, which is determined based on empirical methods. The process used for assessment of cycle-life degradation is presented in Fig. 2. BESS power profile time series is used to calculate DoD time series. A reduced DoD time series is then obtained by identifying peaks and

978-1-5090-4168-8/16/$31.00 ©2016 IEEE

valleys of the original time series which is then passed through the Rainflow Counting algorithm to extract range and cycle information hidden in the DoD time series. Degradation of cycle-life for each of the incurred cycles is then obtained and summed up to estimate the total degradation using (3).

$$D_{CL} = \sum_{j=1}^{n} \frac{\text{Cycle of } R_j}{A \times \left(R_j\right)^B} \times 100\% \qquad (3)$$

where, D_{CL} is the degradation of cycle-life, R_j is the range of j-th micro-cycle in the DoD time history, n is the total number of cycles, A and B are empirical parameters to determine rated cycle-life at different DoD ranges.

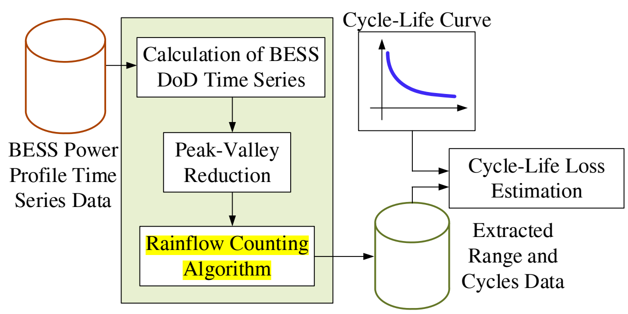

Figure 2. Flowchart for Estimation of Cycle-Life Degradation.

III. A CASE STUDY OF BESS CYCLE-LIFE DEGRATION WHILE OPERATING IN A REAL PV PLANT

Impacts of micro-cycles on BESS cycle-life, while operating in a commercial solar PV plant, is investigated in this section using a 3.3 MW PV plant's data. The plant is located in Queensland, Australia at The University of Queensland (UQ) Gatton campus. It is connected to an 11 kV distribution network owned and operated by Energex, a power distribution utility in Queensland. A 760 kWh Lithium Polymer BESS is proposed for Gatton PV plant for conducting research on BESS application for enabling large scale PV integration. Therefore, control strategy of the BESS will have different functions, such as storing excess PV energy, load shifting/shaving, and ramp rate control. Therefore, the Gatton PV plant BESS is likely to encounter numerous micro-cycles in its operation which will affect cycle-life, and hence is a suitable example for this investigation. The parameters of the proposed BESS are given in Table I.

TABLE I. PARAMETERS OF THE PROPOSED BESS FOR GATTON PV PLANT

Parameters	Values
Rated Capacity/Voltage	760 kWh/ 666 V
Rated Cycle-Life	4000 at 80% DoD
Cell Type	Superior Lithium Polymer
Voltage and Coulomb Efficiency	94% and 98%
BESS Inverter Rating/ Efficiency	600 kW/ 96%

Gatton 3.3 MW PV plant output data corresponding to three days with different degree of variability (Fig. 3) is used for the investigations in this paper. Day 1 is a clear sunny day with no apparent fluctuations in PV output, while Day 2 is a slightly variable PV output day with a few fluctuations and Day 3 is a highly variable PV day with a significant number of fluctuations. The intention of using three different variability days is to analyse how PV variability can affect BESS cycle life. A typical load profile of Gatton campus substation is used for all three days.

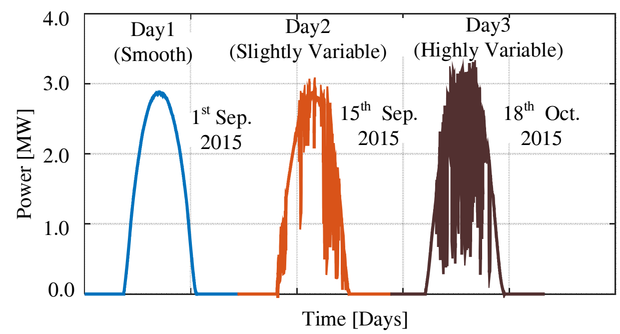

Figure 3. Three typical days' PV data with increasing variability.

Before investigating the impact of variable PV based operation on cycle-life, BESS control strategy used in this paper needs to be briefly described. The BESS has three main power control functions; when there is excess PV power, BESS is charged according to a predefined charging strategy; BESS is discharged to virtually extend the duration of plant output to partially serve Gatton campus load demand with stored solar energy; and during this scheduled charge and discharge operation, BESS power is also controlled on a priority basis to limit unacceptable ramp rate of PV plant output caused by passing clouds. With a rated 4000 cycle-life at 80% Depth of Discharge (DoD) and an assumption of 20 year plant life, capacity usage is limited to a 40% DoD range per day. To consider this limitation, the strategy used in this paper limits the BESS to operation within 50% to 90% SoC range. Operation from 50% SoC would also useful in a highly variable PV day when it may be necessary to discharge before BESS starts to charge from excess PV power without reaching the manufacturer specified maximum DoD limit.

BESS power profile for Day 1 to Day 3 operation is shown in Fig. 4(a). During the clear sunny PV day (Day1), BESS performs only scheduled charging and discharging operations, whereas during the variable PV days (Day2 and Day3), BESS needs to perform numerous short term charge-discharge operations to control ramp rate, as evident from the BESS power profiles. Ramp rates corresponding to these three days are plotted in Fig. 4(b) that shows with BESS, ramp rates are maintained within a given limit. Due to this type of intermittent operation, a number of irregular micro-cycles appear in the SoC profiles of Day 2 and Day 3 in contrast to a single cycle for Day 1, as shown in Fig. 4(c).

Using the Rainflow Counting algorithm described in Section II-A and Fig. 1, micro-cycles for each of the days considered are identified and presented in the histograms of Fig. 5. With a significant amount of variability in PV output, Day2 and Day3 operation contains a number of low range micro-cycles, while Day1 contains only a single DoD

978-1-5090-4168-8/16/$31.00 ©2016 IEEE

cycle of 40% range. As PV variability for Day3 is higher than Day2, DoD profiles for Day3 operation contains a higher number of micro-cycles of comparatively higher range than Day2 operation. These micro-cycles are imposed on a typical Lithium type BESS cycle-life curve shown in Fig. 6. Values of the parameters A and B in (3) are derived from [8, 14]. It is apparent that these micro-cycles, although large in frequency (as shown in Fig. 5), is of low DoD range. As evident from Fig. 6, rated cycling capacity for such low range cycles is exponentially higher than the capacity at a higher range. Lost cycle-life (in percentage of rated cycle-life) for each of the micro-cycle ranges are plotted in Fig. 7 which shows that relative losses corresponding to low range micro-cycles originating from Day2 and Day3 operations are negligible compared to the loss corresponding to Day1 cycle. However, the accumulated effects of these micro-cycles may contribute to an increased degradation of the cycle-life.

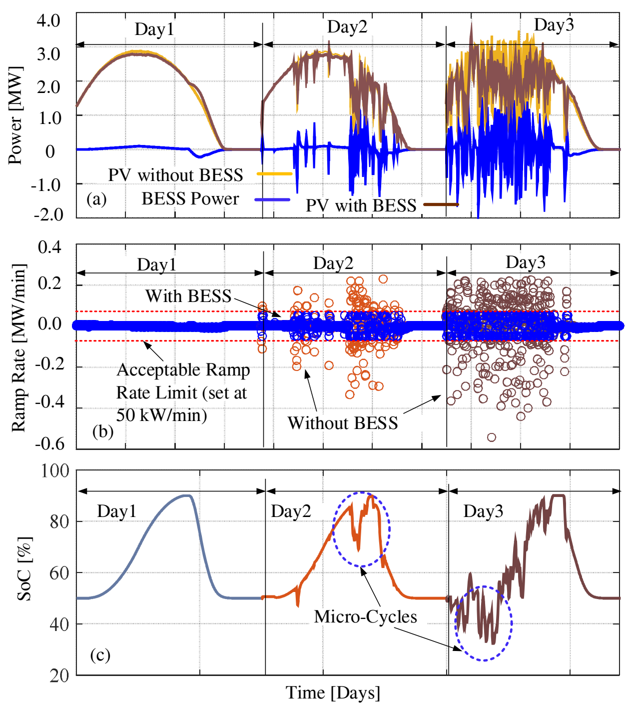

Figure 4. Effect of PV variability on BESS SoC profile. (a) Power profiles. (b) Ramp Rate. (c) SoC profiles.

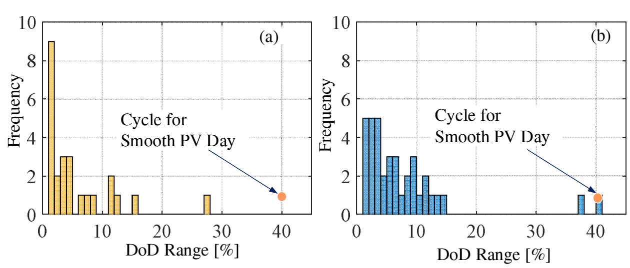

Figure 5. Histograms of micro-cycles in variable PV days. (a) Slightly variable PV day (Day2). (b) Highly variable PV day (Day3).

Cycle-life lost in the three types of days considered are used to estimate the total degradation of cycling capacity over a full year as shown in Table II. When all the days in a year are of type Day1, Day2 and Day3, the total degradation is 3.26%, 3.85%, and 9.05%, respectively. It is apparent that the degradation with the high PV variability day is approximately three times of the degradation with that of the clear sunny PV day. If a more realistic scenario is considered with a mix of three types of days in equal proportion, estimated degradation is 5.26% which is 1.62 times the degradation corresponding to the smooth day.

Based on these estimates of annual degradation, time (in years) necessary to incur 100% degradation is determined to give an indication of lifetime for each of the PV profiles considered. As expected, BESS operation with a highly variable PV day (Day3) would reduce the lifetime to one-third of that with a smooth PV day. Observing the remaining life regularly as a part of asset management program would be vital in avoiding threats of unexpected death of a BESS during a crucial moment.

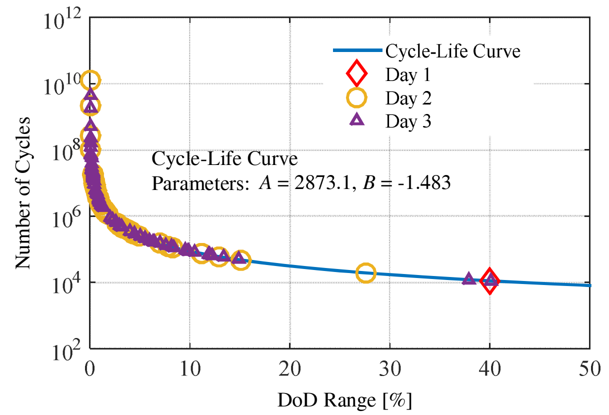

Figure 6. Micro-cycles imposed on a cycle-life curve.

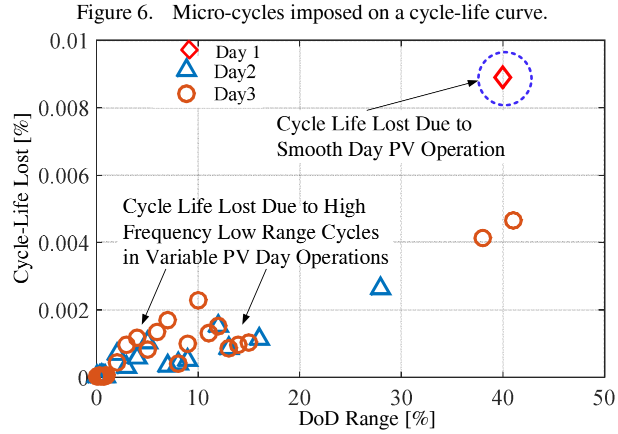

Figure 7. Cyce-life lost for each of the micro-cycles.

TABLE II. ANNUAL CYCLE-LIFE DEGRADATION

Day Type Proportion			**Degradation/Yr (%), Lifetime (Yr)**
Day 1 (%)	Day 2 (%)	Day 3 (%)	
100	0	0	3.26, 30.6748
0	100	0	3.85, 25
0	0	100	9.05, 11
33.33	33.33	33.33	5.26, 19

IV. CONCLUSION

Cycle-life degradation of solar PV integrated BES Systems are investigated in this paper. While operating in

978-1-5090-4168-8/16/$31.00 ©2016 IEEE

response to a variable PV output, BESS needs to undergo numerous low range charge-discharge cycles. While individual effects of these micro-cycles on BESS life is comparatively lower than a larger cycle that would appear without PV variability, their combined effect may create a significant loss of cycling capacity, and therefore, needs to be investigated with due importance. Using an Australian PV plant's data, application of Rainflow Counting method revealed that high frequency micro-cycles exist in BESS DoD profiles as an effect of PV variability. In spite of relatively lower damage of cycle-life for each individual low range cycles in variable PV days, their collective impact could be significantly higher than a smooth PV day. For the specific case studied in this paper, annual degradation for a highly variable PV day was approximately 3 times the degradation for a smooth PV day. This is, however, the worst-case scenario. In a more practical scenario with a mix of days of different variability, the increase in degradation is reasonable (from 3.26% to 5.26%). Allowing BESS to be operated in an intermittent manner with frequent micro-cycles, and hence an increased degradation of cycle-life, is unavoidable in today's power systems with a high penetration of renewable resources. It is rather wise to properly assess the nature and degree of deterioration of cycling capacity so that a precursor to battery end-of-life is available for taking necessary precautions.

ACKNOWLEDGEMENT

This work was performed in part using equipment and infrastructure funded by the Australian Federal Government's Department of Education AGL Solar PV Education Investment Fund Research Infrastructure Project. The University of Queensland is the Lead Research Organisation in partnership with AGL, First Solar and the University of New South Wales.

REFERENCES

[1] C. Christiansen, B. Murray, G. Conway, and C. Chambers, "Energy Storage Study: A storage market review and recommendations for funding and knowledge sharing priorities," Australian Renewable Energy Agency and AECOM Australia Pty Ltd, 13-Jul-2015.

[2] S. Vorrath. (Mar. 2015, Nov. 2015). Energy storage to reach cost 'holy grail', mass adoption in 5 years [Online]. Available: http://reneweconomy.com.au/2015/energy-storage-to-reach-cost-holy-grail-mass-adoption-in-5-years-18383.

[3] D. Socie and G. Glinka. (Jun 2014, Oct 2015). Advances in Fatigue and Fracture Mechanics [Online]. Available: https://www.efatigue.com/training/Fatigue_Methods.pdf

[4] M. Matsuishi and T. Endo, "Fatigue of Metals Subjected to Varying Stress," in *Proceedings of Japan Society of Mechanical Engineering*, Fukuoka, Japan, 1968.

[5] M. Musallam and C. M. Johnson, "An Efficient Implementation of the Rainflow Counting Algorithm for Life Consumption Estimation," *IEEE Transactions on Reliability*, vol. 61, pp. 978-986, 2012.

[6] L. Reddy Gopi Reddy, L. M. Tolbert, B. Ozpineci, and J. O. P. Pinto, "Rainflow Algorithm-Based Lifetime Estimation of Power Semiconductors in Utility Applications," *IEEE Transactions on Industry Applications*, vol. 51, pp. 3368-3375, 2015.

[7] N. DiOrio, A. Dobos, S. Janzou, A. Nelson, and B. Lundstrom, "Technoeconomic Modeling of Battery Energy Storage in SAM," National Renewable Energy Laboratory (NREL) NREL/TP-6A20-64641, Sep. 2015.

[8] M. Chawla, R. Naik, R. Burra, and H. Wiegman, "Utility energy storage life degradation estimation method," in *IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply*, Waltham, MA, USA, 2010, pp. 302-308.

[9] G. Karmiris and T. Tengner, "Control method evaluation for battery energy storage system utilized in renewable smoothing," in *39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, 2013, pp. 1566-1570.

[10] M. A. Tankari, M. B. Camara, B. Dakyo, and G. Lefebvre, "Use of Ultracapacitors and Batteries for Efficient Energy Management in Wind-Diesel Hybrid System," *IEEE Transactions on Sustainable Energy*, vol. 4, pp. 414-424, 2013.

[11] S. You, J. Hu, A. B. Pedersen, P. B. Andersen, C. N. Rasmussen, and S. Cha, "Numerical comparison of optimal charging schemes for Electric Vehicles," in *IEEE Power and Energy Society General Meeting*, San Diego, CA, USA, 2012, pp. 1-6.

[12] "Standard Practices for Cycle Counting in Fatigue Analysis," ed. West Conshohocken, PA, USA: American Society for Testing and Materials (ASTM), Oct 2011.

[13] T. Irvine. (Aug. 2010, Oct 2015). Rainflow cycle counting in fatigue analysis [Online]. Available: http://vibrationdata.com/tutorials/rainflow_counting.pdf

[14] (May 2015). Superior Lithium Polymer Battery [Online]. Available: http://www.kokam.com/new/kokam_en/sub01/sub01_01.html