Proceedings Paper:

Gundogdu, B. and Gladwin, D.T. orcid.org/0000-0001-7195-5435 (2018) A fast battery cycle counting method for grid-tied battery energy storage system subjected to microcycles. In: 2018 International Electrical Engineering Congress (iEECON). 2018 International Electrical Engineering Congress (iEECON), 07-09 Mar 2018, Krabi, Thailand. IEEE . ISBN 978-1-5386-2317-6

https://doi.org/10.1109/IEECON.2018.8712263

A Fast Battery Cycle Counting Method for Grid-Tied Battery Energy Storage System Subjected to Microcycles

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***Abstract*—In this paper, a fast battery cycle counting method for grid-connected Battery Energy Storage System (BESS) operating in frequency regulation is presented. The methodology provides an approximation for the number of battery full charge-discharge cycles based on historical microcycling state-of-charge (SOC) data typical of BESS frequency regulation operation. An enhanced frequency response (EFR) algorithm, a new and fast frequency response service in the UK, that provides a charge/discharge response with respect to the deviations in the grid frequency, is used for analysis. The obtained historical SOC data from the EFR analysis is then considered as an input for evaluating the proposed battery cycle counting estimation method.**

Keywords—grid tied battery energy storage system, frequency regulation, battery cycle counting estimation method, microcycling effect, capacity fade

I. Introduction

Due to the growing environmental concerns and high demand of electricity generation, the increasing exploitation of renewable energy resources is displacing large conventional power plants [1]-[3]. However, intermittent renewables such as solar and wind introduce issues such as power stability, quality and reliability into the power grid. Energy Storage Systems (ESSs) can be used to manage power quality, especially in the UK, by delivering ancillary services such as grid frequency response. In the power distribution network, grid frequency is changing continuously owing to the imbalance between total generation and demand; if generation exceeds demand, a rise in the grid frequency will occur and vice versa. To overcome this issue, the National Grid Electricity Transmission (NGET) – the main distribution network operator in the UK- has introduced a new fast frequency response service, called Enhanced Frequency Response (EFR), that aims to balance the system frequency closer to the nominal frequency (i.e. 50Hz for the UK) under normal operation [1],[4]. For providing such a service, a Battery Energy Storage System (BESS) is an ideal choice due to its fast and flexible response capabilities [5]. However, battery lifetime degradation caused by charge/discharge cycles, calendar life, operating temperature, chemical composition and depth-of-discharge (DOD) is still relatively unknown for different types of power applications [6]-[8]. Similar to other storage devices, BESS cells have a rated life that is typically determined by the total number of deep battery charge-discharge cycles before reaching 80% of the initial capacity [9]. This percentage of current capacity against initial capacity is referred to as the state-of-health (SOH) and an estimation of SOH plot against full charge-discharge cycles is often given by manufacturers. The difficulty in cycle counting for BESS operation in frequency regulation is the presence of irregular charge-discharge cycles of varying state-of-charge (SOC) caused by the real grid frequency variability. These microcycles (small cycles of <5% within a main charge-discharge time history) that exist in a SOC profile for a given period of time need to be interpreted to estimate the total battery cycle information, and to aid in the degradation estimation of the BESS [9]-[11]. It should be noted that other factors such charge-discharge rate and temperature should also be considered to give an accurate estimation of SOH, this paper only focuses on the cycle count approximation. In literature, there is a precedent and acceptance that an approximation technique, called "Rainflow Counting"; and it can be used for fatigue analysis [12], lifetime assessment of power semiconductor switches [13], BESS life degradation analysis for frequency regulation [14] and BESS sizing [15]. The comparison of the proposed fast counting method and the conventional rainflow method are presented as following;

1) The conventional rainflow approach can be applied to extreme points (peak and valleys), and hence the load data is transformed to a data with only peak and valley information, furthermore, it cannot be applied to real time data [18]. However, this paper introduces a faster cycle counting method that approximates the number of full cycles a battery has endured for frequency response delivery. The change in the considered data history is captured for each second by second; the algorithm then considers each positive and negative value as up and down indexes, independently. The sum of all up and down indexes forms the charging data set and the discharging data set respectively. Therefore the proposed cycle estimation method processes all of the stored data and can be applied to real time data.

2) In the rainflow method, half-cycles are counted only at the end of data. Therefore, it is difficult to calculate remaining useful life in between the load points [18]. In this paper, during

the analyses when each battery charging data set and discharging data set reaches to a maximum level of 100%, the half charge and discharge cycles are incremented, independently. A full equivalent cycle is determined as average of battery charge and discharge cycles for the given period of time. This means that, the number of full equivalent cycles are estimated during the analyses rather than at the end of the data set. Therefore, it is simple to calculate remaining useful life in between the load points.

3) In the rainflow method, the calculation of mean temperature is independent of the time period [19], however this is out of scope for this paper and will be published separately in more detail by the authors.

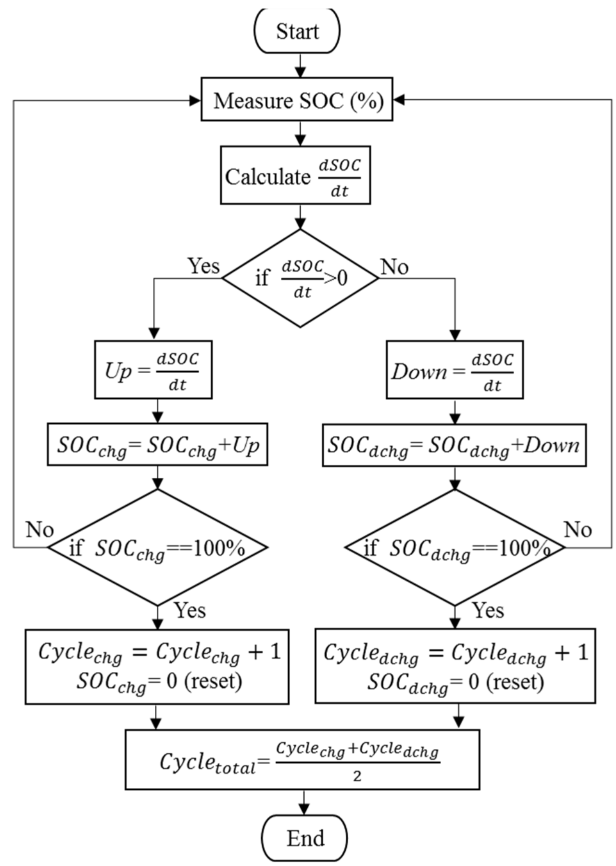
This paper introduces a fast battery cycle counting estimation method for a grid-tied BESS, operation in grid frequency regulation, subjected to microcycles with currents up to 2C. In this paper, an Enhanced Frequency Response control algorithm as described in [1] is simulated to produce battery SOC data for a given time period using historical frequency data, this is then used to demonstrate the battery cycle counting estimation algorithm. Finally, this paper quantifies the microcycling in terms of full cycles to aid in the approximation of the degradation of a battery whilst providing the EFR service.

II. Battery Cyles Counting Method

The lifetime of a battery is affected by a number of factors including the number of charge-discharge cycles [15], [16], estimating the degradation is particularly important for grid scale battery energy storage applications maximise returns on investment. In this paper, a fast battery cycle counting method is proposed for grid-tied BESS, that is subjected to microcycles, to approximate the number of equivalent battery full charge-discharge cycles. The proposed fast cycle counting method is demonstrated for a BESS delivering EFR service to the grid. This service demands from the BESS irregular charge-discharge cycles of varying power caused by the real grid frequency variability.

The proposed fast cycle counting method as shown in Fig. 1 is used to approximate the number of full cycles a battery has endured using historical battery SOC data for EFR delivery. The method is described as following:

- The algorithm loops through the historical SOC data obtained by simulating the EFR control algorithm [1] over a period of time. In the first step, the change in battery SOC ($dSOC/dt$) is extracted for each second by second. According to the proposed algorithm in this paper, if $dSOC/dt$ is greater than zero, the battery is charging; if it is less than zero, the battery is discharging; or if it is equal to zero, the battery is resting.
- The algorithm considers each positive and negative value of $dSOC/dt$ as "Up" and "Down" indexes, respectively. In the second step, the sum of all up indexes forms the battery SOC charging data set SOC_{chg} and the sum of all down indexes forms the battery SOC discharging data set SOC_{dchg}.
- In the third, during the simulation when each SOC_{chg} and SOC_{dchg} equals to 100%, the battery charge $Cycle_{chg}$ and discharge cycle $Cycle_{chg}$ are incremented, independently. A full battery cycle $Cycle_{total}$ is calculated as average of battery charge and discharge cycles for the given period of time.
- The algorithm is repeated over the considered SOC data history providing a total cycle count at the end.



Up : Battery SOC up index (charging)
$Down$: Battery SOC down index (discharging)
SOC_{chg} : Sum of SOC up index
SOC_{dchg} : Sum of SOC down index
$Cycle_{chg}$: Charging cycle
$Cycle_{dchg}$: Discharging cycle

Fig. 1 Flow chart of the proposed fast battery cycle counting estimation method for a grid-tied battery energy storage system subjected to microcycles.

The operational principle of the proposed fast battery cycle counting technique is demonstrated on the 24-hour profile of a battery SOC obtained by simulating the EFR control algorithm [1] for the 21st October 2015 (Fig. 2). Using the proposed method in Fig. 1, it can be seen that one charging and one discharging half-cycle are counted, hence in total one full battery cycle is obtained from 21st October 2015 as shown in Fig. 2. In the EFR control algorithm developed in [1], [2], the SOC of the battery is calculated using (1), where $\mathrm{SOC_{init}}$, Q and P_{batt} represent initial SOC, Watt-hour capacity and instantaneous battery power, respectively.

$$\mathrm{SOC_{out}} = \mathrm{SOC_{init}} + \frac{\int_0^t P_{\mathrm{batt}} dt}{3600 \cdot Q} \qquad (1)$$

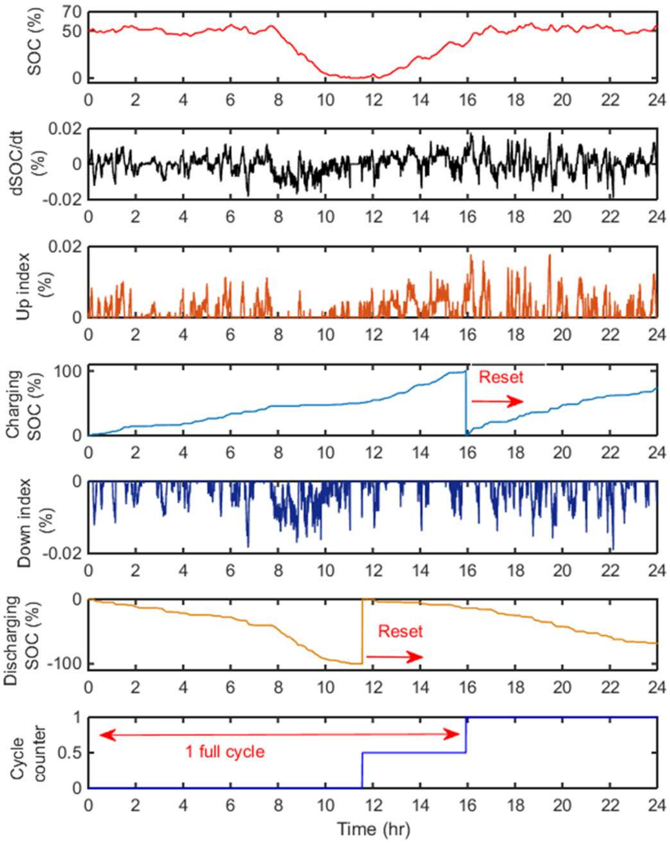


Fig. 2 Demonstration of the proposed fast battery cycle counting method on a 24-hour profile of a battery SOC data set obtained by simulating the enhanced frequency response algorithm for 21st Oct 2015.

III. Simulation Results

A new EFR control algorithm was developed in [1] using real second by second grid frequency data obtained from the National Grid [4]. In this section the considered EFR algorithm has been simulated in MATLAB/Simulink to achieve the output battery SOC data for use in analysing the proposed battery cycle counting control algorithm. The EFR simulation results provided in this paper are all based on a 1MWh BESS model, which has been experimentally validated on WESS plant in the UK [17], with a maximum EFR power of ±2 MW. The parameters used in the EFR algorithm are given in [1].

A. Simulation Results of the EFR algorithm

In order to demonstrate the performance of the EFR control algorithm reported in [1], the real grid frequency data for the October 2015 is used herein, which is a particular month is known to have a large period of under frequency. The EFR simulation results for a "Service-2" EFR are shown in Fig. 3. On the frequency plot, the dead-band (DB) is shown by the green lines.

According to the simulation findings in Fig. 3, the algorithm delivers to the EFR specification, whilst managing the battery SOC to the specified band of 45-55%. In the EFR algorithm it is possible to define two purposes for power flow in and out of the battery; the first is defined as that of charging/discharging the battery i.e power is requested in either direction for the sole purpose of managing the battery SOC and not for EFR; the second is import/export which defines when the BESS is performing a mandatory response to a grid frequency event. The operational principle of the EFR control algorithm and more detail can be found in [1], [2].

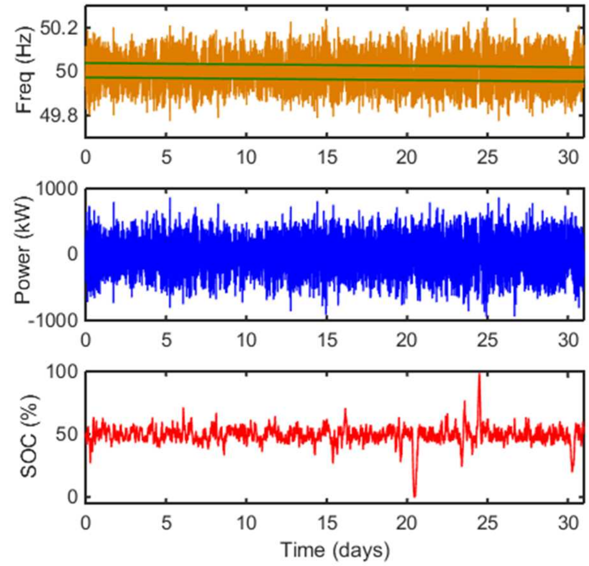


Fig. 3 Simulation results of the EFR control algorithm for October 2015.

B. Simulation Results of the Fast Battery Cycle Counting Estimation Method

In this section, data analysis is carried out using the fast battery cycle counting estimation algorithm described in Section II for a 2MW/1MWh grid-tied BESS in order to quantify the microcycling to the equivalent number of full charge-discharge cycles. Using the battery SOC data obtained by simulating the EFR algorithm for the whole of October 2015, the proposed fast battery cycling counting algorithm is processed in MATLAB/Simulink with the results shown in Fig. 4.

The proposed cycle counting algorithm approximates the total number of equivalent full charge-discharge cycles experienced by the grid-tied BESS for EFR delivery in October 2015. As can be from the simulation results in Fig. 4, the changes in battery SOC over the October are around $\leq 0.2\%$, causing numerous microcycles due to the variability in the real grid frequency. The proposed counting method identifies and detects all microcycles for October 2015 as shown in Fig. 4. Following the next steps in the algorithm, if the changes in SOC are positive ($dSOC/dt > 0$), the battery is charging or if those change is negative ($dSOC/dt < 0$), the battery is discharging. Therefore, by summing the charging (up) and discharging (down) indexes detected from the considered SOC data, 49 battery charging and discharging half-cycles are obtained independently, approximating to a total of 49 battery full cycles. It can be seen from the analysis that this algorithm can be applied to larger SOC data sets or even applied in real-time.

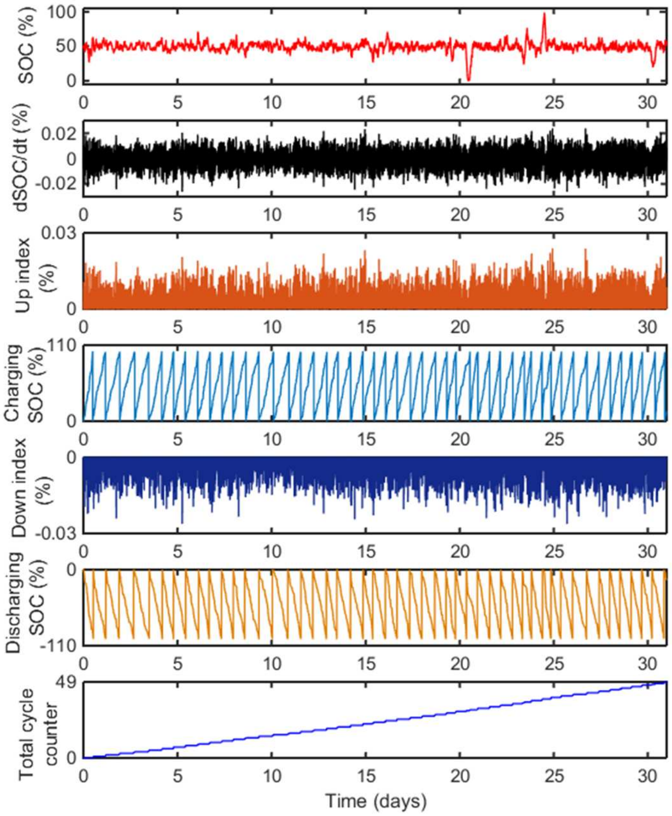


Fig. 4 Simulation results of the fast battery cycle counting estimation method for October 2015.

IV. CONCLUSION

A fast battery cycle counting method for grid-connected BESS, operating in frequency regulation, subjected to microcycles has been developed to achieve an approximation of equivalent battery charge-discharge full cycles. The proposed cycle counting alogrithm detects the total number of cycles endured by the BESS in a given period of time. To demonstrate this, an existing Enhanced Frequency Response control algorithm based on a model of a 2MW/1MWh BESS has been simulated to obtain a historical SOC data set which is then used by the proposed fast battery cycle counting algorithm as an input source. It is revealed that cycle counting for BESS operation in frequency regulation is challenging due to the presence of irregular charge and discharge cycles of varying SOC caused by the real grid frequency variability. The battery cycle life varies for different SOC ranges, therefore all microcycles existing in the SOC profile are extracted to estimate the total battery cycle information. Analysis of the results show that the proposed cycle counting algorithm detects numerous microcycles existing in the considered SOC profile for October 2015 and extracts them to approximate the total full battery charge-discharge cycles. It is revealed that the microcycling for October 2015 approximates to 49 full battery charge-discharge cycles. These cycles can be compared to the manufacturer provided degradation data for full cycles to estimate to aid in the prediction of the BESS SOH. Other factors such charge-discharge rate and temperature should also be considered to give an accurate estimation of SOH, this paper only focuses on the cycle count approximation.

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