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# Aging Characteristics Consideration in Adaptive Control Design of Grid-Scale Lithium-ion battery

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***Abstract*—Lithium-ion battery energy storage systems (Li-ion BESS) have been extensively used for frequency containment reserves for disturbances (FCR-D) and frequency containment reserves for normal operations (FCR-N) in Finland. Typically, for both these applications, active power-frequency (*Pf*) -droop curve defines the Li-ion BESS active power dispatch to the power grid. However, Li-ion BESS's performance is affected due to aging resulting in the reduction of its peak power capability and capacity degradation. These issues needs to be considered when defining *Pf*-droop controller curves. Therefore, adaptive *Pf* -droop control methodology should be developed which considers battery aging characteristics. This will ensure Li-ion BESS to function within its safe operating margins. It also provides the possibility to automatically modify Li-ion BESS control settings and flexibility services provision capability based on battery performance and aging. In this paper, detailed analysis will be performed on the cycling of real-life Li-ion BESS which is installed and operated in Finland in order to understand the cycle aging process when they provide services to FCR-N markets. In addition, an enhanced, simple adaptive *Pf* -droop control curve has been proposed by considering the effect of Li-ion battery aging. Effectiveness and the impact of the proposed adaptive droop control curves will be validated by means of case studies**

**Keywords— Lithium-ion batteries; energy storage systems; adaptive droop control; battery aging;**

## I. INTRODUCTION

Tackling climate change issues has led to rapidly increasing penetration of renewable energy sources (RES) in power systems. One of the major issues in RES integration arises from their intermittency and various ways to mitigate the variability forms a wide range of research topic. BESSs have shown immense capability to address challenges arising due to the RES intermittency in the medium and low voltage (MV and LV) electricity distribution systems, particularity their ability in tendering multiple flexibility / technical ancillary services such as voltage and frequency regulation, black start, load levelling and peak shaving [1].

Recently, Li-ion BESSs have become the forefront choice for utilization in land based grid support applications, by acting as a flexible energy resource (FER) which is capable of providing multiple flexibility services in the distribution system [2]. Most particularly, their appropriate role in short term frequency control applications. In order to enable smooth operation of BESSs in the distribution networks for FCR-N/FCR-D applications, well-co-ordinated automatic BESS controls have to be established in the form of active network management (ANM) schemes. ANM control schemes are typically used to manage voltage or thermal limits related congestion in the distribution network by utilising existing FER, like BESS or RES, reactive and active power (*Q* and *P*) control capabilities together with coordinated control of other options such as transformer on-load-tap-changers [3].

In order to extract FCR-N related services, typical active power-frequency (*Pf*-) droop based controllers (Fig.1) are often used for Li-ion BESS control [4]. Various types of droop controllers have been proposed in the existing literature considering Li-ion BESSs as a solution for system-wide frequency control as well as local distribution network voltage control. Decentralised adaptive droop control tracking the variable virtual resistance was utilised for the BESSs in [5], with the capability of managing bus voltage and load power dispatch keeping the BESS state of charge (SOC) in balance.

Dynamic SOC balance control strategy with an adaptive droop control relying on SOC of the ESSs was established in [6]. Adaptive droop controller for fuel cell-BESS hybrid energy storage system (ESS) was proposed in [7] to minimise the BESS utilisation for frequency support application. The proposed droop controller was for the hybrid ESS as a whole, considering the fuel cell as the primary source, which is complemented by the BESSs, which leads to the decreased cycling and increased lifetime of BESSs. In [8], variable/adaptive incremental cost-voltage droop controllers were proposed based in order to reduce the total battery degradation cost in islanded DC microgrids.

Performance of Li-ion BESSs are affected by various parameters such as depth of discharge, SOC, temperature and aging [9]. Further, performance degradation due to aging, mainly leads to change in battery capacity and their peak power capability. Changes in the peak power capability leads to reduced peak power outputs from Li-ion BESSs, which has not been considered previously in the available droop controller design based literature. Failure to do so might accelerate the overall aging process and may lead to fatality due to internal short circuits, especially when expected peak power can no longer be offered by the Li-ion BESSs, which shall happen particularly when the battery is nearing its end of life.

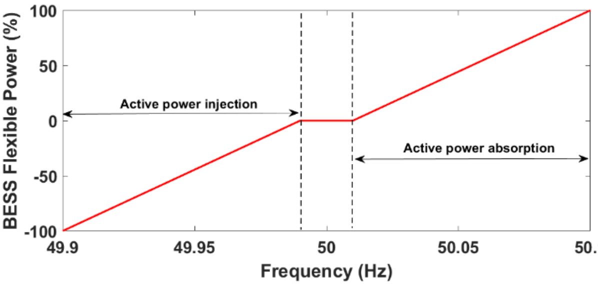

**Fig 1.** Tyspical pf droop curve for BESS participation in FCR-N market

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One of the objectives of this study will be to analyse the impact of load requirements due to FCR-N services on the Li-ion BESS in Finland, mainly in terms understanding their cycling pattern that leads to battery degradation. Followed by proposing an adaptive *Pf-* droop curve, which enables tracking changes in their aging by including the peak power dispatch capability, by keeping power dispatch within its safe operating limits. Therefore, in this paper,

1. Field measurements of Li-ion BESS usage for FCR-N application are used to understand cycling depth and total number of cycles used by means of rainflow counting algorithm [10]
2. Aging model is based on the details provided by manufacturer's datasheet, which describes cycling degradation characteristics of the Li-ion battery at different depth of discharge (DODs)
3. Based on the cycling characteristics of Li-ion BESS in the field and peak power capability decrease due to aging in the battery cells, simple adaptive droop curves have been proposed for better utilisation of Li-ion BESSs for FCR-N and FCR-D applications and the impact such curves on Li-ion BESS operations are analysed

## II. BATTERY FIELD CYCLING ANALYSIS

Battery cell accelerated aging tests in the laboratory are generally performed at higher temperatures and full equivalent cycles of charging and discharging at different current rates in order to observe aging parameters such as internal resistance and capacity loss [11]. However, when utilised in the field, Li-ion BESSs have different depths of discharges at different cycling depths, typically most of the cycle being micro-cycles (very low DODs). In that case, it becomes difficult to predict the Li-ion BESS aging characteristics in the field. Fig. 2 represents the SOC variations of Li-ion BESSs installed in Finland, when utilised for FCR-N services. It can be observed that the cycling characteristics are highly uneven constituting mainly of micro-cycles with very low depths of discharges. Based on the literature, rainflow counting technique [12], which is mainly used in reliability analysis provides an accurate estimate of the overall number of cycles at different DODs, thereby providing an avenue to understand the amount of degradation a particular type of battery has undergone in the field usage.

Fig. 3 shows the results from the rainflow counting algorithms unpacking the information on the cycling characteristics shown in Fig 2. Therefore, from the results, information on total number of micro-cycles, their DODs and occurrences at which particular SOCs shall be gathered. Based on the observation of the results, it is evident that when Li-ion BESSs are utilised for FCR-N application very high number of micro-cycles at low DODs are prevalent. Hence, tracking them is of utmost importance due to its contribution to battery aging.

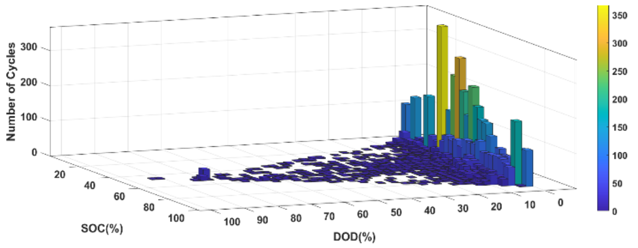

**Fig 3.** Rainflow counting results on field SOC characteristics

## III. BATTERY AGING CHARACTERISATION

Lithium-ion batteries suffer performance degradation due to aging caused by phenomena such as loss of active lithium ions and other active materials, growth of solid electrolyte interface (SEI) layer etc., which in turn are a result of calendric and cyclic aging [13], [14] of the battery cells. These aging processes are affected by battery operating conditions such as temperature, depth of discharge and the magnitude of charge/discharge current (C-rate).

The battery systems when utilised for grid applications are typically installed in an air-conditioning environment, which regulates ambient temperature at pre-defined levels. Hence, temperature as a factor for aging shall be considered constant in this study. However, the power/energy requirements from Li-ion BESSs for FCR-N operations do not follow a steady pattern and is highly variable based on multiple factors such as network parameters, RES intermittency etc. The range of power/energy requirements that Li-ion BESSs can support over a period of time shall vary based on their aging characteristics. Controlling the charge or discharge rate within its maximum allowed power/energy capability of Li-ion BESSs based on the aging of Li-ion batteries forms an important factor in their planning and utilisation, as they lead to efficient operations within the safe operating regions at all times.

Fig. 4 shows the aging characterisation of Li-ion BESSs from the manufacturer's datasheet utilised in Finland for FCR-N applications. Data from Fig.4 provides us with the number of cycles the battery can support at different DOD's (0 to 100%). The usable capacity ($CAP_{BESS}$) is calculated from (1), which is just the difference between the battery capacity at beginning of its life ($CAP_{BOL}$) and its end of life ($CAP_{EOL}$). From both of these information, capacity lost per cycle at different DODs ($CAP_{LOSS,DOD}$) can be calculated from (2). The cumulative loss of battery capacity ($CAP_{LOSS,CUMULATIVE}$) when cycled in the field is caused due to different cycle depth. The information on total number of cycles at different DODs is obtained from the result of using rainflow-counting algorithm in previous section. Therefore,

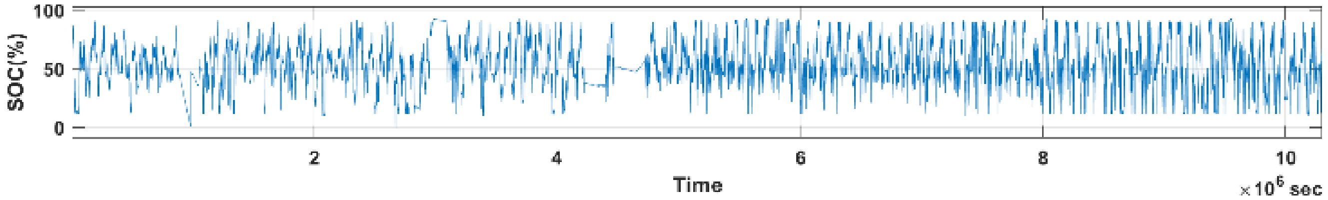

**Fig 2.** Measured real-life BESS SOC behaviour when utilised for FCR-N frequency control markets

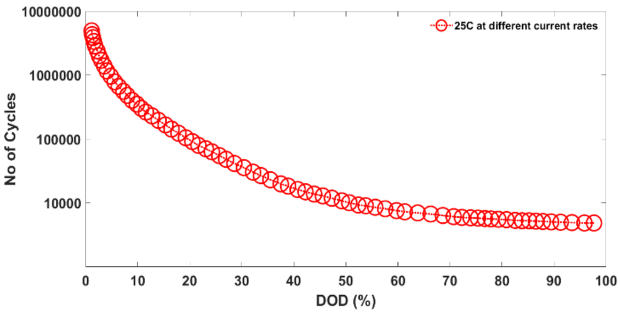

**Fig 4.** Battery aging curve from manufacturer's datasheet based on DoD

$CAP_{LOSS,CUMULATIVE}$ is calculated from (3) where $N_{DOD_n}$ represents number of battery charge/discharge cycles at DOD, *n*. The remaining battery capacity is then calculated by (4). However, the parameter of interest for designing adaptive droop curves is the peak power capability ($P_{PEAK}$) of the battery. State of health (SOH), which gives indication on the evolving $P_{PEAK}$ of the Li-ion BESS is calculated by (5). $P_{PEAK}$ is calculated by (6), where it's a function of $P_{PEAK,BOL}$ corresponds to the Li-ion BESS active power peak during their beginning of life (BOL) and SOH. $P_{PEAK,BOL}$ is obtained from manufacturer's datasheet. Both calculated $P_{PEAK}$ and $P_{PEAK,BOL}$ considered in this study corresponds to the peak power of the battery at 100% SOC. By this means, SOH shall form an input for the Li-ion BESS control loop design for their adaptive control considering aging characteristics. It has to be noted that the ($P_{PEAK}$) at various instances of aging is not a electrochemical hard limit on the Li-ion BESSs, i.e. at SOH of 80%, the batteries are still capable of dispatching peak power at SOH 100%, however, this may accelerate aging to higher magnitudes and may pose significant safely challenges in the long run. Such challenges can be verified by further experimental studies alone.

## IV. PROPOSED DROOP CURVE

Conventional droop control techniques help in managing the output power of an inverter based distributed energy resources (DERs) by local measurement of power system parameters such as current, voltage, frequency, etc. [15]. Based on these measurements, the output power (active and reactive power, *P* and *Q*) of DERs are dispatched by means of droop curves, as depicted in Fig. 1. It is very similar to the operation of conventional generators. Conventional droop curves are designed based on (7), where the required frequency, $f$, is a function of $f_0$, rated frequency of the DER, droop constant $K_p$, DER rated power $P_0$ and DER power dispatch $P$. The value of $K_p$ which decides the slope of the droop controller is as shown in (8), is a function of difference between desired and measured frequencies, $\Delta f$ and maximum active power $P_{max}$ of the DER. Li-ion BESS enables bi- directional power flow by means of charging and discharging characteristics. It has to be observed that the peak power ($P_{PEAK}$) during both charging and discharging powers are affected due the capacity fade of battery systems with aging, i.e. their state of health (SOH). Hence, this property needs to be integrated in the droop controllers making them adaptive in nature. The slope of the adaptive droop controller will be facilitated by (8), which is a function of $\Delta f$ and $P_{PEAK}$ (affected by SOH).

The calculated value of $P_{PEAK}$, being a function of SOH, thereby provides the way to introduce Li-ion BESS aging

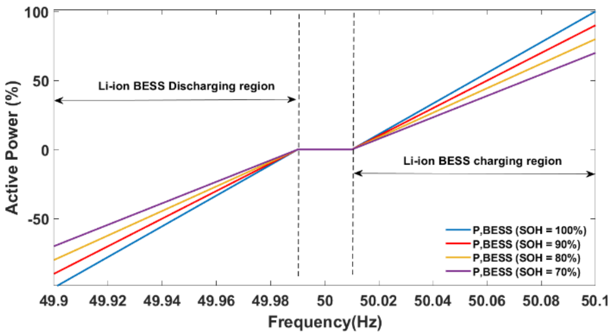

**Fig 5.** Proposed adaptive droop controller

**Table I.** Li-ion BESS Peak Power Calculations

| SOH (%) | Peak Power (kW) |
|---|---|
| 100 | 300 |
| 90 | 270 |
| 80 | 240 |
| 70 | 210 |

$$CAP_{BESS} = CAP_{BOL} - CAP_{EOL} \quad (1)$$

$$CAP_{LOSS,DOD} = \frac{CAP_{BESS}}{N_{CYC,DOD}} \quad (2)$$

$$CAP_{LOSS,CUMULATIVE} = \sum_{i=1}^{n} N_{DOD_1} * CAP_{LOSS,DOD_1} + N_{DOD_2} * CAP_{LOSS,DOD_2} + \cdots + N_{DOD_n} * C_{LOSS,DOD_n} \quad (3)$$

$$CAP_{REM} = CAP_{BOL} - CAP_{LOSS,CUMULATIVE} \quad (4)$$

$$SOH = \frac{CAP_{REM}}{CAP_{BOL}} \quad (5)$$

$$P_{PEAK} = SOH * P_{PEAK,BOL} \quad (6)$$

$$f = f_0 + K_p(P_0 - P) \quad (7)$$

$$K_p = \frac{\Delta f}{P_{max}} \quad (8)$$

$$K_p = \frac{\Delta f}{P_{PEAK}} \quad (9)$$

characteristics to be included in the adaptive droop controller curve design for battery systems. $P_{PEAK}$ of the Li-ion BESS at different SOH is represented in Table I, whose values are calculated based on (6). These values are then utilised to develop adaptive droop control mentioned in Fig. 5, providing inputs of changing peak power capability of the battery system. The proposed adaptive droop controller, whose droop curve slopes are dependent on equation (9), providing a range of power dispatch considering battery aging. Fig. 5 represents the droop curves at different SOH levels for both charging and discharging operations of the Li-ion BESS, whose peak power charge/discharge decreases with aging characteristics. Evolution of $P_{PEAK}$ with aging has been represented in Fig. 5, thereby, embedding adaptive droop characteristics for Li-ion BESS control in order maintain the power dispatch within the allowable limits dictated by the battery's SOH at all times. Following section explains the design of controller for Li-ion BESS including the proposed droop curve.

## V. CASE STUDY

To understand the effectiveness and impact of the adaptive droop curves proposed in section V, case study is conducted on an installed Li-ion BESS in Finland. The specification of the battery system is shown in Table II, whose functionality includes *Pf*- control for FCR-N operation despite supporting other applications. Based on the data sheet information, the peak power supported by this battery system is about 300 kW in the BOL conditions. It is also stated that the EOL conditions are attained when its capacity is reduced by 30%, which provides the peak power calculation to be about 210 kW. Two sub-cases are further considered, where the first sub- case considers the Li-ion BESS which is at its BOL and the second sub-case depicts the operation of Li-ion BESS towards its EOF.

**Table II.** Lithium-ion Battery Characteristics

| | |
|---|---|
| Nominal DC voltage | 700 V |
| Peak Voltage | 790 V |
| Cut-off Voltage | 588 V |
| Nominal Power | ~100 kW |

### *A. Sub-case 1: Li-ion BESS at BOL*

The characteristics of the installed Li-ion BESS is shown in Table II, which is designed for a continuous nominal power of 100 kW with peak support upto 300 kW (pulsed in nature). In this sub-case, the battery is considered at its BOL. One of the purposes of this Li-ion BESS is to provide FCR-N related services, i.e. to stabilize the grid frequency within the limitations specified by grid codes. The field measurements of the grid frequency for three months, .i.e. Dec-2019 to Feb-2020 within the ranges mentioned in Table I is shown in Fig. 6. The active power dispatched by the Li-ion BESS in order to mitigate frequency fluctuation by means of providing FCR-N operations are shown in Fig. 7. They are based on the droop control curve depicted in blue in Fig. 5, which corresponds the BOL characteristics. It is evident that the range of frequency fluctuations has been predominantly between 49.9 Hz to 50.1 Hz and the active power dispatch in the Li-ion BESS has been upto the maximum of 300 kW, by means of *Pf*- droop curve shown in Fig. 1, whose 100% power corresponds to 300 kW. Therefore, the basic non-adaptive droop curve is able to support all the battery-

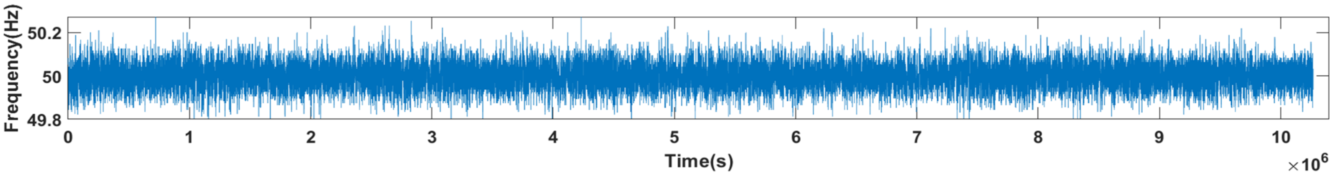

Fig 6. Power System Frequency

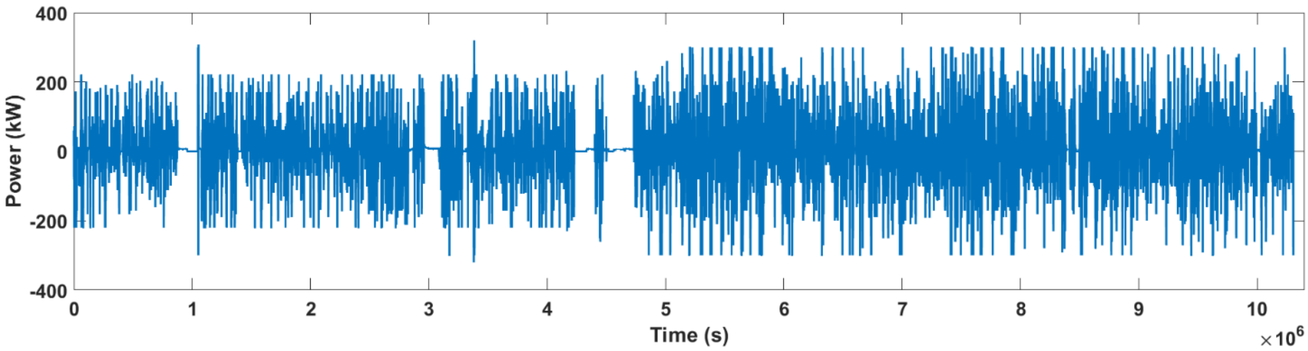

**Fig 7.** FCR-N supported by Li-ion BESS during BOL

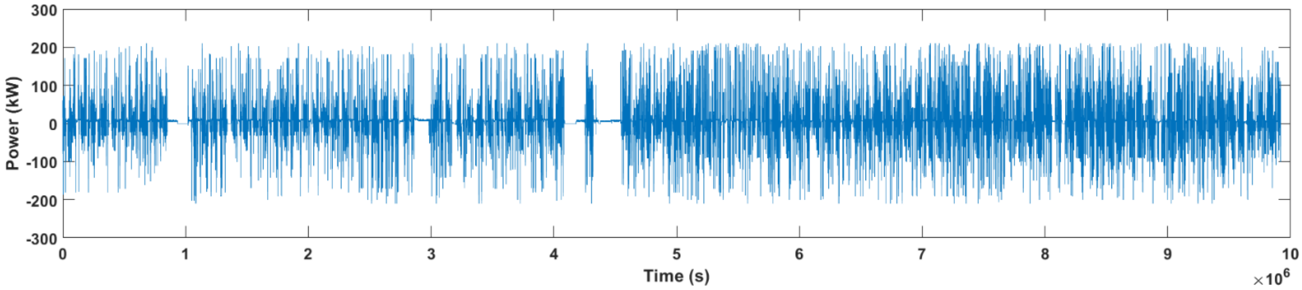

**Fig 8.** Li-ion BESS power dispatch for FCR-N during BOL

required operations at its BOL, whicxh corresponds to the blue line in Fig. 5.

### *B. Sub-case 2: Li-ion BESS at EOL*

Degradation of Li-ion BESSs is a serious concern, particularly when it will be utilized for FCR-N purposes, due to their mission profiles, which seek high power charge/discharge in a shorter span of time, evident from the field data characteristics. The SOH calculation of the Li-ion BESS due to its cycling, its relative capacity loss and subsequently the changes in their peak power capability has been explained in section III. Therefore, to avoid over charging/discharging and to maintain the Li-ion BESSs peak power discharge always within peak power capability at all times, an adaptive droop curves have been designed (section's IV and V). This sub-case has been performed to understand the impacts of the changing Li-ion BESS characteristics (predominantly its peak power characteristics) with respect to aging.

In the previous sub-case where new Li-ion BESS was utilized FCR-N application, it has been observed that the battery dispatch power reaches its peak limit of 300 kW (Fig. 7). During the Li-ion BESSs BOL all FCR-N loads were supported. In this sub-case, we consider the same Li-ion BESS towards its EOF, i.e. capacity of the battery has reduced by 30% of its initial value and that of its reduction in peak power characteristics.

However, based on the proposed SOH sensitive adaptive droop curves, it is evident that the peak power discharge is limited to about 210 kW for the installed Li-ion BESS system towards its EOF. The droop curve dictating Li-ion BESS power flow under these circumstances corresponds to violet colored line in Fig. 5. Hence, the frequency ranges supported for FCR-N operations by BESS towards its EOF, when the proposed adaptive curve is used, is as shown in Fig. 8. The corresponding Li-ion BESS charge/discharge power dispatch is shown in Fig. 9, whose characteristics are different, compared to the battery in its BOL. The charge/discharge power ranges more than 210 kW were not supported, thereby safeguarding the battery operations within their threshold operational limits. Further, it can be observed that the FCR-N operations seeking more than 210 kW power has not been entertained by the droop curve.

## VI. CONCLUSION

Integrating battery-aging characteristics in the control and planning of Li-ion BESSs for grid applications improves overall utilisation of batteries and helps maintain their operations within the safe operating regions. Control of these Li-ion BESSs for FCR-N operation are generally defined by typical Pf- droop curves as in Fig. 1. However, the Li-ion battery degradation characteristics tend to reduce the peak power charge/discharge capability of the BESS. To address this issue, an adaptive droop curve has been proposed which modifies the Li-ion BESSs peak active power capability based on its SOH. The impact of such adaptive droop curves were analysed by means of case studies and it has been established that, as the battery ages, it is advised to omit certain range of FCR-N services (preferably high power charge/discharge operation) keeping the battery safety in check. Thereby, solving the problem of managing the battery charge/discharge operations always within the threshold of their peak active power performance. In order to reduce the computational requirements of counting the cycles of battery usage by means of rainflow counting technique(section III), this task shall be performed periodically (say for e.g. 30 days interval) rather than in real time, as the battery degradation is a slow process and update its corresponding peak power characteristics in the battery inverter control settings.

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