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Lifetime Perspective

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Suggested Operation of Grid-Connected Lithium-Ion Battery Energy Storage System for Primary Frequency Regulation: Lifetime Perspective

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Abstract—**Because of their characteristics, which have been continuously improved during the last years, Lithium ion batteries were proposed as an alternative viable solution to present fast-reacting conventional generating units to deliver the primary frequency regulation service. However, even though there are worldwide demonstration projects where energy storage systems based on Lithium-ion batteries are evaluated for such applications, the field experience is still very limited. In consequence, at present there are no very clear requirements on how the Lithium-ion battery energy storage systems should be operated while providing frequency regulation service and how the system has to re-establish its SOC once the frequency event has passed. Therefore, this paper aims to investigate the effect on the lifetime of the Lithium-ion batteries energy storage system of various strategies for re-establishing the batteries' SOC after the primary frequency regulation is successfully delivered**

Keywords— Frequency Regulation, Energy Storage, Lithium-Ion Battery, Operation, Lifetime

I. INTRODUCTION

Traditionally, the electrical energy has been generated by conventional power plants (CPPs), which are able to regulate their production in order to deliver non-fluctuating power according to a predefined schedule. Nevertheless, driven by various concerns, the energy generation paradigm is shifting from conventional generation based on fossil-fuels to distributed generation based on renewable resources, especially wind and photovoltaic [1].

On the other hand, because of its characteristics (e.g., variable and less-predictable), the grid integration of renewable power might challenge the stable and reliable operation of the grid, especially in countries with an increased penetration level of renewable energy sources (e.g., Denmark, Spain, Germany) [2], [3]. The most common solution used, at present, to mitigate the aforementioned challenges is to commit spinning reserves, which are provided by fast-responding conventional generating units (CGU) [4]. However, in the chase for more environmentally friendly alternatives to the traditional use of fast-responding CGUs, several other solutions have been proposed: large scale aggregation of wind power plants [5], improvement of the wind forecast methods (short- and long-term) [6], improvement of the demand side management techniques [7], and the use of energy storage systems (ESSs) as power and energy buffers [3], [5], [8], [9].

This paper focuses on the use of the latest mentioned solution (i.e., ESSs) for maintaining the stable operation of the grid by providing primary frequency regulation (PFR). Among the available energy storage technologies, Lithium-ion (Li-ion) batteries represent suitable solutions because of their features (i.e., fast response, high power capability, long cycle lifetime at partial cycles, low self-discharge rate), which are matching very well the requirements of the PFR service [10]. Furthermore, because of the aforementioned characteristics, the use of ESSs based on Li-ion batteries for providing frequency regulation is already evaluated in several demonstration projects worldwide [11], [12].

Currently, there are no specific requirements on how the PFR service should be provided by the ESSs, except the response time, time duration (e.g., 15 minutes) and power linearity (i.e., power must increase linearly with the frequency deviation), which were mainly derived for fast-responding CGUs. Thus, the operating strategy of the Li-ion battery ESS (LiBESS) when delivering PFR might be optimized, especially during the SOC re-establishing periods after service delivery.

The capacity and power capability of Li-ion batteries are incrementally degrading, while the batteries are being operated. Thus, the use of Li-ion batteries for a certain application is limited by its lifetime. Moreover, different battery operation scenarios will result in different expected battery lifetime values. Therefore, this paper investigates which control strategy is more suitable, from the Li-ion batteries lifetime perspective, for delivery PFR service with LiBESS.

The paper is structured as follows: the main characteristics of Li-ion batteries are presented in Section II; in the same section, a lifetime model which is able to estimate the capacity fade of the Li-ion batteries is introduced. Section III discusses the characteristics of the PFR service and the use of LiBESS for this application. Furthermore, five different control strategies for delivering PFR with LiBESS are proposed. The results regarding the lifetime of the batteries for the proposed control strategies are presented and discussed in Section IV. Finally, conclusions are drawn in Section V.

II. Lithium-Ion Batteries. Lifetime Model

A. Lithium-ion Battery Family

After dominating the consumer electronics market, Li-ion batteries have become the key technology for the e-mobility applications (electrical vehicles, plug-in electric vehicles etc.) [13]. Driven by the research and development carried out in the two aforementioned sectors, the characteristics of Li-ion batteries have improved continuously. Therefore, because of their outstanding performance such as high efficiency, fast response, low self-discharge rate, long calendar and cycle lifetime, Li-ion batteries have become attractive for short- and medium–time (i.e, minutes to one hour) stationary energy storage applications [13], [14].

At present there are many Li-ion battery chemistries available on the market, each of them with their unique advantages and drawbacks [14], [15]. The PFR application, which is considered in this research, is less demanding in terms of weight and volume (i.e., specific energy and energy density), but more demanding in terms of lifetime (long calendar and cycle lifetime) and self-discharge (low self-discharge) [10]. One of the Li-ion battery chemistries that at present fulfils the best these requirements is the lithium iron phosphate (LFP/C) chemistry. Consequently, this work was carried out considering a LiBESS based on the LFP/C chemistry.

B. Lifetime of LFP/C-based Batteries

It is well known that independent on the chemistry, the performance parameters of Li-ion batteries are degrading in time; this process is also known as ageing. Thus, in order to analyze the long term behaviour of the LFP/C-based batteries in a certain application, information about the ageing behaviour of its performance parameters, capacity and power capability, are mandatory.

A lifetime model, which is able to predict the ageing behaviour of the LFP/C-based batteries, was developed based on the accelerated ageing methodology presented in [16]. The obtained results are extensively presented and discussed in [17]. A shown in [17], for the considered battery chemistry, the capacity, and not the power capability, is the performance parameter, which limits the lifetime of these batteries. Consequently, the lifetime analysis carried out in this work is related only to the capacity of the LFP/C batteries.

The lifetime model, which estimates the capacity fade of the LFP/C battery cells for cycle conditions at 25°C is given by (1) [18]. Moreover, the capacity fade lifetime model for idling (stand-by) at 25°C is given by (2) [18].

$$C_{f\_cyc} = 0.021 \cdot e^{-0.01943 \cdot SOC\_av} \cdot cd^{0.7162} \cdot nc^{0.5} \tag{1}$$

$$C_{f\_cal} = 0.1723 \cdot e^{0.007388 \cdot SOC\_l} \cdot t^{0.8} \tag{2}$$

Where, *cd* represents the cycle depth, *nc* the number of cycles for a certain cycle depth, *SOC_av* represents the average SOC level during one cycle, *SOC_l* represents the storage SOC level, *t* represents the storage time (expressed in months), and C_{f_cyc} and C_{f_cal} represent the capacity fade during cycle and idling, respectively.

Based on the developed cycle lifetime model (1), one can obtain the lifetime characteristic (see Fig. 1), which presents the number of cycles that the LFP/C battery can perform for every cycle depth, until its capacity drops below 80% of the initial capacity. Similarly, based on the calendar lifetime model (2), the capacity decrease during calendar ageing (when the battery is idling) and its dependence on the SOC-level at which the LFP/C battery is idling was estimated and is presented in Fig. 2.

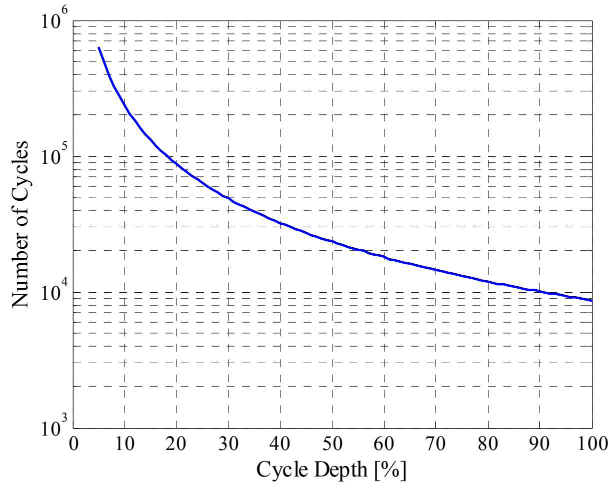

Fig. 1. Lifetime characteristic of the LFP/C battery for cycling at 25°C (valid for a 20% capacity fade end-of-life citerion).

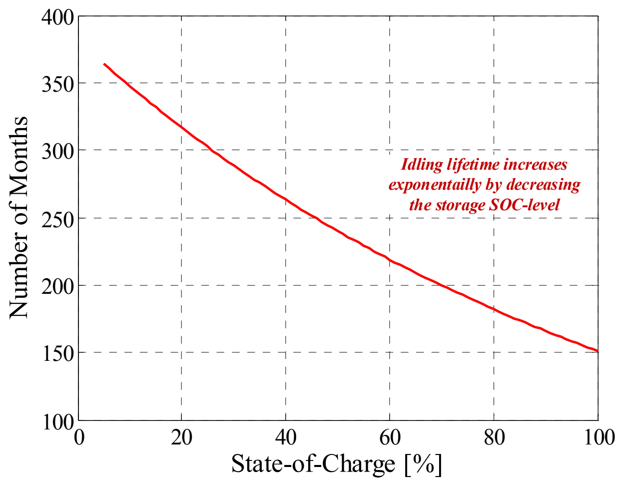

Fig. 2. Calendar lifertime characteristic of the LFP/C battery cell idling at 25°C and various SOC-levels (valid for a 20% capacity fade end-of-life criterion).

As shown in Fig. 2 and given in (2), the calendar lifetime of the studied LFP/C battery cells decreases exponentially by increasing the idling SOC-level. Thus, this stress factors (i.e., storage SOC-level) has to be carefully considered, when the energy management strategy of the LiBESS is developed.

III. PFR WITH LIBESS

A. *PFR with LiBESS*

Traditionally, fast-reacting CGUs, which are online, are providing PFR by increasing or decreasing their production depending if under-frequencies (i.e. $f < 49.98$) or over-frequencies (i.e. $f > 50.02$) were detected, respectively. In a similar manner, grid-connected LiBESSs can provide downward-regulation by charging from the grid and upward-regulation by discharging to the grid, as shown in Fig. 3.

Usually, the PFR service has to be supplied linearly, according to the droop presented in Fig. 1, at frequency deviations between ± 20 mHz and ± 200 mHz from the reference grid frequency of 50 Hz; a dead band of ± 20 mHz around the reference frequency is allowed. The maximum power has to be supplied for maximum 15 minutes, after which a break of 15 minutes is allowed for the reserve to be re-established [19]. Nevertheless, it has to be highlighted that these requirements were established for CGUs and not for ESSs providing PFR.

The behaviour of the LiBESS is straightforward when it has to inject or absorb power according to the frequency event. However, there are no clear requirements on how the LiBESS state-of-charge (SOC) has to be re-established after the event has passed. Thus, this paper proposes three different strategies for SOC re-establishing after the PFR service was delivered.

B. *SOC Re-establishing Strategies:*

The studied strategies influence the energy management of the LiBESS and result in different usage levels of the Li-ion batteries; this will further result in different lifetime values for the LiBESS.

Li-ion batteries have power limitations during discharge at low SOC levels and charge at high SOC levels. Consequently, in order to ensure power linearity with frequency deviation (see Fig. 3), the SOC operation window of the LiBESS was reduced to 10%-90%, for all considered strategies. Moreover, the idling SOC of the LiBESS is set to 50%, allowing the LiBESS to participate in both upward and downward regulation markets.

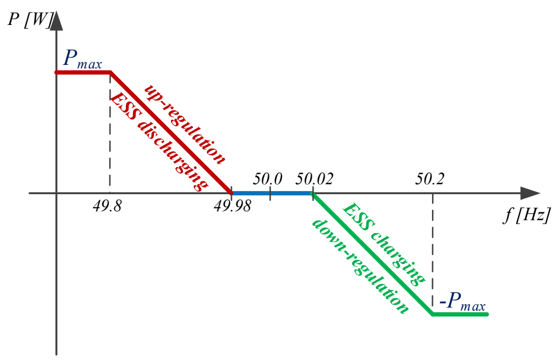

Fig. 3. The characteristic of the PFR service and the action of the LiBESS according to the frequency event.

1) *Strategy A:* By using this strategy, the SOC of the LiBESS is re-established at every time instant when the grid frequency enters the frequency dead-band (i.e., 50Hz ± 20 mHz). Furthermore, in the rare case when the frequency event lasts for more than 15 minutes, the PFR service is interrupted after 15 minutes and the SOC of the system is re-established (at 50%). The flowchart of this strategy is presented in Fig. 4.

There exist transmission system operators (TSOs) which allow the energy market players to participate only in the upward-regulation market or in the down-regulation market and not in both [19]; this is the case of the Danish TSO, Energinet.dk, but also of countries like UK, Ireland, and Belgium [19]. Thus, two strategies were derived from Strategy A. In the first strategy, "Strategy A-down" the LiBESS participates only on the down-regulation market and its SOC is set at 10%. In this case the SOC is re-established when the frequency of the grid is lower than 50.02 Hz. Similarly, in the case of "Strategy A-up", the LiBESS participates only on the up regulation market and its SOC is set accordingly at 90%.

2) *Strategy B:* In the case of this strategy, the LiBESS participates in both up- and down-regulation markets and the SOC of the system is set at 50%. However, for Strategy B, the SOC is re-established only when the lower and upper SOC boundaries (i.e., 10% and 90% respectively) are reached. The flowchart corresponding to this SOC re-establishing strategy is presented in Fig. 5.

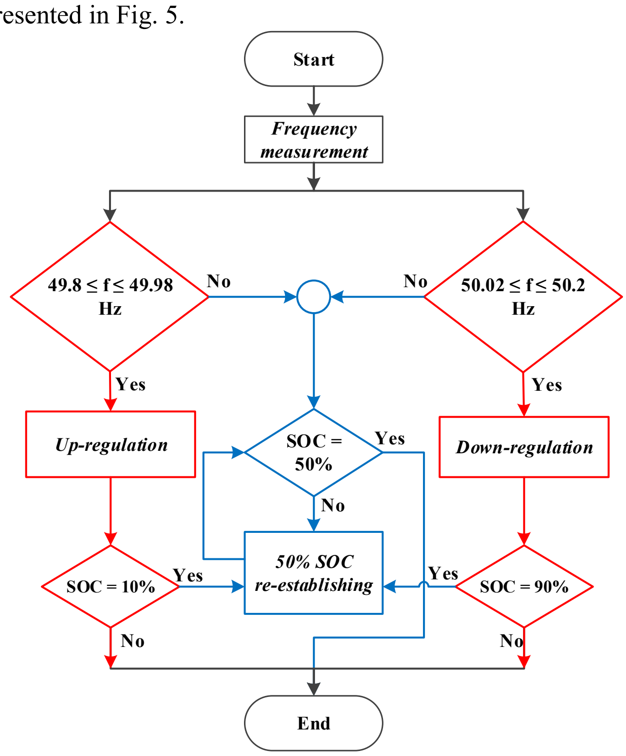

Fig. 4. Strategy A (PFR delivery and SOC re-establishing are highlighted in red and blue, respectively).

3) *Strategy C:* This strategy is based on the assumption that the delivery of the PFR service and the re-establishing of the LiBESS SOC take place in parallel. However, the re-

establishing of the SOC is realized with a lower time constant than the time constant used to deliver the service. The flowchart of this strategy is presented in Fig. 6.

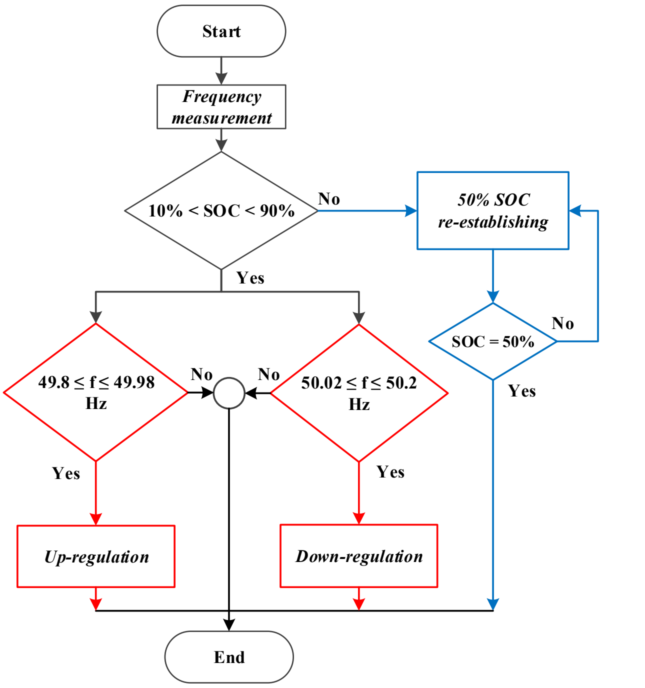

Fig. 5. Strategy B (PFR delivery and SOC re-establishing are highlighted in red and blue, respectively)

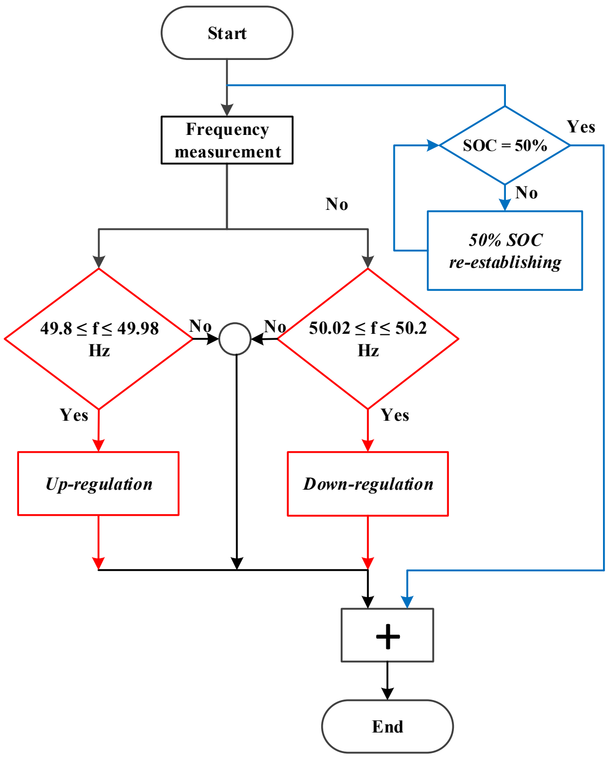

Fig. 6. Strategy C (PFR delivery and SOC re-establishing are highlighted in red and blue, respectively)

IV. Results

A. LiBESS mission profile

In order to analyze the influence of the SOC re-establishing strategy on the lifetime of the LiBESS, a one year frequency profile was considered. The frequency profile, presented in Fig. 7, was obtained from field measurement during the period March 2013 – February 2014. Based on the frequency profile and considering the proposed strategies (i.e., A, A-down, A-up, B and C), five distinct one year SOC mission profiles were generated, one for each strategy. Fig. 8 presents a comparison between the SOC profiles obtained for the five strategies for a one month time interval.

The obtained SOC profiles were decomposed into a cycle mission profile and a calendar mission profile in order to be applied to the developed lifetime models. The results are summarized in Table I, showing in percentage, the periods when the LiBESS was cycled at various conditions (i.e., average SOC-level and cycle depth) and the periods when the system was idling at various conditions (i.e., SOC-level). As illustrated in Table I, the LiBESS is subjected to different ageing conditions, depending on the applied SOC re-establishing strategy, which will result in different estimated lifetime values for the system. Nevertheless, for most of the considered strategies (except Strategy C), the periods in which the LiBESS is idling are much longer than the periods when the LiBESS is cycled. Consequently, it is expected that the calendar ageing component will have a high influence on the total degradation of the LiBESS.

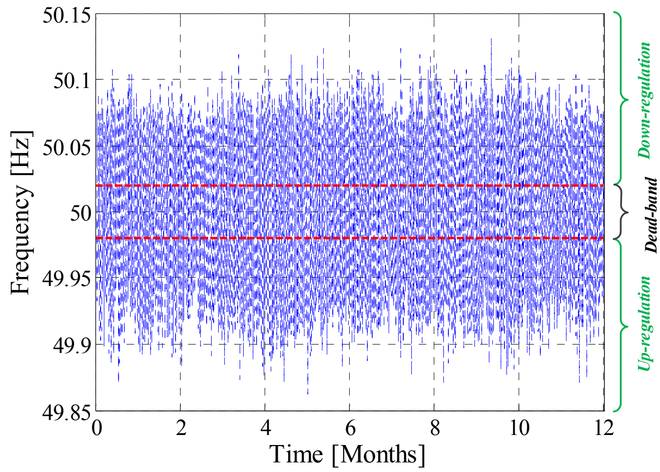

Fig. 7. Field measured frequency profile for a period of one year (March 2013 – February 2014).

TABLE I. Decomposition of the LiBESS Operation Profile into Periods of Cyclcing and Periods of Idling

SOC re-establishing strategy	Periods of cycle ageing [%]	Periods of calendar ageing [%]
Strategy A	34.38	65.62
Strategy A-down	17.63	82.37
Stratgey A-up	16.29	83.71
Strategy B	32.18	67.82
Strategy C	67.05	32.95

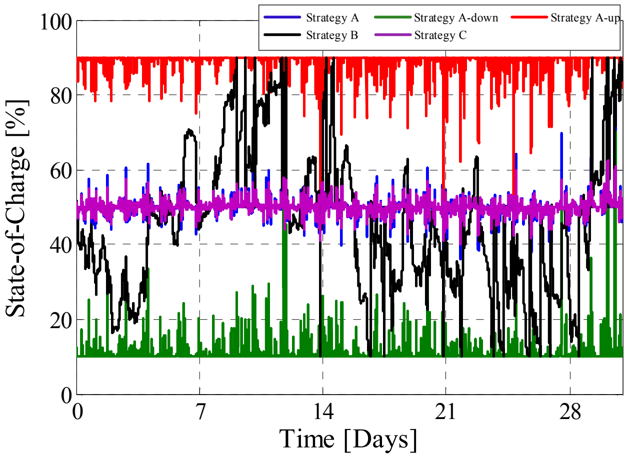

Fig. 8. SOC profile of the LiBESS corresponding to the five strategies for re-establishing the SOC of the system (one month)

B. *LiBESS Lifetime Estimation*

In order to apply the cycle mission profile to the developed lifetime model (1), the SOC profiles (corresponding to the five strategies) were decomposed into cycles of different cycle depths, which were performed at different average SOC levels. For this purpose the rainflow cycle counting algorithm was used. The number of cycles performed by the LFP/C battery at each cycle depth and average SOC level, for the proposed SOC re-establishing strategies are presented in Fig. 9. Furthermore, it has to be highlighted that the extracted number of cycles correspond to both periods of PFR delivery and SOC re-establishment.

The obtained number of cycles (for different cycle depths and average SOC-levels) were applied at the input of the developed lifetime model (1) and the degradation behaviour of the LiBESS was obtained together with the expected lifetime for each of the five proposed SOC control strategies. Because the SOC profile was available only for a period of one year and the expected lifetime of the LFP/C batteries is in the range of years, the SOC profile was applied at the input of the lifetime model successively until the predefined end-of-life criterion, of 20% capacity fade, was reached. During all the simulations, the temperature of the LFP/C batteries was considered constant and equal to 25°C [11], [17].

By considering a constant operating temperature of 25°C and applying the SOC mission profile, which corresponds to each of the five control strategies, to the developed LFP/C battery lifetime, the degradation behaviour of the LFP/C batteries expressed in terms of capacity fade was obtained. The results are presented in Fig. 10.

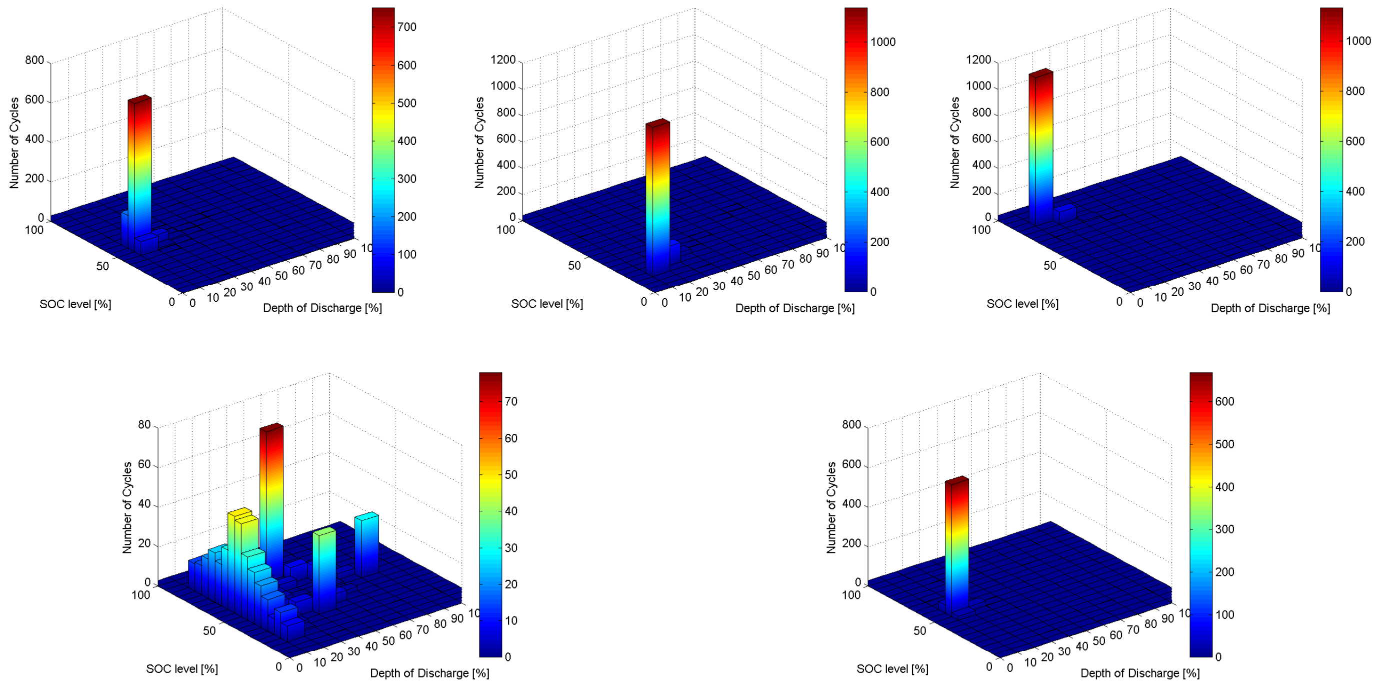

Fig. 9. Distribution of cycles according to their average SOC-level and cycle depth to which the LiBESS was subjected for each of the considered SOC re-establishnig strategies; the number of cycle correspond to one year of operation (top: Strategy A, Startegy A-down, Strategy A-up; bottom: Strategy B and Strategy C).

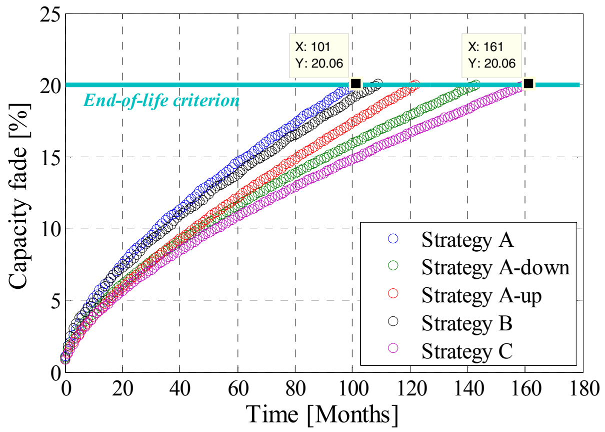

Fig. 10. Estimated capacity fade behaviour of the LiBESS when it is subjected to different SOC re-establishing strategies (for a 20% capacity fade EOL criterion).

TABLE II. DECOMPOSITION OF THE LIBESS TOTAL OPERATING CAPACITY FADE AS A FUNCTION OF THE CAPACITY FADE DUE TO CYCLCING AND IDLING

SOC re-establishing strategy	Cycle ageing [%]	Calendar ageing [%]
Strategy A	13.773	6.2912
Strategy A-down	11.847	8.1894
Stratgey A-up	5.6912	14.328
Strategy B	11.822	8.2308
Strategy C	11.670	8.3861

Furthermore, the estimated individual contribution of the calendar ageing dimension and of the cycling ageing dimension to the total capacity fade caused by the operation are summarized in Table II.

As one can observe in Fig. 10, the longest lifetime, approx. 13.5 years for an end-of-life (EOL) criterion of 20% capacity fade, for the LiBESS is obtained when the SOC of the system is re-established using the Strategy C. On the contrary, the shortest LiBESS lifetime (i.e., 8.5 years) was obtained for the case when the SOC of the system is re-established using Strategy A. The longest LiBESS lifetime obtained for Strategy C is due to the fact that the system is cycled less than in the case of Strategy A and Strategy B since the re-establishing of the SOC was performed in the same time with the provision of the PFR service (this resulted in a low variation of the SOC values – see Fig. 8). Nevertheless, the drawback of the Strategy C is that in order to provide the service and to re-establish the LiBESS SOC, two separate power converters have to be considered; this constraint will result in a higher price of the LiBESS. Alternatively, one converter can be used, which will provide the difference between the power expected to be delivered and the power needed to re-establish the SOC of the LiBESS.

For both Strategy A-down and Strategy A-up, the estimated lifetime of the LiBESS is longer than in the case of the basic Strategy A. However, these strategies make sense only in grids where the TSOs allow for asymmetrical PFR market bidding.

C. *PFR success delivery ratio*

For four of the consider control strategies (i.e., Strategy A, Strategy A-down, Strategy A-up, and Strategy B), there will be moments when the LiBESS will not be able to provide the PFR

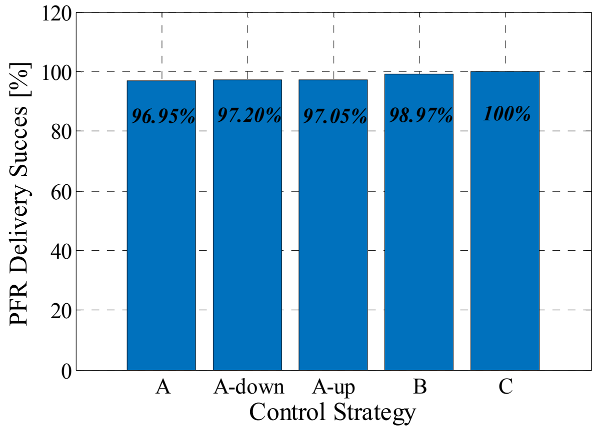

Fig. 11. Comparison of the PFR delivery success ratio for the considered LiBESS control strategies.

service because the SOC of the system has to be re-established to its set-point or because it is saturated to minimum or maximum SOC. By its considered characteristic, Strategy C does not fall in any of the aforementioned situations. Thus, in order to analyze, which of the proposed strategies allows the LiBESS to deliver better the service, the PFR delivery success ratio was computed. As illustrated in Fig. 11, the best service delivery ratio is obtained when the SOC of the LiBESS is re-established using Strategy C. On the contrary, the worst ratio was obtained for Strategy A; this result is caused by the fact that for Strategy A, the SOC of the system is re-established immediately after the PFR service was provided, even though this action did not last 15 minutes.

V. CONCLUSIONS

Li-ion battery energy storage systems represent appealing alternative solution to traditionally CGUs for providing the PFR service. However, at present there are no clear requirements on how the LiBESS should provide this service and how the SOC of the battery has to be re-established after the PFR service was successfully delivered. Thus, this paper has investigated from the LiBESS lifetime perspective the suitability of five strategies for delivering the PFR and re-establishing the systems' SOC. As illustrated, the considered strategy has a big influence on the lifetime of the system; for the proposed PFR delivery and SOC re-establishing strategies, the expected lifetime of the LiBESS has varied between 8.5 and 13.5 years. Furthermore, it was presented that the proposed LiBESS control strategies have resulted in different PFR delivery success ratios (between 96.95% and 100%). Both analyses, have concluded that Strategy A (i.e., symmetrical participation in both up- and down-regulation markets and SOC re-establish immediately after each frequency event passed) is the less suitable strategy for PFR delivery and LiBESS SOC re-establishment.

For the analysis presented in this paper, only the lifetime perspective of the LiBESS system was considered. Nevertheless, the suggested operation of the LiBESS for providing PFR has to consider besides the LiBESS lifetime also the market prices for upward and downward regulation; this aspect will be taken into consideration in a future work.

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