Analysis of the Minimum Activation Period of Batteries in Frequency Containment Reserve

Raphael Hollinger, Agustín Motte Cortés and Thomas Erge
Intersectoral Energy Systems and Grid Integration Fraunhofer Institute for Solar Energy Systems ISE
Freiburg, Germany
raphael.hollinger@ise.fraunhofer.de

Bernd Engel
Technical University of Braunschweig, Institute for High Voltage Technology and Electrical Power Systems - elenia
Braunschweig, Germany

***Abstract*— The capacity of battery energy storage systems (BESS) to adjust power output swiftly and precisely makes them ideal for provision of frequency containment reserve (FCR), the fastest type of frequency control. Since BESS are only recent providers of FCR, there is uncertainty in the applicable requirements while regulation adapts to BESS. In this paper, the minimum activation period as an unresolved regulation issue is investigated. Therefore, two generic methods to calculate the resulting limits of the normal operation range are introduced (considering and not considering corrective power) and compared for a minimum activation period of 15 and 30 minutes. The operation of BESS providing FCR was simulated based on the two calculation methods for numerous system designs. Results of these simulations demonstrate the significance of the regulation on BESS operation and design. Shorter minimum activation period reduces required corrective energy and increase income potential from FCR significantly.**

***Index Terms*-- Battery Energy Storage Systems (BESS), Corrective Power, Frequency Containment Reserve, Minimum Activation Period, Power Reserve Markets**

I. INTRODUCTION

To guarantee operational security in any grid, it is critical to maintain the system's frequency close to its nominal value by means of a power control reserve. In Europe, the ENTSO-E is in charge of dimensioning and operating said reserve, while the national transmission system operators (TSOs) are in charge of its allocation, supervision and deployment. Frequency containment reserves (FCR) are deployed first, after which automatic frequency restoration reserve (aFRR) and manual frequency restoration reserve (mFRR) are activated. Lastly, the replacement reserves (RR) initiate provision as support for additional system imbalances [1].

Traditionally, power control reserve has been provided by conventional power plants. Because of their long start up time, thermal plants providing FCR and aFRR must be continuously in operation in order to comply with the short activation times required [2]. This can significantly increase their costs for reserve provision in times of low energy prices in the market [3], [5]. With an increasing share of renewable energy, the renewable energy generation will exceed electricity demand during peaking times and make reserve conventional must-run capacity infeasible. Therefore, the introduction of new technologies in the provision of ancillary services is necessary.

BESS are well fitted to provide multiple ancillary services; in particular, their high accuracy and minimal lead-time make them remarkably adequate for frequency response. Their potential for participation in the power reserve has been recognized for decades [6], especially for island or isolated grid applications [7], [8]. For the reasons exposed in the previous paragraph, along with a decline in battery prices [9], the interest in large scale BESS as providers of ancillary services has grown. By May 2015, a total of 30 MW of BESS capacity was participating in the German FCR market, with other projects in the pipeline accounting for an 100 MW increase by 2017 [10].

While the outdated power reserve regulation framework is undergoing an adaptation period to make it suitable for new technologies, the limited experience with these technologies results in a lack of precision in regulatory requirements, potentially influencing operation and system design.

According to German TSOs [11], FCR providers shall be able to activate its maximum offered power and maintain provision for a minimum activation period of 30 minutes. With the reworking of network codes at the EU level, the discussion on this subject is still open. The latest draft of the System Operation Guideline states that the minimum activation period shall be set between 15 and 30 minutes based on suggestions from the member states' TSOs stemming from a cost-benefit analysis. It also states that "Where no period has been determined (…), each FCR provider shall ensure that its FCR providing units or groups with limited energy reservoirs are able to fully activate FCR continuously for at least 15 minutes" (Art. 156, p. 9, [12]).

This work was supported by funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 646463.

This paper investigates the implications of different minimum activation periods on battery's SoC management and energy flows resulting from operation through simulations and sensitivity analyses. Section II presents the principles of FCR provision with BESS. Section III exposes two different calculation methods, which ensure battery capacity availability for FCR provision based on the minimum activation period. Section IV covers the simulation and sensibility analyses performed on input variables for each calculation method, and results are presented in section V. Finally, the results and exiting regulation debates are discussed in section VI.

II. FCR PROVISION WITH BESS

A. Principles of FCR provision

BESS can provide power faster than conventional power plants but their energy output is limited by their finite capacity (E_{bat}^{max}). Although BESS could theoretically provide all types of control reserve, aFRR and mFRR require longer periods of power provision, implying larger battery capacity. Therefore, BESS are suited better for FCR provision.

The largest FCR cross-border cooperation in the EU includes TSOs from Belgium, Germany, Austria, Switzerland, the Netherlands and France. Auctions are carried out through a common online market platform [13]. Power bids are submitted and accepted systems must ensure 100 % time availability for provision. FCR is provided by responding to a difference (Δf) between locally measured grid frequency (f) and the nominal frequency (f_N) by changing power output as a function of the total offered power (P_{FCR}^{max}) as shown in (1) and (2).

$$\Delta f = f_N - f \tag{1}$$

$$P_{FCR} = \begin{cases} \pm P_{FCR}^{max}, & |\Delta f| > 0.2\ Hz \\ \pm P_{FCR}^{max} \left(\dfrac{\Delta f}{0.2\ Hz}\right), & 0.01\ Hz < |\Delta f| < 0.2\ Hz \\ 0, & |\Delta f| < 0.01\ Hz \end{cases} \tag{2}$$

The battery's State of Charge (SoC) changes as a function of the power provided. When the frequency is above the nominal value, down regulation is required and the battery charges. Conversely, when frequency is below the nominal value, up regulation is required and the battery discharges. In order to comply with the regulations regarding the minimum activation period (Δt_{crit}), SoC management strategies have to maintain SoC within a range that ensures the ability to provide the total offered power.

B. SoC Management Strategies

Management strategies for maintaining the SoC of batteries have been described in literature [14], [15], [16], [17]. The common feature between these strategies is the use of so-called "corrective energy" to charge or discharge the battery and to keep the SoC away from extreme values. This requires both an external energy source and reserved power from the technical BESS power, independent from the power dedicated for FCR, since corrective measures must be provided simultaneously to FCR provision.

The operation strategy used in this paper is based on [17] and was adopted to the actual regulation in Germany. Further details on this adaptation are found in in [5].

III. THE MINIMUM ACTIVATION PERIOD IN FCR PROVISION

The ENTSO-E provides documentation on FCR [18] and transmission system operation [12] at the European level. In Germany general regulation and prequalification requirements are published by the TSOs [13] with specific documentation addressing the case of BESS [11], [19].

In these documents the operation is described in terms of battery's SoC and the definition of limits expressed as equally sized shares of battery capacity reserved for charging (down regulation) and discharging (up regulation). The capacity, which has to be reserved to ensure provision of FCR at the maximum power offered (P_{FCR}^{max}) during the minimum activation period (Δt_{crit}) can be calculated based on (3).

$$Lim_{FCR} = P_{FCR}^{max}\ \Delta t_{crit} \tag{3}$$

The German TSOs define three cases where a BESS providing FCR is allowed to cross the limits. These cases are defined as "abnormal operation mode" [11]: 1) a frequency deviation outside ±200 mHz, 2) a frequency deviation outside ±100 mHz lasting more than 5 minutes or 3) a frequency deviation outside ±50 mHz which lasts more than 15 minutes. To maintain provision, it is necessary to have sufficient reserved battery capacity for the SoC to change according to these cases before it crosses Lim_{FCR} and reaches the abnormal operation mode. The share of battery capacity to be reserved for this purpose is not mentioned in the document.

To calculate said reserved battery capacity a few considerations are made. According to the cases previously described, a capacity buffer which covers for P_{FCR}^{max} provision for a frequency deviation of ±100 mHz lasting more than $\Delta t = 5\ min$ is considered based on (2). Furthermore, it is necessary to keep in mind that, depending on the source of corrective energy, there can be a lead-time (Δt_{lag}) between calling for a corrective measure and actual provision. In the calculation methods presented, the lead-time for corrective measures provision is assumed to be less than or equal to $\Delta t = 5\ min$ in all cases based on the full activation time requirements for Secondary Control Reserve (the equivalent of FRR in Germany). With this assumption, every power plant able to provide Secondary Control Reserve could technically provide corrective power to a BESS in FCR as well.

The battery power share reserved for corrective measures (P_{corr}) is activated to manage the battery's SoC in case the limits defined by Lim_{FCR} are crossed. The use of P_{corr} can therefore reduce the battery capacity needed as a buffer, described by (4).

$$Buffer_{FCR} = \tfrac{1}{2}P_{FCR}^{max}\,\Delta t_{lag} + \max\left(0, \left(\Delta t - \Delta t_{lag}\right)\left(\tfrac{1}{2}P_{FCR}^{max} - P_{corr}\right)\right) \quad (4)$$

The first summand describes the fraction of reserved capacity needed for the battery to provide necessary FCR power during the time it takes for the corrective energy source to start provision. The second summand describes the fraction resulting from simultaneous down regulation (up regulation) and corrective discharging (charging) during the time remaining to fulfill the $\Delta t = 5\,min$ requirement. If the corrective power is large enough to turn net energy flow in the opposite direction, there is no need for more reserved capacity and the second summand is ignored.

The capacity reserved for Lim_{FCR} can be reduced by using corrective energy. In the worst-case scenario a frequency event larger than ±200 mHz occurs and the battery enters abnormal operation mode, for which the maximum power offered is immediately required. As a result, the buffer capacity, considered for a ±100 mHz event lasting 5 minutes, would be spent in a shorter time. If the buffer is spent faster than the time it takes for the corrective measure to start, there will be a period (Δt_{lagrem}) remaining when SoC has crossed Lim_{FCR} and no corrective measures are yet taking place; this is shown in (5).

After this last consideration is taken, the reserved capacity for FCR provision is calculated according to (6). The first case describes the fraction of reserved capacity necessary for the battery to provide necessary FCR power during the time it takes the corrective measure to start provision. The second case describes a fraction of capacity reserved necessary for the period of FCR provision without simultaneous corrective measures taking place and a fraction resulting from the remaining time ($\Delta t_{crit} - \Delta t_{lagrem}$) when both provision of FCR and corrective measures are active. The case, which leads to the largest reserved capacity needed, is chosen.

$$\Delta t_{lagrem} = max\left(0,\ \Delta t_{lag} - \frac{Buffer_{FCR}}{P_{FCR}^{max}}\right) \quad (5)$$

$$Lim_{FCR} = max\begin{pmatrix} P_{FCR}^{max}\Delta t_{lagrem},\ P_{FCR}^{max}\,\Delta t_{lagrem} + (P_{FCR}^{max} - P_{corr}) \\ max(0, \quad \Delta t_{crit} - \Delta t_{lagrem}) \end{pmatrix} \quad (6)$$

Finally, since both up and down regulation are provided, the total reserved capacity is represented as upper and lower limits, as a share of the total battery capacity.

$$Lim_{low}^{Corr} = \frac{Lim_{FCR} + Buffer_{FCR}}{E_{bat}^{max}} \quad (7)$$

$$Lim_{up}^{Corr} = 1 - Lim_{low}^{Corr} \quad (8)$$

Additionally, corrective measures are set to stop when SoC reaches a stopping limit defined by Δt_{stop} and calculated based on (9), (10) and (11).

$$stopCorr = \frac{P_{FCR}^{max}\,\Delta t_{stop}}{E_{bat}^{max}} \quad (9)$$

$$Lim_{low}^{stopCorr} = Lim_{low}^{Corr} + stopCorr \quad (10)$$

$$Lim_{up}^{stopCorr} = Lim_{up}^{Corr} - stopCorr \quad (11)$$

Figure 1 shows the resulting limits for a variety of system designs for both limit calculation methods introduced in this chapter. The *Base* method uses (3) and (4) as inputs for the final calculation shown in (7) while the *Corr* method considers the use of corrective energy reducing the capacity reserved needed for FCR provision and therefore uses (4) and (6) as inputs. The resulting limits enclose a "range of normal operation", which is reduced with increasing shares of battery power dedicated to FCR, C-Rates and minimum activation periods.

The significance of taking the corrective measures into account is shown by the comparison of the left plots (*Base* method) with the right plots (*Corr* method). In the *Corr* scenarios there is a tipping point at a FCR share of 50 %. , When $P_{FCR}^{max} < P_{corr}$ (i.e. FCR power share is smaller than 50 %) the rate of change of SoC is reversed by corrective power resulting in the same limits for either minimum

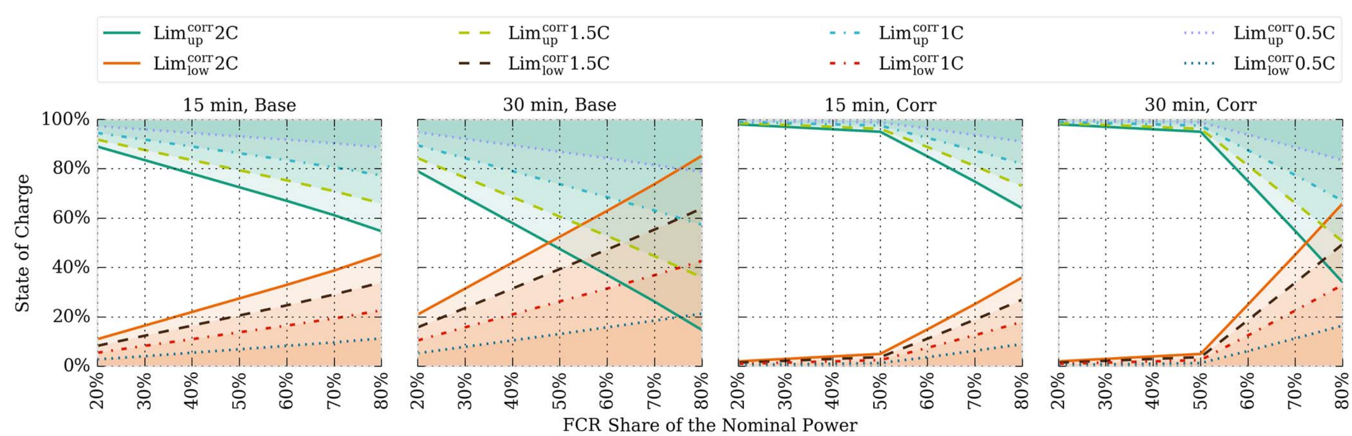

Figure 1. Changing limits and reduction of the normal operation range for various C-Rates, FCR shares and $\mathbf{\Delta t_{crit}}$ for both *Base* (left side plots) and *Corr* (right side plots) calculation methods.

activation period considered. Conversely, when $P_{FCR}^{max} > P_{corr}$ (i.e. FCR power share is larger than 50 %) the rate of change of SoC is not reversed but rather reduced by the corrective power, the 30 minute minimum activation period is responsible for a steeper rate of change after this point.

All scenarios with crossing limits are infeasible, since corrective measures would be constantly activated. This occurs only for the 30-minutes criterion. With the *Base* method this occurs for a C-Rate of 1.5 with FCR shares larger than 60 % and for a C-Rate of 2 with FCR shares larger than 40 %. With the *Corr* method this occurs for a C-Rate of 2 with FCR shares larger than 70 %. Consequently these scenarios are not part of the analysis.

IV. Simulation and Sensibility Analysis

The FCR provision of a stand-alone battery with 1 MWh capacity, 96.8 % battery round-trip efficiency, a monthly self-discharge of 7 % and variable inverter efficiency is simulated. Corrective power is provided by a power plant with $\Delta t_{corrlag}$ of 3 minutes. The time defining the limits for stopping corrective measures (Δt_{stop}) is set to 1 minute. A small Δt_{stop} reduces the amount of corrective energy needed but increases the number of corrective measures taken due to smaller energy consumption per corrective measure event.

The frequency data were provided by Swissgrid and measured in Laufenburg in the year 2012.

In each time step (t), the system identifies its SoC to check whether a corrective measure must be scheduled. If the SoC is above (below) Lim_{up}^{Corr} (Lim_{low}^{Corr}) a corrective measure is scheduled to start at $t + \Delta t_{lag}$. The net required power on the AC side of the BESS (P_{bat}^{AC}) is then calculated as described in (12). $P_{FCR}(t)$ is the required FCR power while $P_{corr}(t)$ is the scheduled corrective power for the time step; possible values for the latter are 0 or P_{corr}.

$$P_{bat}^{AC}(t) = P_{FCR}(t) + P_{corr}(t) \quad (12)$$

To calculate the DC side power (P_{bat}^{DC}) discharged or charged to the battery, a variable inverter efficiency (η_{inv}) model is used. It follows an efficiency curve with a maximum efficiency at 96.8 %. P_{bat}^{DC} is calculated following:

$$P_{bat}^{DC}(t) = \begin{cases} P_{bat}^{AC}(t) \cdot \eta_{inv}(t), & P_{bat}^{AC}(t) \geq 0 \\ P_{bat}^{AC}(t) / \eta_{inv}(t), & P_{bat}^{AC}(t) < 0 \end{cases} \quad (13)$$

Using the value for P_{bat}^{DC}, the energy (E_{bat}) in the battery at the end of the time step is calculated according to (14), where δ_{loss} is self-discharge, η_{bat} is the battery round-trip efficiency and Δt is the duration of the time step.

$$E_{bat}(t+1) = E_{bat}(t)\ \delta_{loss} + P_{bat}^{DC}(t)\ \Delta t \left(\frac{\delta_{loss}}{2}\right) \cdot \begin{cases} \frac{1}{\sqrt{\eta_{bat}}}, P_{bat}^{DC}(t) < 0 \\ \sqrt{\eta_{bat}}, P_{bat}^{DC}(t) \geq 0 \end{cases} \quad (14)$$

Figure 2 shows the operation of the system during one exemplary day. The top plot represents the available energy in the BESS, with the orange lines depicting SoC limits where corrective measures are requested. The middle plot shows the power from corrective measures. Corrective discharging can be seen between 03:00 and 06:00 due to crossing the upper limits (see top plot) and corrective charging can be seen between 19:00 and 22:00 du to crossing the lower limits. The lower plot shows the total power of the battery due to FCR provision and corrective measures.

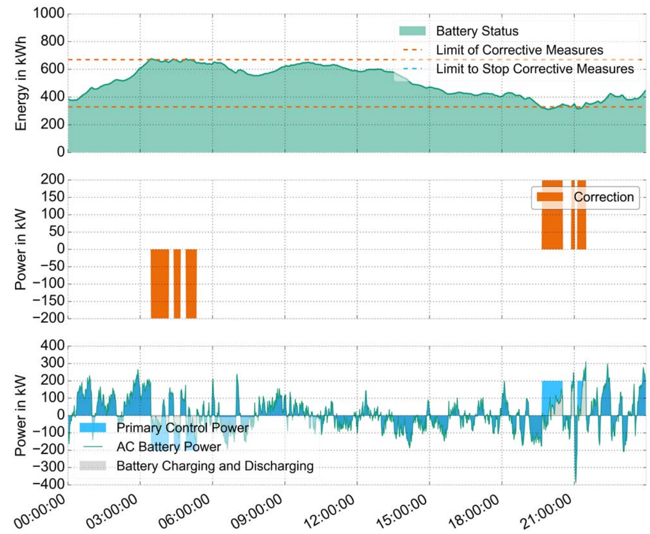

Figure 2 Exemplary Operation of a BESS with 1-C providing FCR with 80 % of the nominal power with 30 minutes minimum activation period and *Corr* method to calculate the limits of corrective measures.

V. Results of Sensibility Analyses

For the sensibility analysis, the variables shown in Table I are manipulated. FCR power share is limited by German TSOs to a maximum of 80 % [11]. As FCR provision is the sole service the battery is providing, the remainder of battery technical power band is used for corrective measures. Because of this fixed shares, varying the battery's technical power also changes the offered FCR power. Energy flows are defined from a battery perspective, inward flows are positive and outward flows are negative.

TABLE I
Variables and Ranges Utilized in the Sensibility Analysis

	Lowest	Highest
Δt_{crit} in minutes	15	30
FCR share in %	20	80
Battery AC power in MW	0.5	2

There are three main effects resulting in an increased need for corrective energy as Figure 3 shows. A larger FCR share increases the rate at which the SoC changes due to FCR provision. On the other hand, the corresponding battery power share dedicated for corrective measures decreases and with this, the rate at which the SoC is corrected. Finally, the reduced size of the normal operation range (see Figure 1) increases the number of times corrective measures are called.

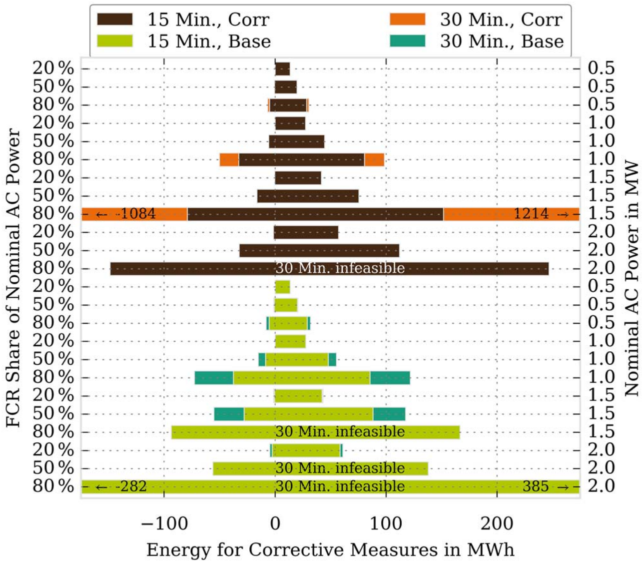

Figure 3. Corrective energy use for *Base* and *Corr* calculation methods, for Δ*tcrit* of 15 and 30 minutes, for various FCR shares and battery powers. Due to crossing limits, simulations for some configurations under the 30-minute criterion were not performed (see Figure 1).

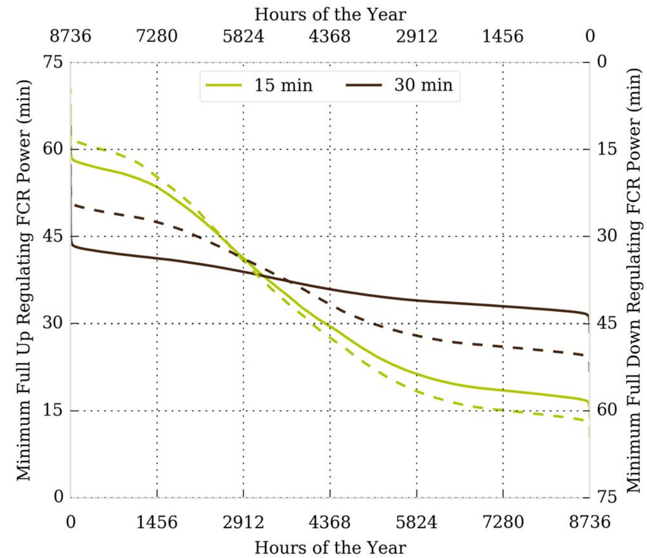

Figure 4. Sorted annual curve of minimum up and down regulating FCR provision time at maximum offered power for a 1C battery with 80% FCR share. 15-minute and 30-minute criteria results are compared. The bottom x-axis corresponds to the left y-axis, and the top x-axis to the right y-axis. Full lines depict results given by the *Base* calculation method and dashed lines the *Corr* calculation method.

Figure 3 shows a comparison of corrective energy used for various cases. Compared to the 15-minute criterion, the 30-minute criterion increases the amount of corrective energy use due to a reduction in the normal operation range with both calculation methods. Similarly, when compared to the *Corr* calculation method, the *Base* method results in greater corrective energy use. For the *Corr* method, there is no difference in corrective energy utilization between 15 and 30 minutes for FCR shares lower than 50 %, as the limits are the same for both cases (see Figure 1).

At low C-Rates (≤ 1C) and FCR shares (≤ 30%) there is zero or relatively sparse need for discharge corrective energy since the upper limit is never or infrequently crossed. This is because of a combination of factors concerning SoC: large space for free fluctuation, small rates of change due to FCR provision, and the tendency to be in low SoC over the year. The latter is caused by losses at the inverter, self-discharge of the battery and a slight bias towards under-frequency (in the 2012 dataset).

There are different combinations of C-Rates and FCR shares which result in the same battery power shares for FCR while having different shares for corrective measures. According to (9), (10) and (11), the stopping limits for corrective measures are the same for these cases; in the simulation the value for Δt_{stop} is set to 1 minute. Since the minimum duration of corrective power provision is also 1 minute (resolution of the simulation), the SoC actually overshoots the stopping limits with increasing corrective power, resulting in an increased net corrective energy use with less corrective measure events.

Figure 4 presents a comparison, for both calculation methods, of the time a 1C battery with an FCR share of 80 % is available to provide up and down regulating FCR power. Depending on the SoC level at a given point in time, the calculation is made for the time it takes for the maximum offered power to deplete the available capacity.

A slight bias to the left side of the plot can be recognized, which means the battery is less available to provide up regulation than down regulation over the course of the year. This is caused by the tendency of the SoC to lower levels, an issue which be addressed by operational strategies involving usage of the degrees of freedom in FCR provision as shown in [20]. Consequently, the larger the normal operation range the more biased the plot will be, making the battery more readily available to provide extra down regulating FCR power than up regulating FCR power.

On the contrary, a more leveled line would represent a battery consistently available to provide both extra up and down regulation. However, this would be the result of a yearly average SoC around 50 %, which relates to a smaller normal operation range and a larger corrective energy use.

VI. Discussion

This paper focused on the influence of different minimum activation periods on operation of stand-alone BESS participating in FCR provision. A control strategy making use of corrective power in order to manage battery SoC was applied to simulate stand-alone batteries providing FCR. Considering the use of corrective energy, two different generic calculation methods for the normal operation range limits were presented. Sensitivity analyses were performed to evaluate the influence of minimum activation periods of 15 and 30 minutes on battery C-Rate and FCR provision shares.

It was shown that, in all cases, the 30-minute criterion increases both charging and discharging corrective energy use when compared to the 15-minute criterion. In fact, exceedingly large limits in some configurations make high

FCR power shares infeasible under the 30-minute criterion. This leads to a limited income potential from FCR service, which is remunerated based on a power price.

A large minimum activation period requirement increases the necessary ratio between installed battery capacity and potentially offered FCR power. The options left for potential bidders are either to offer less power as FCR or increasing battery capacity (lowering C-Rate) and therefore, either decreasing income potential or increasing investment costs.

ACKNOWLEDGMENT

The authors would like to thank W. Sattinger (Swissgrid) for his contribution and the provision of historic data.

VII. REFERENCES

[1] ENTSO-E, “Supporting Document for the Network Code on Load-Frequency Control and Reserves.” 28-Jun-2013.

[2] S. Just and C. Weber, “Pricing of reserves: Valuing system reserve capacity against spot prices in electricity markets,” *Energy Econ.*, vol. 30, no. 6, pp. 3198–3221, 2008.

[3] F. Müsgens, A. Ockenfels, and M. Peek, “Economics and design of balancing power markets in Germany,” *Int. J. Electr. Power Energy Syst.*, vol. 55, pp. 392–401, 2014.

[4] Fraunhofer ISE, “Electricity production in Germany | Energy Charts,” *Energy Charts*. [Online]. Available: https://www.energy-charts.de/power.htm. [Accessed: 19-Jul-2016].

[5] R. Hollinger, L. M. Diazgranados, and T. Erge, “Trends in the German PCR market: Perspectives for battery systems,” presented at the European Energy Markets (EEM15), Lissabon, 2015, pp. 1–5.

[6] H. J. Kunisch, K. G. Kramer, and H. Dominik, “Battery Energy Storage Another Option for Load-Frequency-Control and Instantaneous Reserve,” *IEEE Trans. Energy Convers.*, vol. EC-1, no. 3, pp. 41–46, Sep. 1986.

[7] M. F. De Ana, J. D. Boyes, and W. Torres, “Lessons learned from the Puerto Rico battery energy storage system,” Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US), 1999.

[8] D. Kottick, M. Blau, and D. Edelstein, “Battery energy storage for frequency regulation in an island power system,” *IEEE Trans. Energy Convers.*, vol. 8, no. 3, pp. 455–459, Sep. 1993.

[9] B. Nykvist and M. ans Nilsson, “Rapidly falling costs of battery packs for electric vehicles,” *Nat. Clim. Change*, vol. 5, no. 4, pp. 329–332, 2015.

[10] Germany Trade and Invest, “The Energy Storage Market in Germany,” 2016. [Online]. Available: https://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Fact-sheets/Energy-environmental/fact-sheet-energy-storage-market-germany-en.pdf?v=6. [Accessed: 31-May-2016].

[11] Deutsche ÜNB, “Anforderungen an die Speicherkapazität bei Batterien für die Primärregelleistung.” 29-Sep-2015.

[12] European Commission, “Draft Regulation establishing a guideline on electricity transmission system operation – the System Operation Guideline,” May 2016.

[13] Deutsche ÜNB, “regelleistung.net,” *Internetplattform zur Vergabe von Regelleistung*, May-2016. [Online]. Available: https://www.regelleistung.net/ext. [Accessed: 17-Nov-2015].

[14] A. Oudalov, D. Chartouni, and C. Ohler, “Optimizing a Battery Energy Storage System for Primary Frequency Control,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1259–1266, Aug. 2007.

[15] T. Borsche, A. Ulbig, M. Koller, and G. Andersson, “Power and energy capacity requirements of storages providing frequency control reserves,” in *2013 IEEE Power and Energy Society General Meeting (PES)*, 2013, pp. 1–5.

[16] T. S. Borsche, A. Ulbig, and G. Andersson, “Impact of frequency control reserve provision by storage systems on power system operation,” in *Proceedings 19th IFAC World Congress*, 2014, vol. 19, pp. 4038–4043.

[17] O. Megel, J. L. Mathieu, and G. Andersson, “Maximizing the potential of energy storage to provide fast frequency control,” in *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES*, 2013, pp. 1–5.

[18] ENTSO-E, “Continental Europe Operation Handbook : P1 – Policy 1: Load-Frequency Control and Performance.” 2009.

[19] Deutsche ÜNB, “Eckpunkte Freiheitsgrade bei der Erbringung von Primärregelleistung.” 03-Apr-2014.

[20] R. Hollinger, L. M. Diazgranados, C. Wittwer, and B. Engel, “Optimal Provision of Primary Frequency Control with Battery Systems by Exploiting All Degrees of Freedom within Regulation,” *Energy Procedia*, vol. 99, pp. 204–214, Nov. 2016.