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Implementation of Envelopes as a Regulatory Degree of Freedom for Batteries Participating in Fast Frequency Response

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Abstract

Fast frequency response services become more relevant in power systems with a high share of fluctuating renewable energy sources and decreasing shares of conventional generators. In Germany there are special requirements for providers of Primary Control Reserve (PCR) with limited storage capacity. Furthermore, regulatory degrees of freedom are available for these to control their state of charge (SoC) within allowed limits. In Great Britain, the Enhanced Frequency Response (EFR) service was developed considering storage limitations and thus introduces the concept of envelopes to support SoC maintenance. In this paper, the concept of EFR envelopes is adapted to the provision of PCR in Germany. It is shown that the dynamic use of envelopes effectively maintains SoC away from extreme values and close to 50 % for most part of the year, reducing cycling and significantly decreasing the need for corrective measures from external sources to maintain the battery's SoC.

Keywords: Batteries; Power Control Reserves; Enhanced Frequency Response; Envelopes; Primary Frequency Control

1. Introduction

Currently, the Load-Frequency Control (LFC) concept described by ENTSO-E´s System Operation Guideline (SO GL) considers the sequential deployment of power control reserves. First, the Frequency Containment Reserve

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(FCR) is deployed with providers expected to fully activate offered power within no longer than 30 seconds, depending on the synchronized system. After this period, an automatic frequency restoration reserve (aFRR) is activated followed by a manual frequency restoration reserve (mFRR) in order to restore system frequency to its nominal value and replace the previously activated FCR. Additionally, replacement reserves (RR) can be made available to support FRR against additional system imbalances.

The majority of providers of FCR are currently conventional generators with slow reaction time and high minimum power requirements to be able to response to both low and high frequencies. In addition, increasing variability is introduced on the generation side by solar and wind energy generators, which do not contribute to total system inertia. The interest in fast frequency control originates from the increasing difficulty to balance the system close to real-time and the potential for it to address the aforementioned difficulties.

These developments call for the introduction of new technologies providing system services which gradually displace must-run capacities and are able to ensure a safe and stable operation of the electricity system. Among these new technologies, Battery Energy Storage Systems (BESS) have been gaining support as providers of fast frequency response services in Europe due to their technical characteristics such as a near-instantaneous reaction times and high response accuracy. In particular, Lithium-Ion (Li-ion) batteries are seeing rapidly decreasing costs and a greater overall acceptance in a wide variety of applications, including the participation in the control reserves.

Leading examples of the consideration of these technologies within the technical regulatory framework for the provision of control reserves can be seen in Germany and the UK. The German TSOs published requirements to storage capacity for providers of Primary Control Reserve (PCR) [1] and regulatory degrees of freedom (DEGOF) [2] which providers are permitted to use in order to support state of charge (SoC) management. In the UK, National Grid created a new fast frequency control service under the name of Enhanced Frequency Response (EFR). A total of 200 MW were tendered in the third quarter of 2016, with the majority of the four-year contracts awarded to BESS. EFR is a product designed for fast-reacting providers with limited energy storage capacity. As such, full activation is expected in sub-second scales and the concept of envelopes was introduces in order to support SoC management.

The effects on battery operation of the implementation of the envelope concept to the provision of PCR in Germany are investigated in this paper. Section 2 presents the fundamentals for provision of PCR with BESS. In Section 3 introduces DEGOF in Germany and the concept of envelopes in more detail, as well as exposing a potential design for envelopes in PCR provision. Section 4 covers the simulation and results of PCR provision. Last, Section 5 covers a discussion of the previous section's results and concludes with a recap of system and regulatory implications of new fast frequency control concepts.

2. Fast Frequency Response with Bess

2.1. PCR and the regulatory DEGOF

A provider of PCR delivers power in response to a present frequency deviation $\Delta f(t)$ between locally measured system frequency $f(t)$ and the nominal system frequency value f_N as shown in equation (1). Within a range of ±10 mHz around the nominal value no response is required and outside this range response increases linearly until reaching its maximum at the full activation frequency deviation, which is set at ±200 mHz. For any deviation larger than the full activation frequency deviation, the maximum response power is required. This is shown in equation (2).

$$\Delta f(t) = f_N - f(t) \tag{1}$$

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

In 2014 the German TSOs published additional requirements for units with a limited energy storage capacity [1]

for providers of PCR. Additionally, regulatory DEGOF [2] were also made available in order to support SoC management of these kind of providers. These regulatory DEGOF are shortly defined below and further described by Hollinger et al. [3] and Zeh et al. [4]:

- **Deadband:** The small range around the nominal value where provision of FCR is not required (±0.10 mHz in CE). The deadband accounts for insensibility in measuring small deviations from the nominal frequency.

- **Overfulfillment:** A provision between 100 % and 120 % of the instantaneous power requirement is allowed at any time.

- **Delay:** Regulation recognizes a delay in initial activation of frequency response. This delay originates from the lead time between detection of the frequency deviation, instruction of response and final change in output for provision. An artificial delay is explicitly prohibited in the ENTSO-E System Operation Guideline [5]; however, according to the Network code on requirements for grid connection of generators of the European Commission, "the relevant TSO may specify a shorter time than two seconds [6]" for power-generating modules without inertia.

- **Gradient:** The combination of the full activation time (30 seconds for PCR) and the full activation frequency deviation (±200 mHz in CE) requirements create a ramping gradient which BESS can use to avoid ramping instantly and therefore decrease energy cycled.

- **System Time Correction:** Synchronous time is a time measurement calibrated with the grid frequency which is used to coordinate grid-related activities. Because of the dependency on grid frequency, synchronous time sometimes deviates from UTC time and must be adjusted. If the deviation is larger than a certain criterion (20 seconds in CE) either behind or forward, the frequency set-point is modified slightly (by ±0.01Hz in CE) until the time deviation is adjusted.

2.2. EFR and the envelope concept

EFR is a product designed for fast-reacting providers with a limited energy storage capacity. Consequently full activation is expected at ±500 mHz in less than 1 second with a minimum time of sustained provision of 15 minutes. In order to provide flexibility for SOC management of the proving units the so-called "envelopes" are introduced.

A "wide" and a "narrow" envelope are described for EFR. Each of these envelopes relates to a separate product defined by a) a particular deadband and b) an allowed 9 % of battery nominal capacity for charging (discharging) actions when the frequency signal is within the defined deadband. The narrow deadband is set at ±15 mHz, which is the deadband value described in the SO GL. The wide deadband is set at ±50 mHz and was implemented in order to allow for more providers to take part on the EFR service [7]. To draw the envelopes, the allowed 9 % of battery nominal capacity decreases linearly starting from the deadband frequency deviation value to 0 % of nominal capacity with respect to the reference line when frequency deviation is ±250 mHz (henceforth referred to as "convergence frequency deviation"). This last frequency deviation is regarded as a "post-fault" deviation since the standard operation range in Great Britain is ±200 mHz. The envelopes are allowed since precise response is only required "post-fault" and thus the response requirements can be relaxed to support SoC management for energy-limited providers [7]. The narrow envelope is illustrated in Fig. 1.
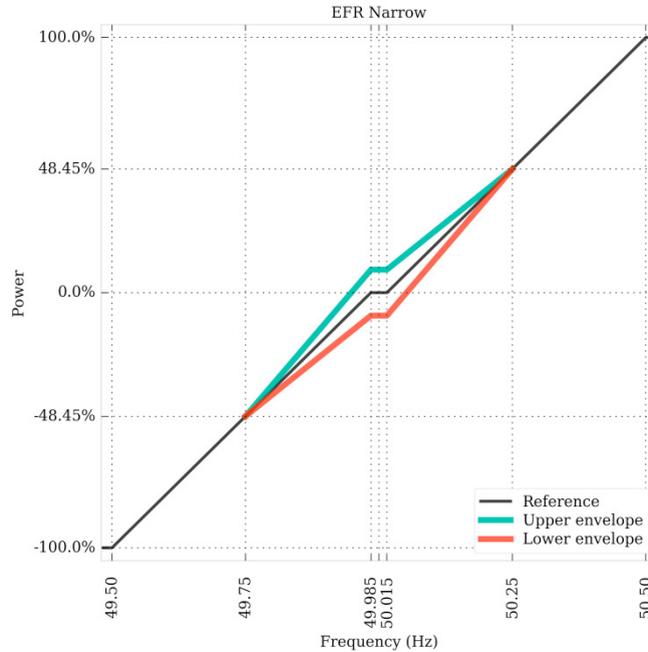
Fig. 1. Narrow envelope described for the EFR service in Great Britain.

Because fast changes in output are expected in this service, various ramp-rate limitations are defined when provision is not following either an envelope or the actual frequency signal, these can be found in documentation for pre-qualified parties [8]. Also, a performance measure is calculated for EFR in order to monitor availability and calculate payment reductions to the provider. If a rolling average over a 12-month period of the performance measure falls below 95 %, underperformance will be discussed with National Grid. If the value falls below 50 % the contract may be terminated [2].

A system time correction process is present in Great Britain as well and is described in the Balancing Code No. 3 "Frequency Control Process". As shown in previous work [3] and also in this paper, the use of system time correction process as a DEGOF can be a highly effective DEGOF in support of SoC maintenance.

2.3. Envelopes adapted to PCR

PCR and EFR are provided in different synchronized systems and therefore designed in consideration of a particular system frequency. PCR is linked to the Central European system frequency while EFR is linked to that of Great Britain. As seen in Figure 2, the system frequency of Continental Europe is comparatively more stable than the one in Great Britain because of several factors such as the greater size of the synchronized system, interconnection and diversity in the generation mix. Therefore, the frequency quality parameters and FCR technical minimum requirements described in the System Operation Guideline [5] are tighter for FCR services in Central Europe, as seen in Table 1.

Table 1. Relevant Frequency Ranges Defined for Continental Europe and Great Britain in the ENTSO-E´s System   Operation Guideline.

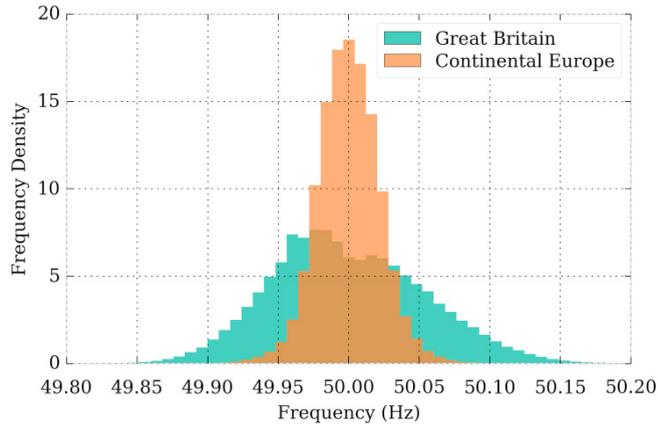|	C. Europe	Great Britain
Standard frequency range	±50 mHz	± 200 mHz
Deadband	±10 mHz	±15 mHz
Full activation frequency deviation	±200 mHz	±500 mHz

Fig. 2. Narrow envelope described for the EFR service in Great Britain.

These values are then taken as a starting point to adapt the concept of envelopes to PCR. Assuming that precise provision is desired particularly outside the standard frequency range, this deviation is chosen as the convergence frequency deviation. As a comparison, within the convergence frequency deviation defined for EFR (±250 mHz), 99.997 % of the system frequency data for Great Britain can be found. Within the chosen convergence frequency deviation (±50 mHz) 97.049 % of the system frequency data for Continental Europe is found.

The deadband value is maintained and for the purposes of illustrating the effect of envelopes on battery operation an allowed output of 9 % is chosen, the same value allowed in EFR. For the avoidance of doubt, both the convergence frequency deviation and the allowed output are chosen starting values chosen mainly for illustration purposes and not considered optimal values, neither from the battery operation point of view nor from the system operation point of view.

2.4. SoC Management Strategy

An SoC management strategy for the provision of PCR, developed at Fraunhofer ISE and further described in previous publications [3] [9], is utilized an adapted to include the use of envelopes. This strategy ensures 100 % availability under the previously mentioned German TSO's requirements for providers with a limited storage capacity. It is composed by three different operation modes which implement a combined utilization of the individual DEGOF presented previously: maximize discharge, maximize charge and minimize cycling.

The maximize charge mode makes use of all DEGOF allowing operation at a higher charging power with respect to instantaneous provision. The maximize discharge mode, on the other hand, uses all DEGOF allowing operation at a higher discharging power with respect to instantaneous provision. Finally, the minimize cycling mode utilizes DEGOF in such a way that the BESS operates as close as possible to zero response output, minimizing charging and discharging energy and thus battery cycling and battery degradation. The three operation modes are combined in a single operation strategy which dynamically switches between the operation modes depending on the present SoC, maintaining it away from extreme charge or discharge levels.

The individual contribution of each DEGOF to the operation modes was analysed by utilizing the system frequency data for Continental Europe for the year 2012 to calculate the energy use per unit of power dedicated for PCR provision throughout the year. The results of this analysis are dubbed as energy turnover and are shown in Fig. 3. Positive bars indicate charging energy while negative bars indicate discharging energy. It is clear that envelopes provide a far larger flexibility potential for SoC management than any of the other DEGOF. It is mostly because of the envelopes that the minimize cycling operation mode results in a much less energy output than instantaneous provision, which represents provision without utilizing any DEGOF. Likewise, the envelopes are the largest contributors to both maximize discharge and maximize charge operation modes.
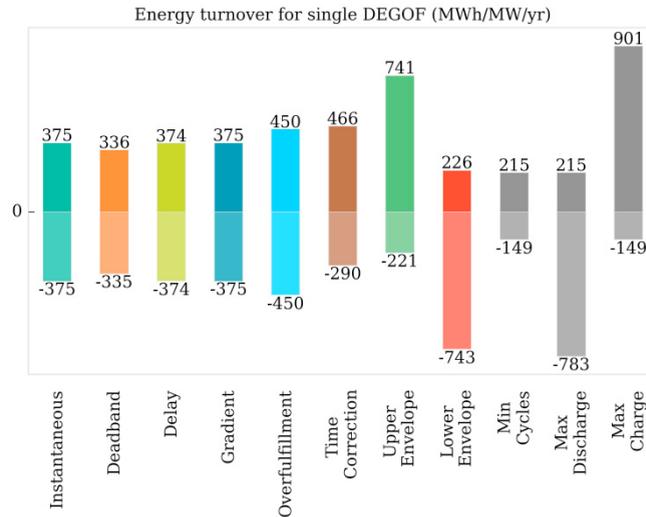
Fig. 3. Individual contribution of each DEGOF for PCR provision including envelopes as an additional DEGOF.

2.5. Simulated PCR Provision and Results

2.6. Simulation conditions

The configuration of the simulated BESS is shown in Table 2. German regulation requires corrective power to be at least 25 % of PCR power [1]. Therefore, 1 MW is allocated for PCR provision while 0.25 MW are reserved for corrective measures, resulting in 80 % of total battery power dedicated for PCR provision. A 1.25 MWh storage capacity dictates that the battery is operating at 1C rate and a minimum activation period of 15 minutes is considered; this has a positive impact for BESS management as demonstrated by [10].

Table 2. Configuration of the simulated BESS providing PCR.

Variable	Value
Storage capacity	1.25 MWh
Power (AC side)	1.25 MW
PCR share	80 %
Minimum activation period	15 min
Self-discharge	7 % per month
Round-trip efficiency	96 %
Limit to start max. discharge	55 %
Limit to start max. charge	45 %

Finally, the SoC strategy remains in the minimize cycling operation mode when the SoC is within 55 % and 45 %. Above this range the operation mode switches to maximize discharge and below this range the operation mode switches to maximum charge.

No ramping limitations are considered since simulations are performed in a minute scale. The tightest ramping limitation is set at 1 % of response power per second. Therefore, for 1 MW of provision power the limitation within the deadband is equal to 600 kW/min, while the largest ramp rate possible in simulation due to the switching between operation modes is 90 kW/min for an allowed output of 9 %.

2.7. Results

Results for the energy dedicated for PCR provision and for corrective measures throughout the year are shown in Fig. 4. Results of provision simulated without using any of the SoC management strategies are shown as the reference case. The case for considering the use of all DEGOF except for the envelopes is labelled as "No Envelopes". In this case, a 9 % increase in charging PCR energy is caused by the use of overfulfillment; however, total PCR energy decreases by 3 %. Most importantly, total corrective energy use decreases by 69 %. The dynamic use of system time correction is the largest contributor to the reduction of both total PCR energy and total corrective energy. This reduction is reflected in a 10 % decrease in cycling to 267 full cycle equivalents down from 297 in the reference case.
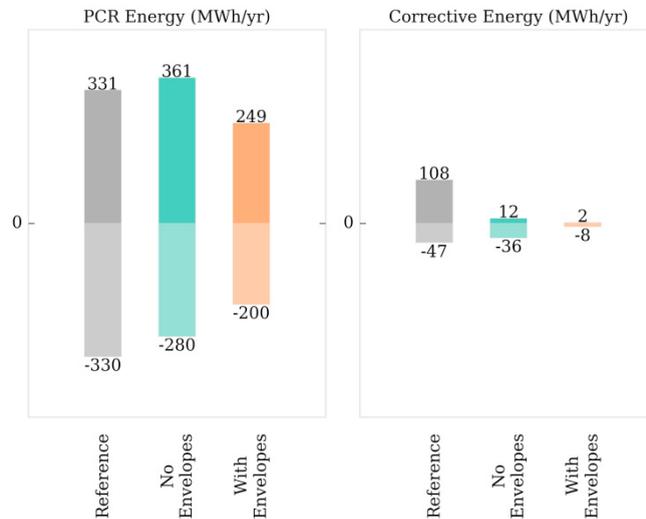

Fig. 4. Energy use for PCR provision (left) and corrective measures (right) throughout the year 2012.

The results of provision when envelopes are added to the available DEGOF are labelled as "With Envelopes". In this case, PCR energy reduces by 32 % and corrective energy does so by 94 %. Since the SoC is controlled more effectively within the defined boundaries, the amount of corrective actions necessary is greatly reduced. The reduction in PCR and corrective energy relates to the battery completing 183 cycles throughout the year, a 38 % decrease in cycling compared to the reference case. This significantly reduces stress in the battery due to rapid cycling which is related to faster degradation.

The effectiveness of the envelopes can also be considered from a systemic point of view. In Fig. 5, the time it takes the maximum PCR power to deplete or fully charge the battery at any given point in time presented as a duration curve. This relates to the readiness of the battery to be able to respond to unexpected extreme scenarios. In the ideal case, the battery's SoC remains at 50 % throughout the year being equally available to provide PCR in any direction. This is represented in Fig. 5 by the dotted line. In comparison with the reference case, the use of a SoC management strategy without envelopes maintains SoC closer to the ideal case during longer periods throughout the year. However, the greatest improvement in availability is observed when utilizing envelopes. In this case the battery's SoC is not only effectively driven away from extreme values but also maintained in the vicinity of the ideal case for the best part of the year.
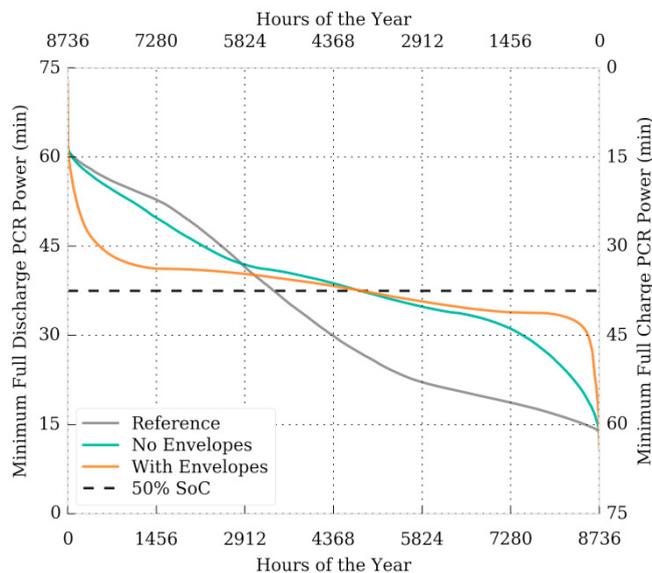
Fig. 5. Sorted annual curve of minimum full power positive and negative PCR provision time showing the availability of the battery to provide PCR in any direction throughout the year.

3. Discussion

The results show that envelopes can be significantly beneficial for the operation of batteries providing PCR in Germany and, by extension, for other fast frequency response services in Continental Europe. With an operation strategy which dynamically switches between available DEGOF and the initial values chosen for the envelopes, considerably less corrective actions are needed, cycling is reduced and the battery is more available to provide PCR in any direction throughout the year. The latter increases the resilience against extreme frequency situations.

Several parameters in the simulation determine the effectiveness of the SoC management strategy using envelopes. Among the most influential factors there are those related to the envelope design itself, such as the convergence frequency deviation and the allowed output within the deadband. For example, a very large allowed output would end up promoting underprovision and therefore decreasing the value of the service for the system operators. A small allowed output on the other hand decreases the value of envelopes for the provider, leading to larger storage capacity needed. The same applies for the convergence frequency deviation. Additionally there are those parameters related to the SoC management strategy such as the SoC limits chosen to switch between operation modes. This choice affects how often are the maximum discharge and maximum charge modes activated and how close to 50 % is the SoC maintained.

In the envelope design presented, some potential disadvantages can be observed, especially if a large share of the control reserve were to be able to utilize them. The first one is the possibility to provide PCR against the system needs (i.e. charge the battery when the frequency is low and vice versa), which is given within and close to the deadband. The second one is the emergence of an "extended deadband" which starts at the lower envelope over the zero provision line until reaching the upper envelope and surpasses the statutory limits delineated both by ENTSO-E and German regulation. These points might gain relevance if a large amount of reserves were to operate with envelopes as a DEGOF

4. Conclusion

New concepts for the provision of control reserves become increasingly relevant with the further integration of variable renewable energy sources. This study adapts the concept of envelopes, recently implemented in the EFR

service in Great Britain, to the provision of PCR in Germany. As an additional DEGOF to those already made available by German TSOs, envelopes show great potential to support SoC management for a battery solely dedicated for PCR provision.

However, further studies at the system level would be necessary to determine an envelope design which results in the greatest value to both the system operators and the provider, investigate the effect of requiring full activation in sub-second scales and to clarify which share of the primary control reserve could be allowed to make use of envelopes or whether additional capacity should instead be contracted in the form of an additional fast frequency response reserve.

Acknowledgements

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