

Fast Frequency Response with BESS: A Comparative Analysis of Germany, Great Britain and Sweden

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Abstract—Technical regulatory frameworks have a great influence in the operation and prospects for Battery Energy Storage Systems (BESS) as providers of fast frequency response. Following this premise, provision of fast frequency response with BESS in Germany, Great Britain and Sweden is analyzed for the products available in each country. An operation strategy, which dynamically utilizes degrees of freedom (DEGOF) found explicitly or implicitly in regulation, maintains the battery’s state of charge (SoC) while also reducing cycling. The extent to which the operation strategy is beneficial for BESS prospects is limited by the adequacy of the technical regulatory framework and the available DEGOF. This strategy provides operational improvements for all products considered, with the largest improvement potentials seen for the products available in Great Britain (FFR and EFR).

Index Terms-- Battery Energy Storage Systems (BESS), Power Reserve Markets, Frequency Containment Reserve, Enhanced Frequency Response, Firm Frequency Response

I. INTRODUCTION

A reliable electricity supply can only be ensured if the power system is stable. One of the indicators of power system instability is a deviation of the system frequency from its nominal value, which relates to imbalances between generation and consumption. A negative frequency deviation indicates a shortage of generation with respect to consumption, whereas a positive deviation indicates the reverse case. In Europe, the recently in-force guideline on electricity transmission system operation (SO GL) describes the Load-Frequency Control (LFC) process, which has the purpose of addressing imbalances close to real time through the sequential activation of control reserves. First, the Frequency Control Reserve (FCR) is automatically activated within a synchronous area with the purpose of stabilizing a frequency deviation at a new operation set point. Then, the automatically and manually activated Frequency Restoration Reserves (FRR) are engaged to return frequency close to its nominal value and are deployed in LFC areas where system imbalances occur. Lastly, the Replacement Reserve (RR) may be available to support and replace the previously activated FRR.

Because of their technical capabilities, Battery Energy Storage Systems (BESS) stand out among the various technologies currently available for the provision of fast frequency response (in terms of the SO GL, response similar to that described for FCR). BESS can deliver response power faster and more accurately than conventional generation; however, their provision is limited by their finite storage capacity. Although BESS could theoretically participate in all types of control reserve, the longer provision periods and minimum power capacities required by some reserves (like FRR and RR) translate into larger storage capacity needs, and thus increased upfront costs. In addition, at least in the common FCR market (regelleistung.net), the potential yearly revenue for participation in fast frequency response reserves is larger than for the subsequent reserves [1].

The characteristics of the different synchronized systems, along with national regulatory frameworks, have an important impact on the operation and prospects of batteries providing fast frequency response. From this perspective, the provision of fast frequency response in Germany, Sweden and Great Britain is analyzed. In section II, fundamentals of frequency response are addressed and the different frequency response products available in each country are described and analyzed. In section III the frequency response simulation and results are given. Finally, a discussion of the results is presented in section IV, followed by a conclusion in section V.

II. FREQUENCY RESPONSE SERVICES IN SELECTED COUNTRIES

A. Fundamentals

Fast frequency response reserves respond to a difference between the nominal value of the system frequency f_N and the locally measured frequency $f(t)$ as shown in (1). Low frequency values correspond to demand being greater than generation and high frequency values correspond to generation being greater than demand. Therefore a battery discharges in response to positive frequency deviations and charges when a negative frequency deviation is measured. Power response must be provided in proportion to the frequency deviation as described in the reference provision curve calculated by (2). When the measured frequency deviation is within the *deadband* Δf_{ab} no response is

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expected. Then, a proportional increase in response power must be delivered starting at a frequency deviation larger than the deadband until reaching the *full activation frequency deviation* Δf_{max} . Finally, maximum response power is expected for frequency deviations larger or equal to the full activation frequency deviation.

$$\Delta f(t) = f_N - f(t) \quad (1)$$

$$= \begin{cases} P_{FCR}^{max} \left(\frac{\Delta f(t)}{|\Delta f(t)|} \right), & |\Delta f(t)| \geq |\Delta f_{max}| \\ P_{FCR}^{max} \left(\frac{\Delta f(t)}{|\Delta f_{max}|} \right), & |\Delta f_{db}| < |\Delta f(t)| < |\Delta f_{max}| \\ 0, & |\Delta f(t)| \leq |\Delta f_{db}| \end{cases} \quad (2)$$

Not every product implements a deadband nor applies this interpretation of the proportional provision, see for example [2] and [3]. To the knowledge of the authors, no regulation specifying the interpretation of the proportional increase after applying a deadband exists at the EU level.

In FCR provision, full activation of maximum power must also be achieved within a specific timeframe: the *full activation time*. The shorter the required full activation time, the more accurate must the response be with respect to the instantaneous change in frequency. The combination of the frequency response capability and the full activation time define the minimum power increase requirements for conventional providing units. FCR providers with an energy reservoir limitation must be able to provide maximum power in a single direction during a *minimum activation period*. In an still ongoing standardization process this period will be set between 15 and 30 minutes based on cost-benefit analyses performed by all TSOs from CE and Nordic synchronous areas, where the requirement is applicable [4]. The previously described parameters for fast frequency response reserves in selected countries are shown in Table I.

B. Product Description

In Germany the first control reserve to be activated is the Primary Control Reserve (PCR). To address the particularities of PCR providers with limited energy reservoirs, German TSOs published additional requirements for their storage capacity [5]. Additionally, a set of degrees of freedom (DEGOF) [6] which provide flexibility in the technical requirements are available for all PCR providers. These

DEGOF can be used by BESS to support SoC maintenance.

In Sweden, the national TSO Svenska Kraftnät manages the procurement of the two fast frequency response control reserves available in the Nordic synchronous system: FCR Normal (FCR-N), which is used to balance the system within the standard frequency deviation range (± 100 mHz) and FCR Disturbance (FCR-D), which is used to control large disturbances with a frequency deviation below 49.90 Hz and above 50.10 Hz, respectively. FCR-D is currently a unidirectional service which energy-limited units, such as BESS, are technically not able to effectively provide. However, in upcoming regulation [7] FCR-D is divided into two products: one responding to frequency deviations lower than 49.9 Hz and the other for deviations higher than 50.1 Hz. Although this new regulation is not yet in force, FCR-D is combined into a single bidirectional product for the purposes of this paper.

In Great Britain, the national TSO National Grid offers Firm Frequency Response (FFR) as a way for providers connected to transmission and distribution networks, such as storage providers and aggregated demand side response, to market a frequency response service. FFR is composed by two products responding to low frequencies (primary and secondary response) and one responding to high frequencies (high response). Most providers offer a combination of these three products and must introduce the expected power response to frequency deviations in so-called capability data tables [8]. The final expected response is then given by linear interpolation between the values annotated. This implies that a lower full activation frequency deviation could be chosen by the provider (e.g. ± 200 mHz) instead of the one found in EU regulation (± 500 mHz).

In addition, National Grid recently developed the Enhanced Frequency Response (EFR) service to address reducing system inertia caused by the increasing shares of renewable generation. EFR is a product with a design more appropriate for providers with limited energy reservoirs. In EFR, two different deadbands define two separate products, which will be further referred to as EFR Narrow and EFR Wide. In addition to the deadband, a so-called envelope provides flexibility in provision in order to support SoC maintenance.

C. Product Analysis

A first insight on the maximum power requirements of

TABLE I CHARACTERISTICS OF THE SELECTED FREQUENCY RESPONSE RESERVES

Parameter	Germany ^a	Great Britain ^b		Sweden ^c	
	PCR	FFR	EFR	FCR-N	FCR-D
Full Activation Time	50% in 15 s, 100% in 30 s	Primary: 10 s Secondary: 30 s High: 10 s	< 1 s	63% in 1 min, 100% in 3 min	50% in 5 s, 100% in 30 s
Minimum Activation Period	With backup unit: 15 min Without backup unit: 30 min	Primary: 30 s Secondary: 30 min High: Indefinite	15 min	15 min	15 min
Full Activation Frequency Deviation	$\geq \pm 200$ mHz $\geq \pm 100$ mHz, > 5 min $\geq \pm 500$ mHz, > 10 min	± 500 mHz (or specified in capability data tables)		± 100 mHz	± 500 mHz
Deadband	± 10 mHz	None	Wide: ± 50 mHz Narrow: ± 15 mHz	± 10 mHz	± 100 mHz (activation frequency deviation)

a. Sources for Germany: [6] [5] [4]. b. Sources for Great Britain: [2] [3] [8] [4]. c. Sources for Sweden: [9] [10] [7] [4].

each of the services considered is obtained by analyzing the system frequency (see Figure 1) in combination with the ranges where frequency response is expected. Every product is analyzed using its corresponding system frequency. In other words, FCR-N and FCR-D are analyzed using the Nordic system frequency, EFR and FFR with that of Great Britain and PCR with the one corresponding to Continental Europe.

The Continental Europe system frequency was provided by Swissgrid for the year 2012. In this case, 97.05 % of the system frequency data are found within a range of ± 50 mHz (i.e. the standard frequency range for PCR shown in Table I). Since the full activation frequency deviation is set at ± 200 mHz, provision with only a quarter of the maximum power is required for the best part of the year. Moreover, 36.30 % of the data is found within the deadband, which means that for more than one third of the year no provision is required.

Sweden is part of the interconnected Nordic synchronous system, which also includes the subsystems of Norway, Finland and Eastern Denmark. Historical system frequency data for the Nordic synchronous system for the year 2015, used for analyzing Swedish services, is openly available in the Finnish TSO Fingrid website. The Nordic system frequency data has a standard deviation of 0.43 compared to 0.022 for CE, this reflects a less stable system with larger imbalances. When comparing this to the small full activation frequency deviation of FCR-N (± 100 mHz), very high utilization of the providing unit throughout the year is expected. In addition, only 17.72 % of the data are found between the deadband (± 10 mHz). On the other hand, FCR-D is first activated at a deviation of ± 100 mHz; since 97.19 % of the data are already found within this range, a very low frequency response requirement is expected.

For Great Britain, second-by-second system frequency data was obtained from National Grid website for the year 2015. About 99.99 % lie within the standard frequency range defined for this area (± 200 mHz). Therefore, taking the full activation frequency deviation in EU regulation (± 500 mHz), less than half of response power would be required throughout the year. This applies particularly to FFR where no deadband is allowed for the reference provision. On the other hand, the implementation of the deadband for EFR follows a different interpretation as the one given in (2). Instead of maintaining the original proportionality as previously described, a discontinuous function is applied in which provision starts at

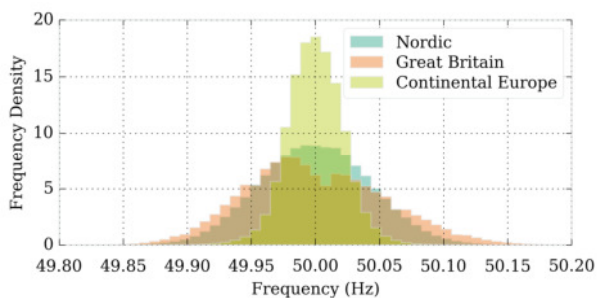


Figure 1 Distribution of system frequency data for Continental Europe (2012), Nordics (2015) and Great Britain (2015).

TABLE II DEGOF FOUND IN REGULATORY FRAMEWORKS CONSIDERED

DEGOF	Description
Deadband	Range around the nominal frequency value where no provision is required.
Delay	Lead time between signal detection and response activation.
Gradient	Rate of power response increase dictated by the full activation time and full activation frequency deviation.
Over-fulfillment	Applicable only to PCR. A maximum allowed output equal to instantaneous power multiplied by a factor of 1.2
Envelope	Applicable only to EFR. Maximum allowed output equal to $\pm 9\%$ starting at nominal value and converging with instantaneous provision at ± 250 mHz (see [1]).
Power Tolerance	Applicable only to FFR. A maximum power tolerance equal to $+5\%$ of instantaneous output for overprovision. For underprovision a maximum tolerance of -5% is given at the nominal frequency value, converging with instantaneous provision at ± 500 mHz (see [7]).
Grid Time Control	Adjustment of synchronous time to astronomical time through a change in nominal system frequency value.

zero charging or discharging power at the limits of the deadband. This means that less power is required, in proportion of the displacement suffered by the original curve.

III. SIMULATION AND RESULTS

A. SoC Management Strategy

In previous publications [11] [12] a SoC management strategy which ensures provision under technical regulatory requirements for PCR in Germany is described. This strategy is based on the use of reserved storage capacity to ensure maximum full power provision for the minimum activation period. Additionally, depending on the instantaneous SoC value and predefined SoC operation limits, this strategy shifts between three operation modes which utilize available regulatory DEGOF to either *minimize cycles*, *maximize charge* or *maximize discharge*. This strategy was adapted to the technical regulatory requirements for the fast frequency response products considered. Unless explicitly noted, all DEGOF described in Table II are available for all products considered. Given the lack of data for the changes made to the nominal system frequency value for grid time control in all different synchronous areas, this DEGOF was not taken into account for provision calculation.

An analysis of the impact of single DEGOF was performed and their aggregated impact (i.e. in the form of a different operation mode) on the potential energy use per MW of power offered for frequency response throughout the year is shown in Figure 2. This value is here referred to as energy turnover. Results for each operation mode can be compared to the instantaneous energy turnover to assess their effectiveness. The instantaneous energy turnover refers to the provision following the reference response curve described in (2) without the use of a deadband.

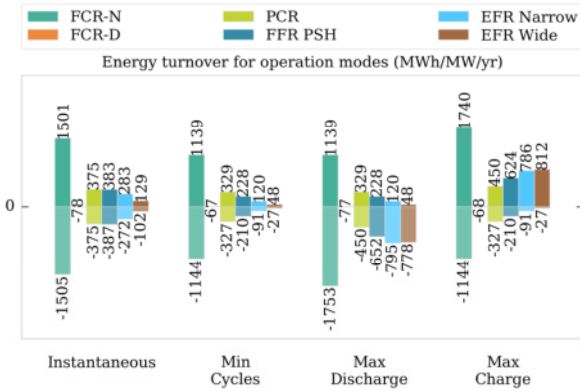


Figure 2 Potential energy use per MW of power offered for frequency response throughout the year.

For the case of PCR, the decrease of 13 % in energy turnover for *minimize cycles* is mainly driven by the deadband. For the other two operation modes, overfulfillment provides the greatest contribution. As expected, FCR-N shows a remarkably high energy turnover. Although the minimize cycles mode reduces total energy turnover by 58 %, energy turnover remains clearly higher than for any other product. For FCR-D on the contrary, the operation modes have almost no effect since power provision is remarkably low due to the activation frequency range of ± 100 mHz.

The mayor contributor to the notable effectiveness of the operation modes for FFR Primary/Secondary/High (FFR PSH) is given by the power tolerance; similarly for EFR, the greatest contribution is given by the envelope. This is mainly because they permit the greatest flexibility in times in which the frequency is close to the nominal system frequency, which is the case the dominant share of the time (see Figure 1).

B. Frequency response provision simulation

Table III shows the parameters used for the simulated provision of frequency response with BESS. It is assumed that a provider wants to maximize the power dedicated for frequency response since it is the sole source of revenue. However, storage capacity regulation in Germany requires that a share equal to at least 25 % of the power offered for PCR is dedicated for corrective measures. Therefore, 1 MW is allocated for FCR provision while 0.25 MW are reserved for corrective measures. A minimum activation period of 15 minutes is chosen for PCR since a larger value can drastically affect the potential of BESS as providers of frequency response services, as shown in a previous publication [13].

TABLE III CONFIGURATION OF THE SIMULATED BESS PROVIDING PCR

Variable	Value
Storage capacity	1.25 MWh
Power (AC side)	1.25 MW
Frequency response power	1 MW
Self-discharge	7 % per month
Round-trip efficiency	96 %

In Figure 3 there are some generally observed effects when applying the operational strategy. First, there is a reduction in energy used for corrective measures; charging corrective measures account for more energy use because of battery self-discharge and the positive skew of the frequency data samples. And second, there is a reduction in response energy use, with the exception of PCR where there is a slight increase caused by the use of overfulfillment DEGOF.

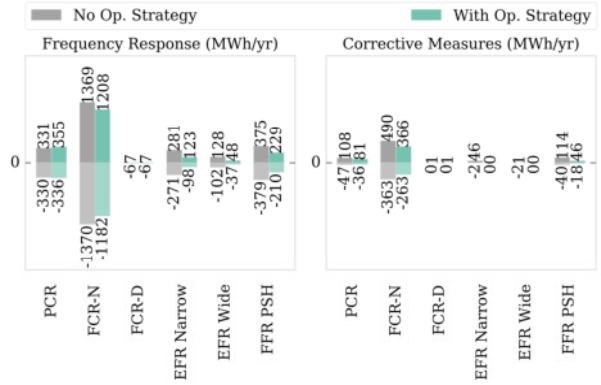


Figure 3 Energy dedicated for frequency response and needed for corrective measures for a simulated year of frequency response provision.

It can also be observed that FCR-N shows the highest provision of response energy, as well as the largest need for corrective energy (21 % of total energy) even when applying the operational strategy. This is due to the combination of the high demand of response power and the strong fluctuations of the Nordic system frequency. The remarkably large total energy results in 928 full cycle equivalents, which stand out against an average of 260 for all products. The large number of cycles along with the extreme and rapid changes in SoC would potentially result in severe battery degradation. Finally, the high share of power dedicated for frequency response (80 %) combined with the high demand of response power, causes the battery to be depleted and unavailable for slightly less than 8 days throughout the year. This shows that BESS with a high share of power dedicated for frequency response is not adequate for provision of FCR-N and could rather be used as support for another provider. On the other hand, FCR-D shows the lowest response energy turnover, the battery completes only about 6 full-cycles in the whole year. The big amount of corrective charging energy is given by the fact that the available DEGOF are insufficient to support SoC management.

The energy reduction achieved by the strategy for products in Great Britain stands out in comparison with the rest. For FFR a reduction of 43% in total energy is achieved and the need for corrective measures is almost eliminated. This is mainly driven by the allowed power tolerance, described in the previous section. EFR Narrow and EFR Wide show a reduction of 63 % and 64 % respectively and a complete elimination of corrective measures is achieved. This suggests that flexibility given by the envelopes provides room for increasing power dedicated for frequency response beyond

80 % while still ensuring 100 % availability without the need of corrective measures from external sources.

IV. ECONOMIC ASSESSMENT

An illustrative assessment of the profitability of providing frequency response is calculated based on (3). The first summand describes the revenue for providing frequency response continuously throughout a year. Here, an hourly average power price p is calculated based on data obtained from tender results as noted in TABLE IV. This power price is paid to providers for the available maximum power dedicated for frequency response P^{max} . The second summand describes the costs related to the degradation of the battery. These costs are expressed as a share of the investment costs IC , assumed to be 776 €/kWh, given by the ratio of the number of full cycles resulting from operation C_{prov} and the cycle life of the battery C_{deg} (5000 cycles). Energy costs related to corrective measures are ignored based on the conclusions of previous work [12], where it was determined that the biggest contributor to total costs are those costs related to the cycle life of the battery.

$$Profit = (P^{max} \cdot p \cdot 8760) - IC \frac{C_{prov}}{C_{deg}} \quad (3)$$

Table IV also shows the potential revenue, cycling costs and profit of providing frequency response for each product considered. For PCR, provision of the service is profitable with cycling costs representing 29 % of potential revenue made in that same year. In other words, 0.29 €/yr are spent for each Euro of revenue. Meanwhile, FCR-N has a relatively low power price, which provides insufficient revenues to outweigh the remarkably high cycling costs and therefore there are losses instead of profits. In contrast, even though the power price is comparatively lower for FCR-D, providing the service still yields a profit due to very low cycling costs. FCR-D has the lowest cost-to-revenue ratio with a value of only 3 %. It could be possible to increase profit from provision by alternatively bidding for both FCR-D and FCR-N.

Both EFR Narrow and EFR Wide present low cost-to-revenue ratios, 17 % and 7 % respectively, not because of a higher power price, but as a direct effect of the low cycling costs resulting from the dynamic use of the envelopes. Furthermore, it could be possible to further increase potential profit by increasing offered power beyond the 80 % of total power cap used in this paper. High revenue is shown for FFR

PSH because of both a high power price and relatively low cycling costs. It must be noted that the power price used for FFR PSH was calculated as an average of accepted FFR bids in 2015 from providers, which offered frequency response in both directions. This price is influenced by the cost structure of conventional providers and thus may prove to be an overestimation for a bid coming from a BESS unit.

V. DISCUSSION

An operation strategy which supports SoC management by taking advantage of the combined and dynamic use of regulatory DEGOF is found to be beneficial for all products investigated. In particular, the envelope and the power tolerance described for EFR and FFR PSH, are found to provide the greatest flexibility as DEGOF to support SoC maintenance. Hence, similar approaches could be beneficial for BESS providing fast frequency response in other countries.

Even though battery cycle life is highly dependent on the energy charged and discharged as a result of FCR provision, none of the European settlement concepts take this into account. The combination of the provision of various types of frequency response products or with other applications may prove to improve the economic case for the BESS. This is especially true for products with low utilization like FCR-D and those who provide enough flexibility such as those found in Great Britain.

VI. CONCLUSION

The different conditions of the power systems from the selected countries increase complexity when considering BESS as FCR providers. Firstly, FCR products are fundamentally coupled with the frequency of each synchronized system and must be assessed accordingly. Secondly, since technical requirements are generally still focused on conventional providers, there is regulatory leeway, which provides flexibility when choosing an operation strategy. And thirdly, the diverse settlement regulation leads to other markets and processes, which are also unclear in regard to applicability of BESS.

Integrating BESS as fast-responding control reserves is central to support power system stability in power systems with increasing shares of variable generation and decreasing inertia. Therefore, the regulatory framework must be revised to ease the introduction of BESS as FCR providers or in other fast-responding frequency regulation services, so that they rely not on regulatory leeway, but can instead take advantage of specifically designed regulation to improve their business case.

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TABLE IV POTENTIAL PROFIT FOR FREQUENCY RESPONSE PROVISION

Product	p (€/MW/h)	C_{prov}	Revenue (€/yr)	Cycling Costs (€/yr)	Profit (€/yr)
PCR	22.67 ^a	301	198 589	57 007	141 582
FCR-N	11.16 ^b	928	97 762	175 653	-77 892
FCR-D	4.65 ^b	6	40 734	1 192	39 542
FFR PSH	31.01 ^c	196	271 648	37 042	234 605
EFR Narrow	11.52 ^d	91	100 915	17 206	83 709
EFR Wide	11.52 ^d	35	100 915	6 692	94 223

Sources for 2015: a. [13], b. [11], c. [12]. Source for 2016: d. [14]

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