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Economic Assessment of Battery Energy Storage for Frequency Regulation in the Nordic Power Systems

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Abstract—The present work aims to determine the technical and economic implications of a Battery Energy Storage System (BESS) to participate in different Frequency Containment Reserve (FCR) markets, in accordance with the Nordic Power System requirement. For this purpose, a 1MW BESS is simulated for FCR provision using frequency data from 2022. The bidding strategy takes into account the endurance and the constraints of limited energy reservoirs. Therefore, this paper proposes that the BESS will contribute to the FCR market every third hour to avoid depletion of the BESS. The economic feasibility of the BESS providing FCR is assessed through Net Present Value (NPV) and payback period analyses. The results indicate that a BESS bidding in the frequency containment reserve for disturbance for up regulation (FCR-D up) market has the shortest payback period, approximately 2 years. In contrast, BESS bidding in the Frequency Containment Reserve for Normal operation (FCR-N) market exhibits the longest payback period compared to other FCR products, totaling 7 years.

Index Terms—BESS, Bidding Strategy, FCR market, Nordic power system, Payback period.

I. INTRODUCTION

The integration of renewable energy resources into the electricity sector is crucial for achieving sustainable decarbonization. However, these resources have inherent unpredictability and fluctuation, which make it difficult to maintain the stability and reliability of the power grid. Maintaining power balance between supply and demand is necessary to keep the frequency within normal range. Excessive supply increases frequency, while excessive demand decreases it. If the frequency deviation is large, this may lead to disconnection of loads.

In Sweden, the transmission system operator, Svenska kraftnat (Svk), is responsible for maintaining the frequency stability. Thus, SvK buys frequency ancillary services mainly from hydro power plants. Nevertheless, there is a growing demand for resources with quicker response times in a renewable-dominated power system. Therefore, new players like Battery Energy Storage Systems (BESSs) and electric vehicles (EVs) are starting to be involved in the frequency ancillary services market. The rapid response times and high-power capabilities of BESS make them well-suited for delivering FCR, despite their limited energy reservoir [1].

Jan et al. [2], have investigated different strategies for recovering the BESS for frequency containment reserve for normal operation (FCR-N) in the Nordic market. However, this study has not investigated frequency containment reserve for disturbance (FCR-D) despite, it is considered one of the most profitable FCR services. Peter et al. evaluate a techno-economic analysis of BESS for peak shaving and FCR in the Norwegian electricity distribution systems. The results reveal that using a BESS for balancing power seems to be the most feasible application [3]. Yu et al. identify that FCR is the most profitable service for BESS in the European market [4]. However, further investigation of the BESS into the profitability of BESS for providing Frequency Containment Reserve for Disturbance for up regulation (FCR-D up) in combination with Frequency Containment Reserve for Disturbance for down regulation (FCR-D down) is needed. This study compares techno-economic factors of BESS participating in various Nordic frequency ancillary service markets, more specifically the FCR-N, FCR-D up and FCR-D down markets.

The contributions of this paper include: 1) Designing a simple bidding strategy in the different FCR markets that account for the technical capability of the BESS in addition to the frequency market requirement. 2) Comparing the payback period of BESS when bidding in different FCR markets. Furthermore, a sensitivity analysis is conducted to evaluate the impact of saturation of the FCR market. Additionally, it is essential to assess the effect of bidding for all hours on the payback period aligning with recent FCR requirements.

II. FREQUENCY CONTAINMENT RESERVES IN THE NORDIC SYNCHRONOUS AREA

A. Technical requirements

In the Nordic Synchronous Area, FCR serves the objective of stabilizing and maintaining frequency in the event of power imbalance. This service includes FCR-N and FCR-D. FCR-N handles short-term stochastic net power variation in production and consumption and ensure frequency stability and quality. FCR-D ensures frequency stability corresponding to large disturbances. FCR-N and FCR-D are automatically activated when there is a frequency change within the designated frequency range that they are intended to support. FCR-N operates symmetrically, requiring the entity supplying it to be capable of increasing/decreasing its power within the

frequency range of 49.90-50/50-50.10 Hz. Unlike FCR-N, FCR-D is a non-symmetrical service. FCR-D is traded as two products, FCR-D up and FCR-D down. FCR-D up is activated when the frequency is between 49.5–49.9 Hz, and FCR-D down when the frequency is between 50.1-50.5 Hz. For an entity to participate in the FCR market, a minimum bid size of 0.1 MW is required. Additionally, the FCR-N service requires an endurance of 1 hour while FCR-D requires only 20 min. Fig. 1 shows the FCR activation with respect to frequency deviation, where 100% in injected power represents the total amount of the contracted FCR provision.

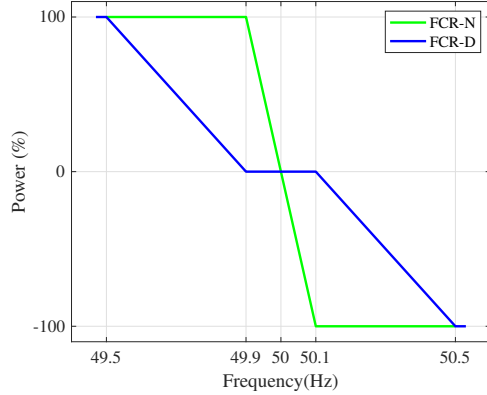


Fig. 1. FCR activation with respect to frequency deviation

B. Market process

In the Nordic region, owners of a BESS, can participate in the FCR market by submitting bids either two days (D-2) or one day (D-1) prior to the day of operation (D). The submission of bids is subject to a specific time constraint known as the gate closure (GC). Before the GC, all submitted bids are organized based on their price per megawatt (MW). Following this sorting process, the bids are evaluated, and they are either accepted or rejected based on their competitiveness. The GC for FCR bidding in the Nordic region occurs before 15:00 for bids submitted one day ahead (D-1) and before 18:00 for bids submitted two days ahead (D-2). The schedule of bidding and GC is shown in Fig. 2.

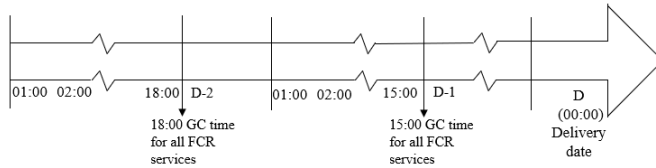


Fig. 2. Schedule bidding in Nordic FCR market

C. Compensation scheme

Participants in the FCR market receive compensation for the submitted bid capacity. Additionally, participants in the

FCR-N market receive compensation for the activated energy during the hour of delivery. The energy fee will be paid by Svk in accordance with the balancing market when the FCR-N is activated. This implies that Svk compensates the FCR-N provider based on the up-regulation price when they inject energy into the system (BESS discharging) or based on the down-regulation price when they consume energy (BESS charging). The capacity fee is paid regardless of activation and is calculated based on the submitted bid capacity.

III. PROPOSED METHODOLOGY

The methodology section is divided into three parts. First, a general overview of the model is provided. Second, Bidding strategy and State of energy (SOE) recovery have been illustrated. Third, the economic model to calculate net present value (NPV) and payback period is described.

A. Frequency-droop model

A simulation model was developed in MATLAB, allowing the battery to provide FCR services. The calculation of the power to be supplied by BESS unit is determined through the application of droop control signals to frequency data, using frequency data measured at 1Hz during 2022. The droop control equations for FCR-N, FCR-D up and FCR-D down are presented as

$$P_{\text{FCR-N}} = P_{\text{FCR-N}}^{\text{Max}} \times \begin{cases} 1, & \text{if } f \leq 49.9 \text{ Hz} \\ \frac{f_{50} - f}{\Delta f_{\text{FCR-N}}^{\text{Max}}}, & \text{if } 49.9 \text{ Hz} \leq f \leq 50.1 \text{ Hz} \\ -1, & \text{if } f \geq 50.1 \text{ Hz} \end{cases} \quad (1)$$

$$P_{\text{FCR-Dup}} = P_{\text{FCR-Dup}}^{\text{Max}} \times \begin{cases} \frac{f_{50} - f}{\Delta f_{\text{FCR-D}}^{\text{Max}}}, & 49.5 \text{ Hz} \leq f \leq 49.9 \text{ Hz} \\ 1, & \text{if } f \leq 49.5 \text{ Hz} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

$$P_{\text{FCR-Ddown}} = P_{\text{FCR-Ddown}}^{\text{Max}} \times \begin{cases} \frac{f_{50} - f}{\Delta f_{\text{FCR-D}}^{\text{Max}}}, & 50.1 \text{ Hz} \leq f \leq 50.5 \text{ Hz} \\ 1, & \text{if } f \geq 50.5 \text{ Hz} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

where f_{50} is the nominal frequency in Sweden, which is 50 Hz, f is the actual frequency in Hz, $\Delta f_{\text{FCR-N}}^{\text{Max}}$ is the maximum frequency deviation for FCR-N activation, which is 0.1 Hz, and $\Delta f_{\text{FCR-D}}^{\text{Max}}$ is the maximum frequency deviation for FCR-D activation, which is 0.4 Hz. $P_{\text{FCR-N}}^{\text{Max}}$, $P_{\text{FCR-Dup}}^{\text{Max}}$ and $P_{\text{FCR-Ddown}}^{\text{Max}}$ are the bid capacities in MW for FCR-N, FCR-Dup and FCR-Ddown, respectively.

B. State of energy recovery calculation

The energy level of the battery is determined by the following expression

$$e(t) = e_0 - \int P_{\text{FCR}} dt, \quad (4)$$

where e_0 is the energy level at the start of hour of delivery and P_{FCR} is the power provided by BESS for different FCR services. The SOE of the battery is calculated by the relation

$$\text{soe}(t) = \text{SOE}_{\text{init}} + \frac{100 \times e(t)}{E_{\text{max}}}, \quad (5)$$

The recovered power is determined by the equation:

$$P_{\text{rec}} = \frac{(SOE_{\text{fin}} - SOE_{\text{init}}) \times E^{\text{max}}}{1 \text{ hour}}, \quad (6)$$

Where SOE_{fin} is the SOE level at the end of hour of delivery and SOE_{init} is the initial SOE which depend on the FCR service as explained in Section (III-C).

C. Proposed bidding strategy

The bidding strategy involves decisions on when to place bids, bidding capacity, and for what service to place bids. In the Swedish regulation market, there are constraints regarding the submission of bids. A crucial constraint for any frequency regulating supplier with a Limited Energy Reservoir (LER), such as a BESS, is the requirement of recovery. The recovery requirement mandates that a supplier with a LER must plan for the resource's recovery after the bidding period, ensuring readiness for the next period of providing frequency regulation. As FCR-N is a symmetrical service, there is a possibility that it involves both discharging and charging the battery within a single hour. This means that the BESS may self-recover during the FCR provision. However, when bidding in the market the worst-case scenario should be considered, i.e. the frequency is either above 50.1 Hz or below 49.9 Hz during the entire hour of delivery. If the BESS owner fails to provide the FCR-N service, the system operator may exclude them from the market. In this context, the bidding strategy entails that the BESS will submit bids every third hour. Consequently, the BESS will offer FCR services for one hour, followed by a one-hour standby period before the recovery occurs in the third hour. The standby period is essential because the recovery is executed through the intraday market, which concludes one hour prior to the recovery period. The bidding strategy is summarized in Fig. 3.

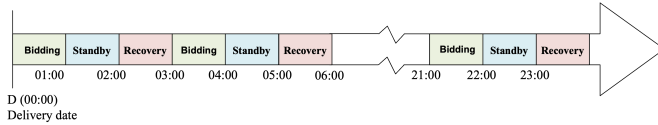


Fig. 3. Bidding strategy to participate in Nordic FCR market.

The proposed bid capacity takes into account the technical capabilities of BESS in addition to the frequency requirement as

$$P_{\text{FCR-N}}^{\text{Max}} = P_{\text{FCR-D}}^{\text{Max}} = \min \left(\frac{(SOE_{\text{max}} - 50\%) \times E^{\text{max}}}{\text{Endurance}}, P^{\text{max}} \right) \quad (7)$$

$$\begin{aligned} P_{\text{FCR-Dup}}^{\text{Max}} &= P_{\text{FCR-Ddown}}^{\text{Max}} \\ &= \min \left(\frac{(SOE_{\text{max}} - SOE_{\text{min}}) \times E^{\text{max}}}{\text{Endurance}}, P^{\text{max}} \right) \end{aligned} \quad (8)$$

Where $P_{\text{FCR-D}}^{\text{Max}}$ is the bid capacity in MW for bidding simultaneously in FCR-Dup and FCR-Ddown markets. E^{max} is the maximum battery energy capacity in MWh, SOE_{max}

and SOE_{min} are respectively the maximum and minimum permissible SOE of the battery in percents.

Fig 4 shows the initial SOE for bidding in different FCR markets. FCR-N is a symmetrical service that requires the BESS to provide up and down regulation. For this reason, the SOE_{init} should be between SOE_{min} and SOE_{max} . In this study, the SOE_{init} is set to be 50%. This also applies for bidding in both FCR-D up and FCR-D down markets simultaneously. For FCR-D up, that is not a symmetrical service. Therefore, in this case $SOE_{\text{init}} = SOE_{\text{max}}$ in order to take advantage of the BESS energy capacity. However, in case of FCR-D down $SOE_{\text{init}} = SOE_{\text{min}}$.

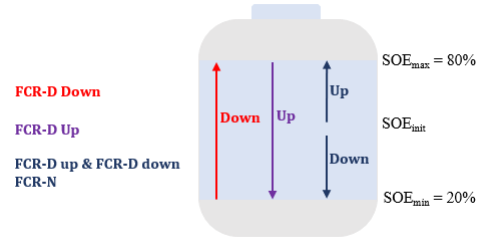


Fig. 4. Initial state of energy for bidding in different FCR market

D. Economic model

The economic model is developed with the aim of assessing the economical feasibility of BESS. The feasibility of BESS can be evaluated by calculating the NPV:

$$NPV = \sum_{n=1}^N \frac{CashFlow_n}{(1+r)^n} - InitialInvestment, \quad (9)$$

where $CashFlow$ represents the revenue from FCR market minus operation and maintenance (O & M) cost. $InitialInvestment$ includes the BESS power and energy capacities cost and other project costs, r is the a discount rate of the project which is considered to be 5% and n refers to the project lifetime which is estimated to be 10 years in this economic model. The income from participating in the FCR market for a BESS involves getting paid for the bidding capacity (in MW) and energy provided (just in case of FCR-N), as explained in II-C. However, since usually the frequency variations are even, the energy compensation is very small. There are also recovery costs, but these even out as the BESS alternates between absorbing and injecting power. It has been assume that tariff costs are neglected. Jan et al. [2] performed a techno-economic analysis of a BESS. The results show that the capacity payment is the domination when calculating profit from FCR-N. An additional assumption incorporated into this analysis, is that the prices for FCR will remain consistent throughout the entire operational lifespan of the BESS. The FCR prices used in this study are the FCR prices of 2022 [5]. Fig. 5 shows the hourly compensation for FCR-N, FCR-D up and FCR-D down.

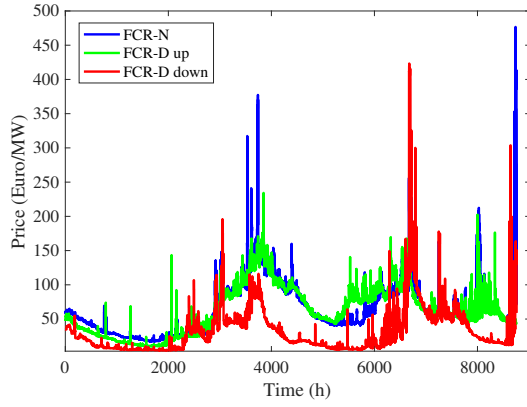


Fig. 5. FCR capacity remuneration

FCR-N and FCR-D up have very similar prices, except for some hours when the FCR-N has a much higher value compared to FCR-D up. FCR-D down on the other hand is relatively cheaper. This is because the demand on FCR-D down service is lower.

The capital cost of a lithium-ion battery was assumed to be 170 € per kWh. Additional costs to consider in the context of Li-ion batteries include O & M which are assumed to be around 2% of the total investment costs.

Another economic metric that has been investigated to quantify the feasibility of BESS in the FCR market is the payback period formulated as

$$\text{Payback period} = \frac{\text{Initial investment}}{\text{Average annual cash flow}}. \quad (10)$$

IV. SIMULATION RESULTS

A. Dynamic results of BESS providing FCR-N service

This section will only focus on a BESS providing FCR-N. As the FCR-N requires more energy than FCR-D, maintaining the SOE is more critical. Figure 6 illustrates the frequency deviation in the Nordic synchronous system on first of January 2022. The corresponding BESS dispatched power for FCR-N provision and the SOE are shown in Fig.7 and Fig.8, respectively.

The frequency deviations are within -0.1 Hz and 0.1 Hz most of the time, except for a few occasions. Whenever the frequency is outside the normal band, the BESS activates its maximum bid capacity which is 0.3 MW for FCR-N. If the frequency is within the normal band, the BESS power follows the steady state frequency-droop characteristics as described in Section (II-A) and illustrated in Fig. 1.

It is evident that the SOE level starts from 50% at the beginning of the simulation. At the end of the first hour, the SOE level has gone down to around 45%. The BESS is then in standby mode, which explains why the SOE is constant in the following hour. In the third hour, the BESS will absorb power from the grid to restore the SOE level to 50% to be ready for another cycle of FCR provision. The amount of power needed for SOE recovery is illustrated in Section (III-B).

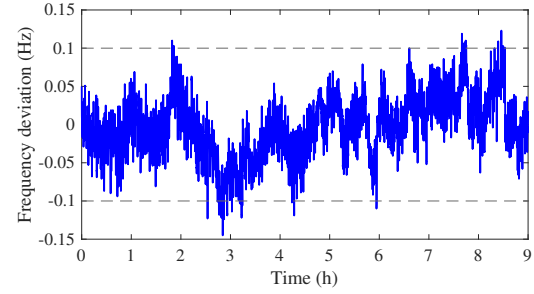


Fig. 6. Frequency deviation of the Nordic synchronous system on January 1, 2022

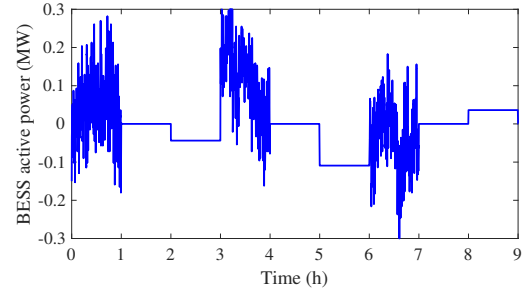


Fig. 7. BESS active power for FCR-N service

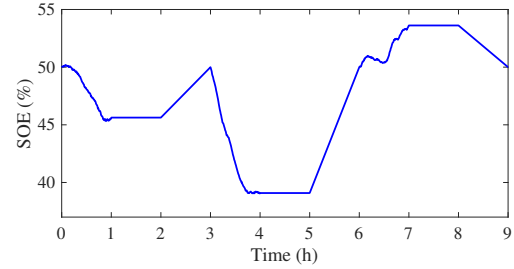


Fig. 8. SOE of BESS providing FCR-N

B. Feasibility study and sensitivity analysis

Fig. 9 shows the NPV of the BESS when providing different FCR services. The NPV is positive for all the FCR services, indicating that all the FCR services are profitable. Using a BESS for providing FCR-N exhibits the lowest NPV among the considered FCR services. The maximum NPV is attained when the BESS serves FCR-D up, which has a yearly market value of 0.6 million EUR. The NPV for FCR-D down has a lower revenue than that of FCR-D up due to the lower market value for FCR-D down. When bidding in the FCR-D up and FCR-D down markets simultaneously, the profit increases but is still less profitable than bidding only in the FCR-D up market.

According to the new FCR market requirements in the Nordic Synchronous Area, it is now possible for LER to bid in all the hours. This is due to the possibility of the LER to recover during the hour of delivery [6]. By bidding in all the hours, this can reduce the payback period of the BESS by three times as compared to bidding every third hour. This is

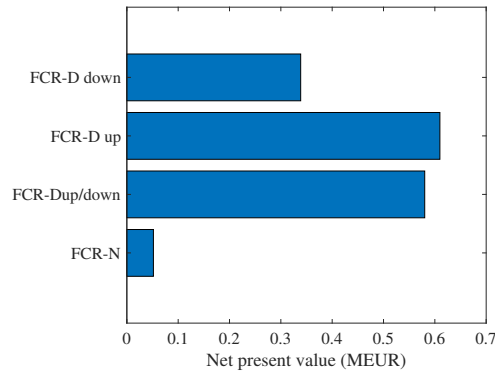


Fig. 9. Net present value of BESS bidding in the FCR market every third hour.

under the assumptions that the BESS will be cleared in all the hours in the market.

In this study, the FCR market remuneration prices are considered to be the same for the next 10 years. However, as more BESSs are planned to be installed in Sweden in the next few years [7], this may saturate the FCR market, resulting in a significant drop in FCR remuneration prices. The sensitivity of the payback period to the reduction of FCR capacity remuneration prices is illustrated in Fig. 11. The results reveal that the payback period will be longer when the capacity reimbursement is decreased. It becomes evident that if the remuneration for FCR capacity is decreased by 50%, the payback period will extend twofold. Worth nothing is that the payback period for FCR-N extends to 14 years, which is longer than the length of the project. This makes the investment economically unfeasible.

V. CONCLUSION

This paper aims to investigate the technical and economic implications of a BESS participating in different FCR markets. The technical factors taken into account when designing the bidding strategy are the needed endurance for the various FCR services, the special requirements for LER, in addition to the BESS power and energy capacities. Thereby, this paper suggests BESS contributing in the FCR market every third hour to not deplete the BESS. Moreover, the maximum power bid without depleting the energy reserve is calculated. The economical feasibility of the BESS providing FCR is investigated using the NPV and the payback period. The results reveal that a BESS bidding in the FCR-D up market has the shortest payback period which is about 2 years. This can be compared to the needed 7 years for BESS bidding in the FCR-N market, which has the longest payback period among the other FCR products. However, as the new requirements in the Nordic Synchronous Area permit BESS of bidding in all of the hours, this may attract more investment in BESS. Infact, the results show that the payback period reduces by three-folds considering the new requirements. However, the results also reveal that as more BESSs enter the FCR market, this

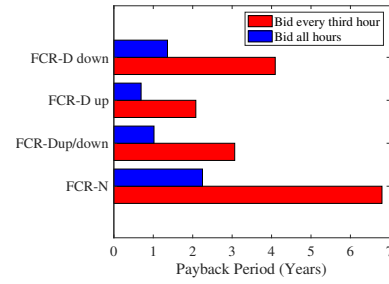


Fig. 10. Payback period of BESS with bidding all hours

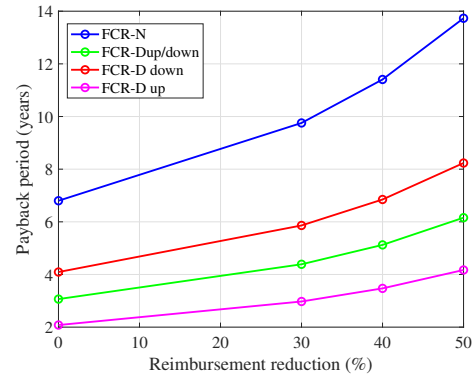


Fig. 11. Payback period with FCR capacity remuneration reduction

may saturate the market resulting in a lower remuneration. If the FCR market prices decrease by 50%, the payback period increases by two-folds.

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