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Valuation Models for Frequency Services Provision with an Energy Storage System

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Abstract— Energy Storage Systems (ESSs) potentially enhance the flexibility of power grids, and their operators can benefit from various streams of revenues to recover the investment. This study targets the estimation of revenues expected from the provision of Frequency Containment Reserve (FCR), or primary reserve, in the European market. A reference model is introduced, where the FCR activation is decided based on the actual frequency measurements (Model 1). As those measurements may not be systematically available, this paper proposes two additional models in the form of offline approaches that enable the ESS operator to determine the economic viability of targeting the FCR market without the need for actual frequency data. Model 2 is an improved version of a conventional formulation based on a constant coefficient of activated energy concerning the battery-rated power (i.e. reserved capacity). Model 3 is a novel simplified model based on a variable activation coefficient that depends on the total activated reserve by the system operator. The validity of the proposed models is assessed compared to the exact formulation over six months considering the French market in 2021. Results show that adopting Model 2 is preferable in the cases where the quantity of activated energy is high (high-frequency gain), resulting in a 3 % error compared to Model 1. However, in the opposite case (low-frequency gain), Model 3 is favorable to use, with an error of 2 %.

Index Terms— Ancillary services, Energy Markets, Energy Storage, Frequency services, Optimization.

NOMENCLATURE

$\pi_t^{fcr,r}$	FCR reserve price (€/MW)
$\pi_t^{fcr,a}$	FCR activation prices (€/MWh)
P_t^{fcr}	Power committed FCR reserve (MW)
$P_{t,i}^{fcr,+}, P_{t,i}^{fcr,-}$	Activated power up / downward FCR (MW)
dt	Time resolution for FCR energy (15 min)
P_{max}	Maximum power limit for the battery (MW)
$P_t^{reserve_total}$	Total procured reserve by grid operator (MW)
E_{cap}	Maximum battery energy capacity (MWh)
$u_{t,i}$	Binary variable for FCR committed reserve.
K	Frequency gain for ESS (MW / Hz)
$\Delta f_{t,i}^+, \Delta f_{t,i}^-$	Upward / downward frequency deviation (Hz)
$SOc_{t,i}$	Battery state of charge (%)
SOc_{max}	Minimum value for the stage of charge (%)
SOc_{min}	Maximum values for the stage of charge (%)
η^-, η^+	Charging/discharging efficiency (%)

T	The time horizon of one day (24h)
$a_{t,i}^+, a_{t,i}^-$	Activation signals for up / downward FCR
β^+, β^-	Fixed activation coefficients up / downward
ζ_t^+, ζ_t^-	Variable activation coefficients up / downward

I. INTRODUCTION

Energy Storage Systems (ESSs) are increasingly viewed as a more sustainable solution to enhance grid reliability and cope with more volatile profiles due to new energy usages and renewable sources [1]. Under current regulations and market organization, various stakeholders and owners can benefit from investing in storage systems - transmission or distribution operators seeking to maintain grid stability, energy suppliers or balance responsible parties (BRPs) pursuing increased profits, or consumers aiming to reduce costs or achieve more significant revenues, are increasingly seeking ESSs [1].

Frequency services are currently recognized as lucrative revenue streams for investors in ESSs [2]. In the literature, the profitability of frequency regulation has been historically carried out by considering it as a single commodity or within a stack of services [3]. Mixed integer linear programming models are typically implemented to estimate the maximum revenues achievable by ESSs participating in balancing markets, which were found to be four times greater than those obtained from energy arbitrage [4]. Furthermore, the profitability of ESS providing frequency services has also been evaluated, with historical data from the California Independent System Operator (CAISO), Electric Reliability Council of Texas (ERCOT), and New York Independent System Operator (NYISO) markets in the USA [4,5].

In the German market, case studies have investigated a combination of services provided to transmission system operators (TSO) and distribution system operators (DSO) [7]. The results revealed that none of the accommodations are financially viable without considering the reserve market. In the Nordic market, the proportion of revenue from frequency services is highly dependent on wind production, particularly in Denmark [8]. The results in Europe were similar to those observed in the USA markets. Although the balancing market exhibits high variability, it increases the return on investment for ESSs.

According to the latest European regulation for ESS participating in FCR, the response must be available in less than 500 ms, with less than 30 s to reach the committed reserve at a fixed output power for a maximum of 15 min [9], as shown in Fig. 1. Thus, frequency measurements are needed to accurately estimate the expected revenues from the FCR provision, but data are not systematically available. However, the accepted and activated reserves are usually published one day later for most countries. This paper then proposes two approaches that enable the ESS operator to determine the economic viability of targeting the FCR market without the need for actual frequency data. The main contribution is a comparison between three mathematical formulations to model the FCR provision and thus estimate the revenues of any storage system:

- A reference model based on actual frequency measurements and frequency gain to calculate the activated energy at each time step.
- An improved traditional approach corresponding to a fixed upward and downward coefficients as the portion of committed reserve activated at every time step.
- A novel formulation that assumes a variable activation coefficient at every timestep based on TSO data (i.e. total procured reserve).

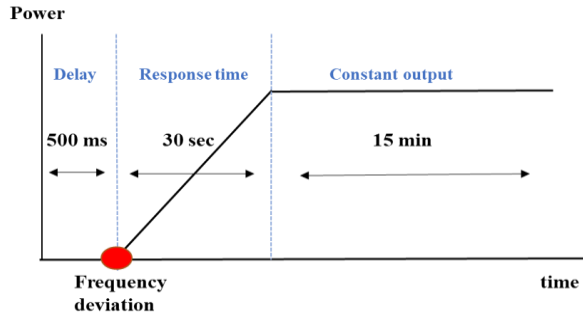


Fig. 1. Respond time for FCR [8]

The rest of the paper is organized as follows. Section II describes the frequency regulation markets in Europe. Section III introduces the mathematical modeling for the three investigated approaches. Section IV compares the models based on six months of simulations while the fitting of the coefficients is performed on a different period (models 2 and 3). Section V concludes with an assessment of the models and proposes perspectives for future work.

II. EUROPEAN FREQUENCY REGULATION MARKETS

The Electricity Balancing (EB) cooperation has integrated all resources in European countries to increase the security of supply and decrease costs for the customers. The cooperation of European grids and Ensto-e have implemented four distinct regulation services including Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (aFRR), Manual Frequency Restoration Reserve (mFRR), and

Replacement Reserve (RR) [10].

The sequence of reserves activation is shown in Fig. 2, where FCR is automatically activated within 30 s after the frequency deviation incident, to stop the frequency from deteriorating further. Then the secondary reserve, which includes both aFRR and mFRR is activated to restore the frequency into the safe range. This reserve is activated after 5 min and presents a longer duration, especially for the manually activated one. The tertiary reserve (or RR) is the last to be activated after 15 min and for a duration of 60 min or up to several hours in case of multiple incidents. The goal of that reserve is mainly to recharge the consumed primary and secondary reserves while clearing the last imbalances [10]. Note that contrary to FCR and FRR, not all TSOs in the EU use RR products.

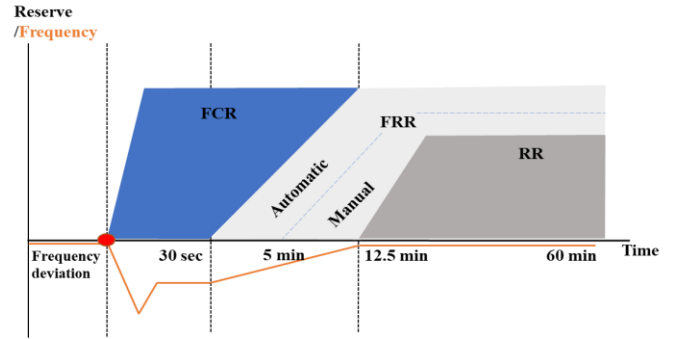


Fig. 2. Frequency regulation services characteristics [4]

For all the frequency products in the European market, the remuneration is provided in two parts to the participating actors (ESS here). The first part is the remuneration in capacity, where the operator gets paid per reserved power (in €/MW). This reserve remuneration is always positive so that the ESS owner gains profit by either providing upward or downward reserves. The second remuneration is for the energy activated (in €/MWh) positive in the case of upward regulation and negative if downward regulation is supplied [11].

III. FCR MARKET MODELING

The FCR reserve products are symmetric, which means that the same power can be activated in both upward and downward regulations during the delivery period. The market operates with a resolution of 4 h for the FCR reserve (power) product - i.e. six bids are supplied in fixed delivery periods, in the hours [0 – 4, 4 – 8, 8 – 12, 12 – 16, 16 – 20, 20 – 24] for every day. On the other hand, the actual activated energy changes automatically according to the frequency deviations. As mentioned, the output power shall be able to be supplied over maximum period of 15 minutes for ESS participating in the FCR market [11]. In the following sections, three approaches are presented to model the FCR operation and estimate the expected revenue from this market. Model 1 is the reference case, using the actual grid frequency measures to calculate the activated energy. Models 2 and 3 are proposed models that do not need those frequency data which are not

systematically available for investment decision-making. The three models rely on the formulation and solving of optimization problems.

A. Model 1: Frequency measurements

This model integrates actual frequency measures to calculate the optimal quantity of activated energy for FCR. A frequency gain (K) is defined in the range of 5 – 25 MW/Hz according to the regulation for ESS participation in frequency services [9]. The frequency gain represents the amount of power that is needed to increase the frequency of the system by one hertz. The selection of the frequency gain should guarantee a full reserve activation incase of maximum of deviation (200 mHz). The formulation in (1) shows the objective function to maximize the revenues from both the reserve and the energy in the FCR market. The average of the frequency measurements is calculated every 15 minutes, then divided into up/down deviations ($\Delta f_{t,i}^+$, $\Delta f_{t,i}^-$). The resolution of the optimization is obtained over one day where, $t \in \mathcal{T}$ is the set of timesteps per day with a 4 h resolution and $i \in \mathcal{I}$ is the set of timesteps within the 4 h with a 15 min resolution. The negative sign in the activation part shows that the ESS owner pays while supplying downward regulation (i.e. charge).

$$\max_{p_t^{fcr}} \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} \pi_t^{fcr,r} \times p_t^{fcr} + \pi_{t,i}^{fcr,a} \times dt \times (p_{t,i}^{fcr,+} - p_{t,i}^{fcr,-}) \quad (1)$$

$$p_t^{fcr} \leq p_{\max} \times u_t \quad (2)$$

$$p_{t,i}^{fcr,+} = K \times \Delta f_{t,i}^+ \times u_t \quad (3)$$

$$p_{t,i}^{fcr,-} = K \times \Delta f_{t,i}^- \times u_t \quad (4)$$

$$soc_{t,i} = soc_{t,i-1} + \left(p_{t,i}^{fcr,+} \times \eta^+ - p_{t,i}^{fcr,-} / \eta^- \right) \times \frac{100 \times dt}{E_{cap}} \quad (5)$$

$$soc_{\min} \leq soc_t \leq soc_{\max} \quad (6)$$

Constraint (2) ensures that the reserved capacity must be lower than the storage system-rated power. The binary variable u_t indicates whether the reserve is committed or not in the delivery period of 4 h. Constraints (3) and (4) calculate the activated energy for each delivery time, which is null if no capacity is committed (i.e., $u_t = 0$). Two efficiencies (η^+ , η^-) are considered for charging and discharging to estimate the soc along the operational period in (5). The battery state of charge is updated every 15 min and shall remain within the limits (6). Real-time measurements shall be collected to run this model, which does not make it practical and scalable, thus justifying the definition of alternative propositions for investment decision-making. Model 1 is thus the reference to assess the performance of the two next formulations.

B. Model 2: Fixed ratio of activation

The second approach represents the activated energy through fixed coefficients β^+ and β^- , defining the portions of the reserve capacity (in MW) that are activated each 15 min. A typical value considered for both upward and downward regulation coefficients is 0.13, which was introduced in USA market studies [11,12]. Furthermore, similar models were used in Ireland and UK markets [14] with values of 0.15. The same

objective function (1) is used, with constraints (2) – (4) replaced by (7) – (9) as follows:

$$p_t^{fcr} \leq p_{\max} \quad (7)$$

$$p_{t,i}^{fcr,+} = p_t^{fcr} \times \beta^+ \times a_{t,i}^+ \quad (8)$$

$$p_{t,i}^{fcr,-} = p_t^{fcr} \times \beta^- \times a_{t,i}^- \quad (9)$$

Note that in that formulation (in constraints (8) and (9)), four main parameters impact the quantity and time of activated energy. Especially, two binary parameters $a_{t,i}^+$, and $a_{t,i}^-$ represent the time steps at which the reserve is activated. These parameters are determined based on collected historical data (day before) from RTE in France. If the upward reserve over this 15 min on the day before was activated, hence $a_{t,i}^+ = 1$. similarly, If the downward reserve over this 15 min on the day before was activated, then $a_{t,i}^- = 1$. The other two parameters are β^+ and β^- which determine the fixed portion of reserve to be activated.

C. Model 3: Ratio of total procured reserve

In the third model, the activated energy depends on variable coefficients ξ_t^+ and ξ_t^- that represent the ratio between the maximum reserve that could be committed by the ESS operator and the total activated energy in same delivery time on the day before by the system operator (historical data from TSO). The values of these coefficients change every delivery period of 15min. The two binary parameters $a_{t,i}^+$, and $a_{t,i}^-$ represent the time steps at which the reserve is activated as described in Model 2. The same objective function (1) is used, with constraints (10) – (12) replacing (2) – (4) as follows:

$$p_{t,i}^{fcr,+} = p_t^{fcr} \times \xi_t^+ \times a_{t,i}^+ \quad (10)$$

$$p_{t,i}^{fcr,-} = p_t^{fcr} \times \xi_t^- \times a_{t,i}^- \quad (11)$$

$$\xi_t^- = \xi_t^+ = p_{\max} / p_t^{reserve_total} \quad (12)$$

IV. SIMULATIONS AND RESULTS

In this study, the participation of the ESS in the FCR market is simulated over six months to i) validate the accuracy of the simplified models and ii) estimate the revenues for ESS participating in this market. The data were collected for the French market using RTE and ENTSO-e databases [15]. The ESS parameters and energy prices are inputs for the model, where the parameters are as follows: $\eta^+ = \eta^- = 0.9$, $soc_0 = 0.5$. The simulation is conducted with successive daily optimizations (i.e. $T = 24$). The frequency gain is selected according to the maximum reserve to assure full activation when (200 mHz) deviation is reached. In the following simulation we investigate a 1 MW/MWh battery, with a frequency gain of $K = 5$ MW/Hz. Also, large reserves are considered with 5 MW/MWh battery, which resulted in a frequency gain of $K = 25$ MW/Hz. The BESSs are allowed to participate in the FCR with a rule imposing the availability of the procured reserve for at least 15 minutes at any time [9]. Thus, this 15-minute criterion allows the battery to only participate in the FCR market in the range of $soc_{\min} = 0.25$, $soc_{\max} = 0.75$.

A. Six months of simulations

A first set of simulations are carried out while varying the level of activated energy by changing the frequency gain (K), specifically 5 MW/Hz and 25 MW/Hz, to account for low and high activated quantities. At first, Model 2 considers typical values for parameters described in the literature, where $\beta^+ = \beta^- = 0.15$. The results, displayed in Table 1 and Table 2, indicate a significant potential for ESS in the FCR market, with the capacity generating most of the revenues. The activated energy profits are found to be negligible due to symmetrical bidding and continuous frequency deviations in both directions, leading to total activated energy being roughly equal in both directions. Thus, the revenues from upward energy are either equal to or less than the costs of downward energy.

The analysis suggests that, in the case of low-frequency gain, Model 3 is superior to Model 2, with an error of 2.3 % compared to the reference Model 1. Conversely, Model 2 demonstrates a high error of 34 % with the typical parameter values for β^+ and β^- . In the case of high-frequency gain, both model 2 and model 3 display high errors of 34 % and 51 % respectively. However, the coefficients of Model 2 can be fine-tuned to achieve greater accuracy.

Table 1. Six months' revenues for the FCR market ($K = 5$ MW/Hz)

Revenues in €	FCR reserve	FCR energy	FCR total	error
Model 1	81,973	-1,115	80,857	--
Model 2	54,966	-1,303	53,663	33.6 %
Model 3	80,253	-1,263	78,990	2.3 %

Table 2. Six months' revenues for the FCR market ($K = 25$ MW/Hz)

Revenues in €	FCR reserve	FCR energy	FCR total	error
Model 1	409,865	-5,575	404,289	--
Model 2	274,833	-6,518	268,315	34.2 %
Model 3	206,805	-8,348	198,456	50.9 %

B. Tuning the parameters for Model 2

A sensitivity analysis was performed to adjust the fixed coefficients β^+ and β^- for Model 2 through successive simulations. The model tuning was based on the data of the first six months of 2021 (validation was performed over the last six months). The results in Fig. 3 indicated that appropriate tuning of the coefficients, with $\beta^+ = \beta^- = 0.08$, could achieve a 2.3 % error compared to the reference model. Another assumption is made while individually tuning the coefficients for upward and downward regulations (i.e. $\beta^+ \neq \beta^-$). The results show that the error increases when $\beta^+ < \beta^-$, as seen in the yellow corner with the highest errors. This is due to the increase in cost while providing high quantities of downward regulation. The optimum tuning, where the results are nearly identical to Model 1 with error = 3.1 % for the first 6 months, is reached when $\beta^+ = 0.1$, $\beta^- = 0.14$.

The simulation was repeated for the second half of 2021, with the assumption of $\beta^+ = \beta^- = 0.08$ for Model 2. a and $\beta^+ = 0.1$, $\beta^- = 0.14$ for Model 2. b. The results show a significant improvement in the simplified model performance for both cases. The results in Table 3 suggest that the

assumption of equal values for the coefficients in both directions of activation was better, where Model 2.a had achieved a low error of 2.9 %. Model 2.b has also shown higher performance than Model 2 with the typical values when evaluated based on the total profits. On the other hand, it shows a significant error in the FCR energy profits. That's due to the different activation ratios in both directions, where in actual cases the activation is nearly symmetric. Thus, it can be concluded that, for energy storage systems with high-frequency gain, Model 2. a is preferable to Model 3.

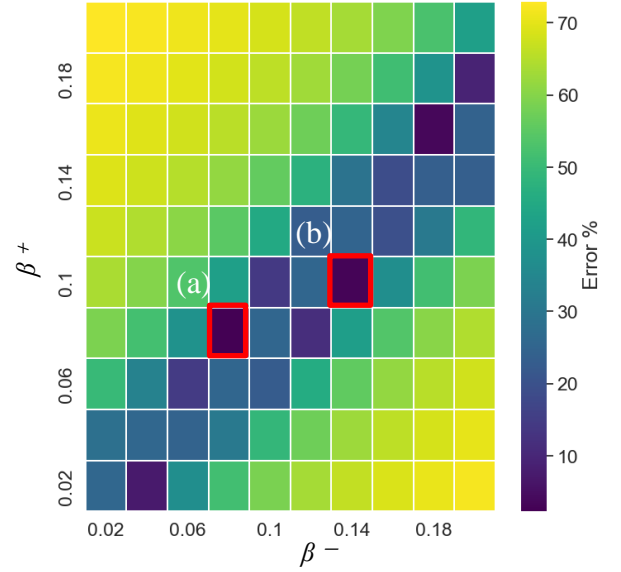


Fig. 3. Sensitivity analysis for different values of activation ratios

Table 3. Six months' FCR revenues with tuned parameters ($K = 25$ MW/Hz)

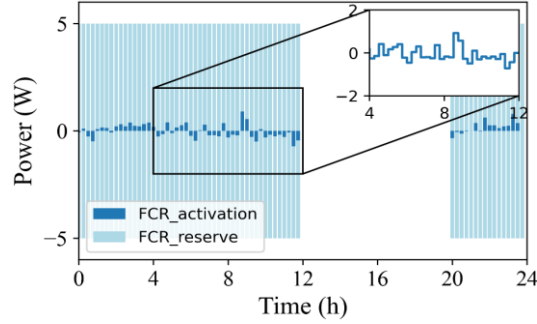
Revenues in €	FCR reserve	FCR energy	FCR total	error
Model 1	409,865	-5,575	404,289	--
Model 2. a	419,528	-3,457	416,070	2.9 %
Model 2. b	439,961	-89,498	350,463	13.3 %

A sample of the scheduled reserve and activated energy along one day ($K = 25$ MW / Hz) is presented in Fig. 4. The simulations show that the tuned Model 2.a presents similarly committed reserves as the reference model (Model 1). Moreover, the activated energy quantities are in the same range but not accurately representing the direction of activation. On the opposite, Model 3, shown in Fig. 4 (c), presents different results for the reserve, and also the quantity of activated energy is much less than the reference model, which results in higher error. That explains the high errors because less energy is activated, hence there is a small effect on the *soc* level, which allows more capacity to be committed.

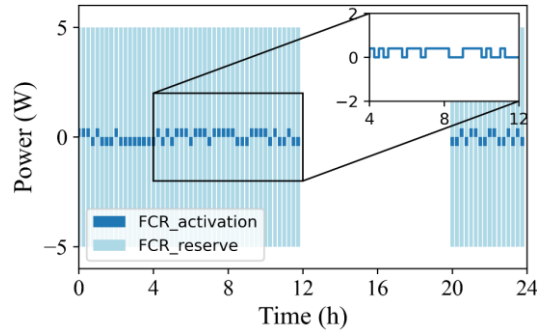
V. DISCUSSION AND CONCLUSION

This paper introduces the primary reserve, also known as frequency containment reserve (FCR) as one of the potential revenue streams for grid-connected energy storage systems. Three models were presented for an offline evaluation of the expected profits. A reference formulation (Model 1) is presented where the activated energy depends on a predefined

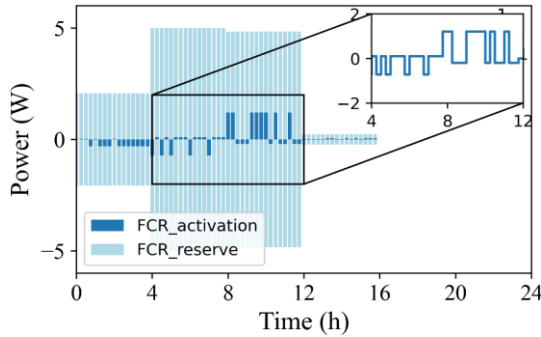
frequency gain that controls the output power based on the grid frequency measurements. Two alternative models for investment decision-making are proposed, where the ESS operator can estimate the FCR revenues and reserve schedules with no need for the actual frequency data. Model 2 uses a fixed coefficient that represents a portion of reserves to be activated. Model 3 assumes that the activated energy is in a proportional ratio of the committed reserve to the historical total activated reserve which is calculated at every delivery time.



(a) Model 1: using frequency measures



(b) Model 2: using a fixed ratio



(c) Model 3: using variable ratio

Fig. 4. Daily FCR power commitment for ESS

The performance of the two simplified models is compared to the reference case using a simulation over the second six months of 2021. The results show that Model 3 is the favorable approach in case of a low quantity of activated energy (i.e. low-frequency gain). In the case of high-frequency gain, the analysis reveals that the tuned Model 2 outperforms Model 3 with an error reduced down to 3 % compared with Model 1. The coefficients for Model 2 were fitted based on the first six

months of 2021. The results of these tuned parameters exceed the typical values in the literature that typically achieve a higher error with an order of magnitude of around 30 %. Thus, the simplified models proved to be a reliable option to model the FCR market in Europe over high and low levels of activation.

The study showed the optimal range of parameters to be considered in both models based on minimum and maximum allowable values for the frequency gains. However, these parameters shall be tuned with every bid to assure full activation when maximum frequency deviation is reached. A future study will include a control algorithm to assure the availability of energy while providing the frequency regulation services. As BESS is a limited energy sources, it can be fully charged or discharged during the operation. Hence, a controller is needed to assure symmetric operation and avoid penalties.

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