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***Abstract* — Battery energy storage systems (BESSs) are more and more considered as a potential asset to provide frequency containment reserve (FCR) services. In practical deployment, it is challenging for the BESS owner to secure benefits when submitting bids for FCR one day ahead under the uncertainty of prices and frequency deviations. Moreover, the energy capacity constraints for such a system make it difficult to assure the availability of the reserve over the day without knowing in advance the need for regulation. Thus, in this paper, an operational planning consisting of a look-ahead bidding strategy followed by a rule-based control is presented for a BESS participating in the FCR market. Historical data are used to compute the day-ahead bids before four different controllers are proposed for real-time operation on the day of delivery. Yearly simulations show the trade-off between profits, penalties for non-activation, and BESS lifetime. The results show that corrective charging/discharging in real-time enables the BESS to achieve up to 97% of the maximum theoretical profits.**

***Index Terms*— Energy markets, Bidding Strategy, Frequency Reserve, Price Uncertainty, Battery degradation.**

I. Introduction and State-of-Art

The increasing integration of renewable energy sources and the quest for a sustainable energy future has underscored the critical need for innovative solutions to maintain grid stability. In this context, Battery Energy Storage Systems (BESS) have emerged as a major technology, offering dynamic and versatile approaches to address grid stability challenges and participate in different energy markets [1]. One important characteristic of BESSs is their rapid response capability. Unlike traditional power plants, BESS can instantaneously inject or absorb power in response to fluctuations in frequency [2]. This inherent agility positions BESS as an ideal candidate for applications like Frequency containment reserve (FCR), where immediate regulation action is essential to prevent frequency excursions that could trigger cascading disruptions [3].

A. Frequency Containment Reserve in Europe

In Europe, the current TSO requirements for BESSs participating in FCR do not impose any rules on the battery operation while restoring the state of charge (soc) level. There are only requirements for the product itself as response time, ramping time, product duration, and activation linearity with the frequency deviation [4]. On the other hand, the BESS operating constraint in energy increases the complexity of frequency regulation. Indeed, if not properly managed, the BESS may face occurrences where it is impossible to deliver the requested power. This could incur financial penalties, as the BESS owner must guarantee the availability of reserve at all times. Hence, optimized operation planning is required [5]. Moreover, the FCR biddings are submitted one day before the delivery without knowledge of prices or frequency deviations. These uncertainties need to be considered also while planning for the FCR bidding.

B. Related Literature

Recently in Europe, BESSs are allowed to participate in the FCR with a rule imposing the availability of the procured symmetric reserve for at least 15 minutes [6]. That leads to constraints on the State of Charge (SOC) in the operating phase. Since controlling the SOC level of the participating BESS can be challenging, degrees of freedom are proposed by the TSO. In this article, two degrees are considered, i) dead band: The BESS is allowed to not provide FCR in the range of (Δf_{db} = ±10 mHz).ii) overfulfillment: The BESS can supply up to 120% of the required energy in both directions with no penalties applied [4].

To address the operation of BESS, the authors in [7] proposed a standard drop characteristic while correcting the SOC when pre-defined limits are reached. In [8], the usage of FCR degree of freedom for participating in BESS was investigated. The study showed that the dead band exemption is the most effective method to reduce the required energy while providing FCR. The work in [9] evaluated different SOC management strategies while considering their effect on battery degradation. The results showed that the optimal strategy is to correct the SOC in parallel with FCR services, which results in a 17% capacity fade after 10 years. It is worth noting that the previous studies assumed a perfect forecast of prices and frequency deviation, where the main goal was only to compare different operation strategies. However, such approaches do not allow a correct assessment of the benefits that could be expected from participation in the FCR markets (and accounting for potential penalties).

To maximize profits under uncertainty, a comprehensive bidding strategy is needed. Stochastic reserve scheduling was proposed in [10], where Day ahead and reserve markets were stacked. However, it was scaled on an hourly market and had less range of frequency deviation compared to European FCR. A Robust approach has also been introduced by [11] to optimize the battery operation for FCR and self-consumption purposes. A simplified model for ancillary markets was introduced in [12], which considers a penalty for not delivering the FCR reserve. Moreover, efforts are made to enhance the way the soc

is replenished to minimize the penalties paid to the TSO. The work in [13] proposed a bidding strategy for batteries in the FCR market in addition to an online control of the soc level. The results of the Nordic market study showed that the optimal strategy is to reserve time for soc recovery during lower market prices which results in a six-year payback period.

The reviewed studies presented bidding strategies for the FCR market, using complex optimization approaches in [11, 12] and soc management strategies in [13]. However, the soc management strategies in real time were not compared to a perfect forecast to estimate the loss of profits from a theoretical optimum (with no uncertainties on price and frequency signal). Such a baseline is considered in this paper. A bidding strategy for the FCR reserve is presented based on historical data, in addition to proposing four operation controllers for soc management in real time. The four controllers are compared to the perfect case while considering: 1) the Latest European regulation for FCR activation for BESS, 2) the FCR reserve penalty, 3) Imbalance settlements, 4) TSO welfare (activation failure ratio), 5) The lifetime of the BESS. In the previous work [7, 13], each study focused on one or two parameters to evaluate the proposed bidding strategy. However, in this article, all parameters are considered under uncertainties to find the impact on both the BESS owner and the TSO. Note that the BESS owner in this study is assumed to be a price taker and bid in quantity only. The prices, frequency deviation, penalty, and imbalances are calculated based on real market data for the French system in 2021. In this context, the main contribution of the paper can be summarized as:

- A comprehensive operational planning strategy for a BESS participating in the FCR market under uncertainty.
- Four soc controllers were evaluated based on profits, TSO welfare, and battery degradation.

The rest of the paper is organized as follows. Section II presents the FCR market in detail with the mathematical models for bidding strategy and the proposed soc controllers. Section III displays a comparison between the four controllers based on annual simulations. Section IV concludes the paper and discusses the ongoing investigations.

II. Mathematical models and proposed controllers

A. Bidding in the FCR market

FCR is conventionally provided automatically by controllable generation units. The local automatic control system measures the frequency deviation and reacts within 30 seconds [5]. The control system continuously measures the frequency deviation (Δf). Then the FCR-activated power ($p_{t,j}^{fcr+}$) is determined as a ratio of the procured reserve ($p_t^{reserve}$),where 100% of the reserve is activated if the maximum deviation is reached ($\Delta f_{\max}$ = 200 mHz) [4].

In the European Market, the FCR product is symmetric with a 4h duration. The BESS owner gets remunerated for the reserved capacity ($p_t^{reserve}$) in €/MW. Also, there is a remuneration for the upward regulation ($p_{t,j}^{fcr+}$) and a cost for the downward regulation ($p_{t,j}^{fcr-}$) in €/MWh [5]. The gate closure for reserve bids is at 08h on the day before delivery. Then, in real-time the BESS power provisions depend on the actual frequency deviations ($\Delta f_{t,j}$). BESSs are allowed to participate in the FCR under the rule of " 15 min criterion" , which imposes the availability of the procured symmetric reserve for at least 15 minutes [6]. That leads to constraints on the State of Charge (soc) in the operating phase. Ultimately, the BESS owner must submit the reserve bids without knowledge of prices or frequency deviation on the day of delivery.

In the look-ahead phase, the proposed bidding strategy relies on backcasting, where the reserve prices, activation prices, and frequency deviations of the day before ($\hat{\pi}_t^{reserve}, \hat{\pi}_{t,j}^{fcr}, \Delta\hat{f}_{t,j}$) are used to bid for the following day. The objective function for FCR bidding is presented in (1), where the BESS tries to maximize the reserve profits while decreasing the cost of downward regulation. The temporal set $t \in T$ represents one day (at a resolution of 4 h), and $j \in J$ is a subset of T with a resolution of (dj = 10 sec). The FCR reserve ($p_t^{reserve}$) is limited by the battery power capacity (p_{max}) as shown in (2). The 15-minute criterion rule is presented in (3), where the reserve is also limited by energy capacity (E_{cap}). The soc limits are calculated in (4) and (5). The update of the soc calculations are shown in (6) and (7) using charging and discharging efficiencies (η^-, η^+). The activated energy of the FCR is calculated based on the frequency deviations as in (9) - (10).

$$\max_{p_t^{reserve}} C_{fcr} = \sum_{t\in T}\sum_{j\in J} \hat{\pi}_t^{reserve} \times p_t^{reserve} + \hat{\pi}_{t,j}^{fcr} \times dj \times \left(p_{t,j}^{fcr,+} - p_{t,j}^{fcr,-}\right) \quad (1)$$

$$p_t^{reserve} \le p_{\max} \quad (2)$$

$$E_{cap} / p_t^{reserve} \ge 0.5h \quad (3)$$

$$soc_{\max} = 1 - 0.25h \times P_t^{reserve} \times \left(1/E_{cap}\right) \quad (4)$$

$$soc_{\min} = 0.25h \times P_t^{reserve} \times \left(1/E_{cap}\right) \quad (5)$$

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

$$soc_j = soc_{j-1} + \left(p_{t,j}^{fcr-} \times \eta^- - p_{t,j}^{fcr+}/\eta^+\right) \times 100 \times dj \times \left(1/E_{cap}\right) \quad (7)$$

$$p_{t,j}^{fcr+/-} = p_t^{reserve}, \quad if \quad \left|\Delta\hat{f}_{t,j}\right| \ge \left|\Delta\hat{f}_{\max}\right| \quad (8)$$

$$p_{t,j}^{fcr+/-} = \left(\left|\Delta\hat{f}_{t,j}\right| / \Delta\hat{f}_{\max}\right) \times p_t^{reserve}, \quad if \quad \left|\Delta\hat{f}_{db}\right| \le \left|\Delta\hat{f}_{t,j}\right| \le \left|\Delta\hat{f}_{\max}\right| \quad (9)$$

$$p_{t,j}^{fcr+/-} = 0, \quad if \quad \left|\Delta\hat{f}_{t,j}\right| \le \left|\Delta\hat{f}_{db}\right| \quad (10)$$

The output of this optimization is the FCR reserve schedule to be provided on the following day. In actual operation, the frequency deviations are not known at the bidding stage. This uncertainty requires a controller to guaranty the availability of energy at the activation time. otherwise, it leads to penalties consisting of two components:

1) Reserve penalty

The Transmission System Operator (TSO) imposes a high penalty to encourage the suppliers to ensure the availability of the scheduled reserve. The penalty is five times the regulated capacity price (*PFC*), set at the beginning of each year [5]. The penalty is calculated on an every 30-minute basis, with a failure ratio that represents the number of provision failures over the total number of frequency incidents [5]. A provisions failure is counted when the battery soc exceeds the limits and hence no reserve is available. The mathematical calculation of the reserve penalty is shown in (11).

$$penalty_t = 5 \times PFC \times failure\ ratio \times p_t^{reserve} \quad (11)$$

2) Imbalance settlements

At the end of every delivery period (30 minutes), the TSO measures the difference between the actual energy profile and the scheduled energy profile for each supplier/consumer. The imbalance settlements include all the energy markets (especially day-ahead and intraday), unlike the penalty which is specifically for FCR reserves. The BESS is considered positively imbalanced in cases of overproduction/underconsumption, then gets paid for the difference [14]. The BESS is considered negatively imbalanced in cases of underproduction/overconsumption, then pays for the difference. The French system has two prices for positive and negative imbalances, which change every 30 min based on the total system imbalance [14].

B. Rule-based controller for FCR operation

As the FCR reserve is scheduled based on backcasting, a controller is needed to manage the BESS soc level under the uncertainty of frequency deviation in real-time. In the following section, a baseline rule-based controller for instantaneous BESS operations is introduced with successive improvements (four controllers in total):

1) Baseline controller using soc limits

At every time step, the inputs of this controller are the FCR reserve schedule and the actual frequency measurements. This basic controller limits the FCR activation at the soc-predefined thresholds. According to the 15-minute criterion rule presented in (3)- (5), the valid soc operating range is 25%-75%. Hence, in case the soc is out of this range, this means the symmetric reserve is not available anymore and the BESS cannot activate the required energy. The flowchart of the baseline controller is presented in Fig. 1.

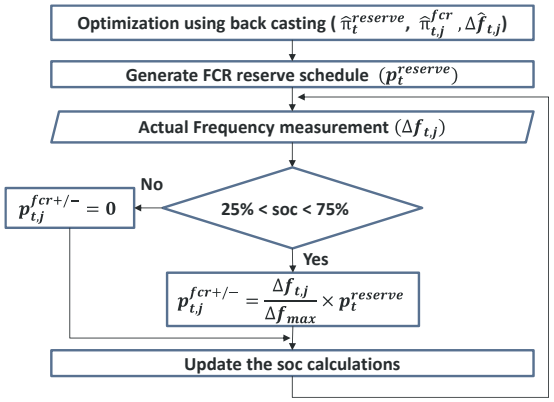

Fig. 1 Baseline controller (soc limits)

2) Controller A

The BESS in this controller takes advantage of the degree of freedom provided by the dead band. In cases where the soc level is very high, the BESS only provides upward regulation to discharge the soc towards 50%. Similarly, when the soc level is too low, only downward regulation is provided to charge the soc. The flowchart of controller A is presented in Fig. 2 with setting the gain *G* to 1 (i.e. only the required energy is activated).

3) Controller B

The BESS in this controller takes advantage of both the dead band and over-fulfillment degree of freedom. It works similarly to controller A, however, it provides 120% of the upward/downward regulation in cases of high/low soc level. The flowchart of controller B is presented in Fig. 2 with setting the gain *G)* to 1.1 (i.e. 110% of the required energy is activated).

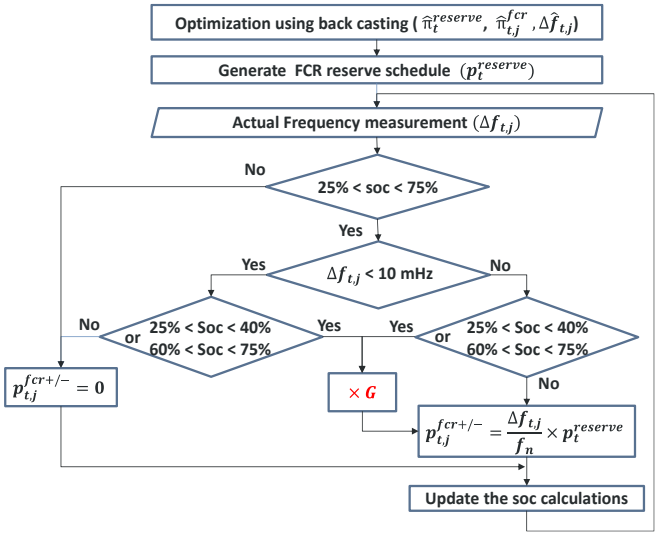

Fig. 2 Controller A (G = 1) , Controller B (G = 1.2)

4) Controller C

In this controller, the BESS tracks a 50% soc reference by corrective charging and discharging in addition to the reserve provision. This corrective power can be purchased as part of the Intraday market or the Imbalance settlement (which was chosen in this work). The BESS charges when the soc drops in the range of 25% - 40%. Similarly, it discharges when the soc is in the range of 60% - 75%. The corrective power is limited by the difference between the BESS power capacity and the FCR-activated power to reach 50% soc. The flowchart of controller C is presented in Fig. 3.

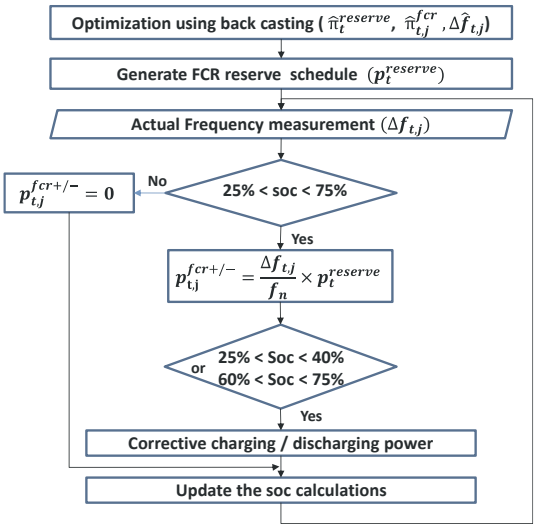

Fig. 3 Controller C (Corrective charging and discharging)

5) Controller D

The last controller uses the same corrective power strategy as controller C, except it is only applied in the dead band. This controller allows only frequency regulation or corrective charging/discharging at a time. So, in the dead band, FCR is not activated and corrective power is utilized to restore the soc level to 50%.

C. Degradation Model for BESS

The proposed controllers will affect the BESS operation and hence they will have an impact on its degradation over time. For example, controller A forces the Battery to be in an idle state in the dead band which increases the calendar aging. On the other hand, controller C allows charging and discharging extra corrective energy besides the FCR activation, which in turn increases cycling aging. Even if battery aging is not at the core of the proposed paper, a degradation model developed by [15] is used to evaluate the capacity fade behavior caused by each proposed controller. The authors have developed and parametrized the models using LiFePO4/C battery cells at 25 ºc to measure both cycling and calendar aging.

The calendar aging represents the capacity loss ($c^{loss,\,cal}$) as a function of the idling soc level (soc^{l}) and the time in months (t), as shown in (12). The cycling aging represents the capacity loss due to the soc variation either charging or discharging. The cycling capacity loss ($c^{loss,\,cyc}$) is a function of the depth of discharge (dod), the number of cycles that occurred at this dod (n), and the average soc during these cycles (soc^{av}), as presented in (13). The degradation model embeds a rain flow algorithm that is developed and applied to the annual soc profile of each controller, to count the number of cycles at each distinct depth of discharge and also compute the average soc during these cycles.

$$c^{loss,cal} = 0.1723 \times e^{0.0073 \times soc^{l}} \times t^{0.8} \quad (12)$$

$$c^{loss,cyc} = 0.021 \times e^{-0.0194 \times soc^{av}} \times dod^{0.716} \times n^{0.5} \quad (13)$$

III. Simulations and Obtained Results

Energy, reserve prices, activation prices, and frequency deviations were collected from the French TSO (Rte) and Entso-e 2021 databases [16]. A 10 MW/10 MWh ESS is considered with the following parameters: $\eta^{-} = \eta^{+} = 0.9$, $soc_0 = 50\%$. Due to the 15–min criterion rule, with a maximum reserve ($p^{reserve}$) of 10 MW, the soc limits are set to $soc_{min} = 25\%$, $soc_{max} = 75\%$, according to equations (3) - (5). The baseline is simulated using backcasting to generate the FCR reserve schedule. The proposed controllers are then tested on the same schedule. The obtained revenues by the controllers are calculated using the exact prices on the day of delivery and compared to the optimal case (with perfect forecast) to evaluate the robustness against uncertainties.

A. Annual profits and penalties

The results, summarized in Table 1, show the negative impact of the frequency deviation's uncertainty and unperfected price forecast. Operating the BESS based on historical data and soc thresholds (Baseline) only results in 32% of the maximum profits with significant penalties and imbalance paid. Hence, a more advanced controller was needed to mitigate these uncertainties. By taking advantage of the dead band activation exemption and over-fulfillment degree of freedoms (controller B), the BESS could save energy in these periods and activate it later when needed. That led to a decrease in the penalties by 40 % and hence an increase in the collected revenues by up to 71% of the maximum revenues.

Most of the profit loss is due to the huge penalties imposed on the FCR reserve. Thus, incorporating corrective charging/discharging power to decrease the penalties while increasing the imbalance settlement was an optimal decision for the BESS owner. Controller D shows a significant decrease in the reserve penalty (98%) while achieving 97% of the maximum profits. The results show that the cost of tracking the 50% soc point (increase in imbalance settlements) is insignificant compared to the penalties or the gained profits.

Table 1 One-year simulation results for FCR bidding

Controller	Profits in €	%max profits	Penalty in €	Imbalance settlements in €
Perfect case	656,981	-	0	0
Baseline	199,886	32.1	387,209	34,982
Controller A	375,968	60.3	231,158	16,134
Controller B	441,952	70.9	179,969	-927
Controller C	595,841	95.7	8,071	49,383
Controller D	601,878	96.7	5,103	46,314

B. Reserve failure ratio

Failing to provide the FCR reserve not only decreases the profits due to the high penalties but also impacts the TSO's welfare and reliability. When the BESS fails to provide the FCR reserve, other costly solutions are needed by the TSO. The results in Fig. 4 show a decrease in the failure ratio by 9 % when using controller B compared to the baseline. That can be explained by the red line in Fig. 5, where the soc profile of controller B is more compressed by saving energy from the dead band and over-fulfillment. Furthermore, adding corrective energy assures the FCR delivery with less than a 1 % failure ratio as achieved by Controllers C and D. As the BESS continuously tracks the 50% soc point, as shown in the green lines in Fig. 5, it rarely fails to provide the needed energy activation – i.e. soc values never reach 25 % or 75 %.

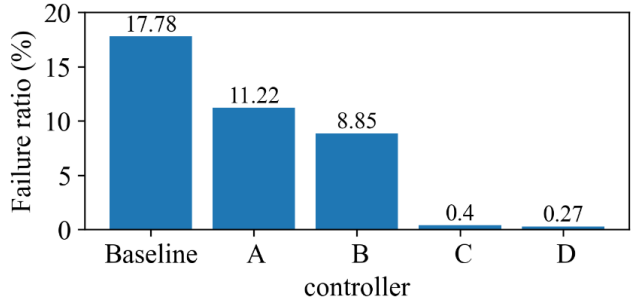

Fig. 4 FCR activation Failure ratio over one year

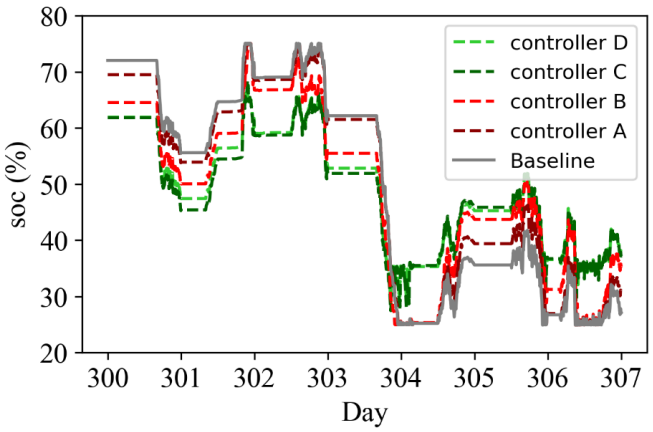

Fig. 5 Soc profile over a week using different controllers (10 sec time step)

C. Battery lifetime analysis

The soc profiles were decomposed into idling and cycling profiles to calculate the capacity fade due to calendar and cycling aging. Since the simulation was only for one year, the posterior degradation analysis was performed by feeding the same soc profile successively to measure the accumulated behavior over 10 years using the correction factors presented in [15]. The results in Table 2 show that due to uncertainty, the BESS goes more in the idling state which increases the calendar aging by 4% compared to the perfect case. The total capacity fades while applying controllers A and B is similar ~23%, where most of the degradation is due to calendar aging. On the other hand, there is a doubling of the cycling aging with controller C, due to the additional corrective charging and discharging as shown in Fig. 6. The combination between corrective energy and dead band degree of freedom resulted in an optimized solution in Controller D. As a result, the BESS could achieve 97% of the maximum profits by only increasing the capacity fade by 3% compared to the baseline.

Table 2 Lifetime analysis over 10 years

controller	Idling %	Cycling %	Capacity fade in 10 years
Perfect case	14.4%	5.8%	20.2 %
Baseline	18.7%	4.5%	23.2 %
Controller A	18.6%	4.7%	23.3 %
Controller B	18.5%	5.5%	24.0 %
Controller C	18.4%	10.1%	28.5 %
Controller D	18.9%	7.3%	26.3 %

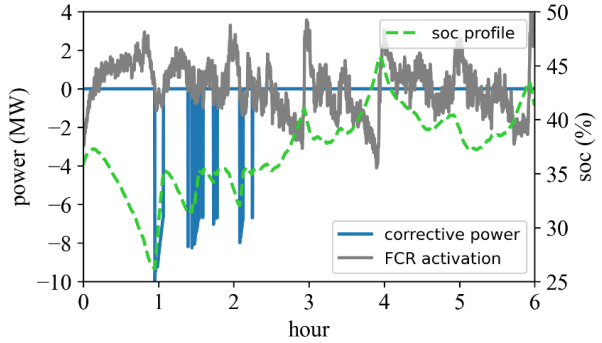

Fig. 6 Corrective charging/discharging using controller C - 6 hours on day 283

IV. Conclusions

The paper has presented comprehensive operational planning and real-time control for a Battery Energy Storage System (BESS) participating in the Frequency Containment Reserve (FCR) market. A bidding strategy based on historical data was introduced to the FCR reserve. Furthermore, Four controllers were proposed to mitigate the uncertainty of frequency deviations while ensuring energy availability. The Annual simulations for the French market in 2021 show that with the usage of the frequency deviation dead band and over-fulfillment (Controller B), only 70% of the maximum profits could be reached. The addition of corrective charging/discharging power (Controller D) to maintain the soc around 50 % allows for reaching 97% of the maximum profits while calculating the estimated battery degradation over ten years.

The study emphasizes the importance of enforcing high penalties to encourage the commitment of the suppliers. Also, it shows the huge difference between the reserve penalty and energy imbalance settlement which may affect the TSO costs to cover the imbalances. This study is planned to be extended with an economic analysis to evaluate the financial impact of each controller. Moreover, a more accurate representation of the BESS efficiency during part-load operations is to be included in future research.

V. Acknowledgment

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