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Optimum Operation of Battery Storage System in Frequency Containment Reserves Markets

Poria Hasanpor Divshali and Corentin Evens

***Abstract*— This paper focuses on the bidding strategy and online control methodology of battery storage systems (BSS) to participate in the frequency containment reserve (FCR) market. The new technical requirements for the FCR markets in the Nordic power system does not allow controlling the BSS in other ways than on the basis of frequency. Therefore, control mechanisms such as recovering the state of charge (SOC) whenever the power system frequency is in its acceptable (dead-band) range cannot be used. In this regard, this paper proposes and compares different control mechanisms to recover the SOC that are in line with the new regulation and maximizes the BSS profit using the lifetime model of the BSS. In order to compare different control mechanisms, this paper investigates the behaviour of a large BSS unit installed in the Helsinki area by simulating the proposed strategies over measured frequency and market data from 2014 till 2019.**

***Index Terms*—Battery storage system, Flexibility market Frequency containment reserves, Frequency regulation, Planning and control.**

I. Introduction

The frequency of the power system is kept stable by keeping the balance between production and consumption. Frequency control is performed on different levels of timeframe. The fastest level, reacting within the first few seconds, is referred to as primary frequency control (PFC) [1]. Traditionally, PFC is performed by conventional power plants adjusting quickly their productions to counteract any change in the power system frequency. However, frequency regulation in modern power systems are more challenging, because of 1) the shift from traditional power plants to renewable energy sources (RES), with a variable and less-controllable power output; and 2) power system deregulation that limits the PFC provision according to the provider's profit.

To mitigate these challenges, transmission system operators (TSO) encourage all energy sectors to provide PFC services through ancillary service markets. In these circumstances, different sources can be used to regulate frequency, such as conventional generation units [2], demand-side management [3], electrical vehicles [4], [5], and energy storage system [6].

The cost of battery storage systems (BSS) is steadily decreasing [7] and they are able to provide very fast response times. BSS have therefore been attracting a great deal of attention in recent years [8]. Although BSS can be used in different applications to provide a range of services to the power system, the provision of PFC is the most cost-effective service for the BSS operator in the current ancillary service markets [9].

BSS applications in regulating the frequency of an isolated/islanded power system back to several years ago [10]. In recent years, by increasing the penetration of RES, different methodologies have been developed to optimize the sizing and operation of BSS in isolated microgrids with a high share of RES [11]–[13]. They use BSS in coordination with RES to compensate for the error in RES forecasting and to help the frequency regulation. A coordinated control strategy with wind turbines is developed in [14] and with PV is developed in [15].

Some other research [16]–[19] focuses on using BSS to regulate frequency in a connected power system. Some of them, e.g. [16], [17], use a droop control and recover the state of charge (SOC) of the battery to 50%, whenever the frequency is in the acceptable range (dead-band) or reach the upper or lower limit, called SOC recovery. Some other research focuses on the lifetime of the BSS. A robust control method to minimize the use of the BSS is developed in [18]. Different SOC recovery methods and their effect on battery lifetime are investigated in [19].

Some other research focuses on field operations. Swierczynski, etc. in [20], [21] investigate providing PFC from a large Lithium BSS installed in Denmark and measured the degradation of the BSS capacity during about 2 years of operation. They continue their work and develop a degradation model for Lithium battery providing PFC in [22].

Although the above-mentioned research [10–21] focused on frequency regulation, they did not optimize the profit that a BSS can make by providing PFC through the ancillary service (flexibility) market. In this regards, a simplified model for ancillary service markets including a penalty for not providing the promised PFC is developed in [23] and the SOC recovery process is optimized to reduce this penalty. This research shows that recovering the SOC to 50%, is not always the optimum decision and the optimum SOC range depends on the penalty, BSS efficiency, and distribution of power system frequency. This methodology is developed further in [24] to find the optimum SOC range for several battery sets, working

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as a group, to provide a certain amount of PFC.

Although these research [23], [24] developed a framework to optimally control the BSS in order to provide PFC, the framework needs to be developed further to take into account (1) the optimum bidding strategy, (2) the effect of the BSS degradation cost, (3) and a more detailed market model. In practice, the BSS operators should decide the optimum price to bid in the day-ahead market. In addition, the energy price of charging and discharging BSS are not equal, especially during SOC recovery time, as will be detailed in Section II and III. Therefore, the energy cost/profit of the BSS should be modelled to find the optimum operation. Furthermore, performing the SOC recovery whenever the frequency is in the dead-band may cause more frequency deviations in the case of a high share of BSS. This concern led TSO to start to prevent the SOC recovery in the dead-band, for instance in the Nordic flexibility market. PFC in the Nordic flexibility market is referred to as the frequency containment reserve (FCR) market, which does not allow, at the times when assets are providing the service, to control it in any other way than based on the frequency as detailed in the service agreement [25].

In this regard, this paper, as part of the EU-SysFlex project [26], develops a bidding strategy and online control methodology to maximize the profit that a BSS makes from its participation in the FCR market, using a BSS lifetime model. The main contributions of this paper are:

(1) Develop a bidding strategy and online control methodology based on the detailed FCR market model,
(2) Optimise the SOC recovery methods taking into account the degradation cost and energy and balancing cost.

Finally, this paper evaluates the proposed bidding strategy and online control methodology using empirical BSS installed in Helsinki, Finland market data, and Nordic synchronous system frequency from 2015 to 2019. The remainder of this paper is organised as follows: Section II details FCR in the Nordic flexibility market; Section III proposes the optimum operation of BSS; Section IV describes the simulation set-up, and Section V reports the simulation results. Finally, section VI concludes the papers.

II. Frequency Containment Reserves Market

In the Nordic flexibility markets, PFC includes FCR-N, the frequency containment reserve for normal operation and FCR-D, frequency containment reserve for disturbance. FCR-N deals with small power fluctuation in the system and is supplemented by FCR-D, the variant for larger disturbances. FCR-N is a symmetrical reserve service that aims to assist the power system by fast-reacting to frequency deviations, in order to stabilise the power system frequency in an acceptable range.

For this purpose, the FCR-N providers measure continuously the frequency and change their output power according to the frequency deviation. The frequency deviation comes from dynamic characteristics of the power system and real-time mismatch of demand and supply. The relation between frequency deviation and required FCR-N is determined by the system operator in technical requirements of the market.

In Finland, the Finish TSO, Fingrid, determined the technical requirements of FCR-N in [25], including the relationship between the output power of FCR-N providers and frequency deviation. This relation shows in Fig. 1, where 100% injected power is the total amount of contracted FCR-N service provision.

Although the technical requirements of FCR-N market in Finland is used for this study, the other system operators have a similar structure. This section reviews the three main parts of the technical requirements of FCR-N from [25], which are necessary to model the BSS in the FCR market.

A. Energy Capacity Requirement

Regarding energy capability, the technical requirements [25] state that a general provider "*shall be capable of activating the reserve in full for the entire delivery period*", i.e. whenever the frequency is out of the dead-band no matter how long it lasts. It is important to notice that since the dead band as shown in Fig. 1, is so narrow (0.02 Hz), the delivery period can be last for several minutes. The statistical analysis of historical data of Nordic frequency, Section IV, shows that the average time of over frequency event and under frequency event is 5.77 and 5.73 minutes, respectively; while the longest event was over 300 minutes.

However, the technical requirements made an exception for units with limited activation capacity, e.g. BSS, and it states that they "*shall be dimensioned so that the unit is capable of continuous full activation for at least 30 minutes*". In other words, since the provision of FCR-N has to be symmetrical, the battery should have at least the energy capacity equals to providing the maximum power service for one hour. In this case, it will be able to absorb or inject the power for 30 minutes if it starts from a state of charge of 50%.

B. SOC Recovery Obligation

Performing SOC recovery when the frequency comes back into the dead-band could negate the effects of the FCR provision and could create new frequency deviations, especially assuming a high share of BSS starts to charge or discharge together, as will be shown in Section IV. Therefore, new technical requirements prevent SOC recovery while in the dead-band. The control diagram of Fig. 1 explicitly shows that the output active power of the FCR-N providers must be zero when the frequency is in the dead-band. However, since some methods use the SOC recovery during this time, the new

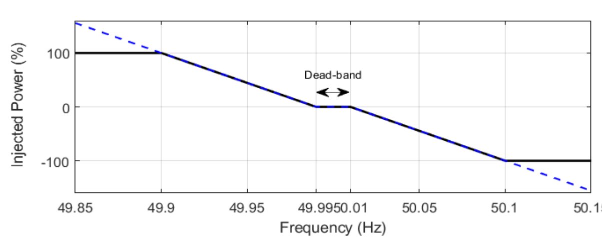

Fig. 1. The FCR-N control curve. The solid line is the typical curve from [24], while the dash lined is parallel method, introduced in Section III.

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Finnish technical requirements [25] added the following term to prevent the SOC recovery during the dead-band.

"*The power taken from the grid or fed into the grid by an energy storage facility that participates in the maintaining of the FCR-N shall not be controlled in ways other than on the basis of frequency in accordance with reserve operation. This principle applies to the power and energy capacity. When the power and energy capacity of the energy storage facility is not reserved for the maintaining of the reserve, the use of the capacity is not limited*."

C. FCR Remunerations

The FCR-N providers should bid their hourly FCR-N capacity to Fingrid in day-ahead and they are compensated for providing capacity and traded energy. The capacity fee is paid based on the provided capacity even when it doesn't get activated. The capacity fee is determined on a yearly or hourly basis, based on the chosen market agreement. For a yearly agreement in 2019, the capacity fee for FCR-N is 13.5 €/MW,h [27]. In the hourly market, the capacity fee is determined by competition for each hour in a day-ahead market (statistics on daily market price is provided in Section IV). If a FCR-N provider fails to provide the energy promised on the day-ahead market, they must pay a penalty equal to the capacity fee.

In addition to the capacity fee, the energy fee will be paid/charged by Fingrid according to the balancing market when the FCR-N is activated. It means Fingrid pays the FCR-N provider based on up-regulation price when they inject energy to the system (BSS discharging) and charge them based on down-regulation price whenever they consume (BSS charging) [28]. Since the up-regulation price is always higher or equal to down-regulation price, the energy fee could be a sort of compensation for BSS regardless of efficiency and degradation cost.

However, during the SOC recovery, the energy price will be selected according to imbalance settlement regulation for demand. The amount of energy needed for BSS recovery cannot be predicted in the day-ahead market due to uncertainty in frequency deviation. Therefore, it will be counted as imbalanced energy, which has a higher cost. Fingrid sells imbalance power during up-regulation hour at the up-regulation price and otherwise at the spot price [29]. In the same way, imbalance power is purchased at the down-regulation price during down-regulation hours and otherwise at the spot price.

III. BSS Optimum Operation

To find the optimum bidding strategy and online control methodology, the profit of a BSS operation during the battery lifetime should be maximized. Here, it is assumed that the BSS participate in the day-ahead market by bidding $P_{bid,h}$ kW power at the price of $\pi_{bid,h}$ Euro for hour h. In these circumstances, the profit of providing FCR-N reserve will be mathematically modelled in this section, as follows:

$$\text{Profit} = \sum_h \left(R_{cap,h} - P_{cap,h} + R_{eng,h} - C_{\text{rec},h} \right) - \sum_m C_{trf,m} - C_d, \quad (1)$$

where $R_{cap,h}$ is the revenues obtained from offering the FCR-N capacity over the hour h; $P_{cap,h}$ is the loss corresponding to the penalties when the BSS fails to deliver the reserve; $R_{eng,h}$ is the revenues obtained from the energy exchange for providing FCR in the hour h; $C_{rec,h}$ is the energy cost of SOC recovery at hour h; $C_{trf,m}$ is a fee of the grid tariff in the month m; and C_d is the degradation costs associated with operating the BSS over the whole period.

A. FCR Energy Exchange

As mentioned in section II, an FCR-N provider is expected to deliver power followed by the control curve illustrated in Fig. 1, as fast as possible. However, in practice, the calculation for capacity revenue and penalty is performed based on one-minute energy exchange.

The expected one-minute energy exchange from the battery bank ($E_{exp,m}$) in kWh can be calculated as follows:

$$E_{\text{exp},m} = \begin{cases} -\dfrac{P_{bid,h} \cdot P_{av,m}}{60 \cdot 100} \cdot \dfrac{1}{\eta} - E_{nl} & P_{av,m} \geq 0 \\ -\dfrac{P_{bid,h} \cdot P_{av,m}}{60 \cdot 100} \cdot \eta - E_{nl} & P_{av,m} < 0 \end{cases}, \quad (2)$$

where $P_{av,m}$ is the average active power (in %) during the minute m, calculated from the control curve of Fig. 1, according to the frequency deviation; $P_{av,m} > 0$ means discharging the battery and $P_{av,m} < 0$ means charging the battery; E_{nl} is the no-load energy loss of the BSS per minute; and η is the linear estimation of variable loss.

The BSS can inject the expected energy if there is enough energy available and it can absorb the energy if there was enough empty capacity. Therefore, the actual delivered energy to the battery in the minute m ($E_{del,m}$) can be calculated as follows:

$$E_{del,m} = \begin{cases} \max(E_{\text{exp},m}, \dfrac{SOC_{\min} - SOC_m}{100} \cdot E_{BSS}) & P_{av,m} \geq 0 \\ \min(E_{\text{exp},m}, \dfrac{SOC_{\max} - SOC_m}{100} \cdot E_{BSS}) & P_{av,m} < 0 \end{cases}, \quad (3)$$

where E_{BSS} is the rated capacity of the battery in kWh; SOC_{min} and SOC_{max} are respectively the minimum and maximum allowable SOC of the battery operation; and SOC_m is the actual SOC of the BSS at the beginning of the minute m. The SOC of the battery at the beginning of the next minute (SOC_{m+1}) will be updated as follows:

$$SOC_{m+1} = SOC_m + 100 \cdot \frac{E_{del,m}}{E_{BSS}}, \quad (4)$$

Delivering expected FCR energy for each minute leads to gain revenue from the energy exchange at hour h ($R_{eng,h}$), which can be calculated as follows:

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$$R_{eng,h}=\begin{cases}\pi_{eng,h}\cdot\sum_{m=1}^{60}\left(\left(E_{del,m}+E_{nl}\right)\cdot\right)\eta & P_{av,m}\geq 0\\ \pi_{eng,h}\cdot\sum_{m=1}^{60}\left(\left(E_{del,m}+E_{nl}\right)\cdot\right)/\eta & P_{av,m}<0\end{cases},\quad(5)$$

where $\pi_{eng,h}$ is the energy price of exchanged energy for FCR provider and according to the market regulation, it is calculated as follows:

$$\pi_{eng,h}=\begin{cases}\pi_{up-reg,h} & \sum_{m=1}^{60}P_{av,m}\geq 0\\ \pi_{dn-reg,h} & \sum_{m=1}^{60}P_{av,m}<0\end{cases},\quad(6)$$

where $\pi_{up-reg,h}$ is the up-regulation price and $\pi_{dn-reg,h}$ is the down-regulation price of the hour h. As mention in Section II, Since the up-regulation price is always larger or equal to down-regulation price, it could make a revenue. However, due to BSS efficiency and degradation cost, this revenue could be negative.

B. Capacity Reward and Penalty

The main revenue of an FCR-N provider comes from capacity remuneration, which can be calculated at hour h as follows:

$$R_{cap,h}=\pi_{FCR,h}\cdot\frac{\sum_{m=1}^{60}cap_m}{60},\quad(7)$$

where $\pi_{FCR,h}$ is the capacity fee for providing one-hour FCR-N in €/kW,h. cap_m is the provided FCR capacity in minute m. When the delivered energy in all minutes of the hour h equals to the expected energy ($E_{del,m}=E_{exp,m}$), BSS will be remunerated based on the bid for that hour ($P_{bid,h}$). However, if they cannot provide all the expected energy, they will be just compensated proportionally to what they provide. Therefore, the FCR capacity (cap_m) can be calculated as follows:

$$cap_m=\begin{cases}P_{bid,h} & E_{del,m}=E_{\exp,m}\\ -\min\left(0,(E_{del,m}+E_{nl})\cdot\eta\right) & P_{av,m}\geq 0\ \&\ E_{del,m}<E_{\exp,m}\\ \max\left(0,(E_{del,m}+E_{nl})/\eta\right) & P_{av,m}<0\ \&\ E_{del,m}<E_{\exp,m}\end{cases},\quad(8)$$

As shown in (7) and (8), the larger bid can make a larger revenue. In order to prevent overbidding by BSS, the technical requirements of FCR set two terms: 1) the penalty for not providing the capacity 2) limit the maximum bidding.

If the FCR providers cannot provide energy as agreed in the day-ahead market, they have to pay a penalty for hour h, as follows:

$$P_{cap,h}=\pi_{pen,h}\cdot\left(P_{bid,h}-\sum_{m=1}^{60}cap_m\right),\quad(9)$$

where $\pi_{pen,h}$ is the penalty fee for not providing FCR-N in €/kW,h.

As mentioned in section II, the BSS must be capable of full activation for at least 30 minutes in either direction. In these circumstances, the maximum bidding capacity ($P_{bid,max}$) can be calculated as follows:

$$P_{bid,\max}=\min\left(P_{\max},E_{BSS}\cdot\frac{\left(SOC_{\max}-SOC_{\min}\right)}{100}\right),\quad(10)$$

where P_{max} is the maximum power of the BSS converter. This formula guarantees that BSS has enough energy to provide half an hour up-regulation or enough available space to provide down-regulation, assuming it to start from 50% SOC.

C. SOC recovery methodology

The frequency deviation in power systems is the results of the real-time mismatch of production and consumption, due to some prediction errors or unforeseen events. Therefore, the frequency deviation has extremely random behaviour, whose duration and magnitude cannot be predicted. In these circumstances, keeping battery SOC as far as possible from its boundary (SOC_{min}, SOC_{max}), called SOC recovery, can increase the delivered energy in FCR-N market and decrease the penalty cost.

In an ideal BSS, the optimum operating point is when the battery is charged to (SOC_{min} + SOC_{max}) /2, where it can provide the same amount of up- and down-regulation. However, in practice, charging and discharging leads to energy loss, degradation cost, and charging cost due to the difference in the charging and discharging price of energy. In these circumstances, the recovery cost could be larger than the expected penalty cost. Therefore, it could be better to recover the SOC only when it is far enough from its optimum operating point.

Fig. 2 explains the optimum actions in SOC recovery. The optimum recovery actions are charging the battery when the SOC is less than the $SOC_{opt,min}$, no action when the SOC is in ($SOC_{opt,min}$, $SOC_{opt,max}$), and discharging when the SOC is greater than $SOC_{opt,max}$. Therefore, the actual exchange energy for SOC recovery in the minute m ($E_{rec,m}$), can be calculated as shown in (11) at the bottom of this page. It is worth mentioning that as the no-load loss is calculated in $E_{exp,m}$, it will not appear in the SOC recovery energy exchange.

Since the energy of SOC recovery cannot be determined in the day-ahead, it would create imbalance energy from the day-

$$E_{\text{rec,m}}=\begin{cases}-\max\left(\frac{-P_{\max}}{60\cdot\eta},\frac{SOC_{opt,\max}-SOC_m}{100}\cdot E_{BSS}\right)\cdot\eta & SOC_m>SOC_{opt,\max}\\ 0 & SOC_{opt,\min}\leq SOC_m\leq SOC_{opt,\max}\\ -\min\left(\frac{P_{\max}\cdot\eta}{60},\frac{SOC_{opt,\min}-SOC_m}{100}\cdot E_{BSS}\right)/\eta, & SOC_m<SOC_{opt,\min}\end{cases},\quad(11)$$

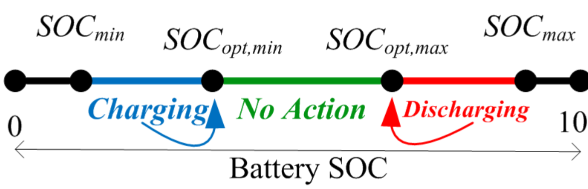

Fig. 2. Optimum action of SOC recovery methods

ahead profile. It means that the BSS operator must pay the imbalance price for SOC recovery. Therefore, the SOC recovery cost at hour h ($C_{rec,h}$) can be calculated, based on the imbalance market as explained in section II, as follows:

$$C_{rec,h} = \min\left(\pi_h, \pi_{up-reg,h}\right)\cdot \max\left(0, -\sum\nolimits_{m=1}^{60} E_{\text{rec,m}}\right) + \max\left(\pi_h, \pi_{dn-reg,h}\right)\cdot \min\left(0, -\sum\nolimits_{m=1}^{60} E_{\text{rec,m}}\right), \quad (12)$$

where π_h is the spot price of the market; and the summation is over the time that SOC recovery is performing. The SOC recovery can be performed using different methods. This paper proposes two new methods and compares them with the dead-band recovery methods.

1) ***Method 1****: Dead-band recovery*. In this method, BSS recovers SOC when the frequency is in the dead-band of control curve (between 49.99 Hz and 50.01 Hz in Fig. 1). This method is suggested and used by previous work, e.g. [23], [24]; however, new regulation in Finland prohibits this recovery method for upcoming BSS as explained in Section II.

2) ***Method 2****: Reserve time for SOC recovery when no FCR bids are made*. The new technical requirements limit the usage of the BSS according to the control curve whenever it is reserved to maintain FCR. In these circumstances, the BSS can reserve some time, e.g. whenever the price is less than π_{bid}, and performs SOC recovery in those hours. In other words, BSS can bid the price of π_{bid} in the day-ahead market, and recover SOC during the hours the bid is not accepted.

3) ***Method 3****: Providing extra Power for SOC recovery*. In this method, the BSS charges or discharges the battery with higher power than bid in the day-ahead market whenever the frequency deviation is more than 0.1 Hz and the SOC needs to be recovered in that direction. In other words, BSS follows the dash-line in Fig. 1. In this case, since the BSS recover their SOC in favour of the power system, they will not pay a higher rate of imbalance power for SOC recovery.

D. Grid Tariff

The BSS is connected to the distribution grid, usually medium voltage (MV). Therefore, the BSS need to pay the grid Tariff, which is calculated as follow,

$$C_{trf,m} = BC_m + \pi_P \cdot P_m + (\pi_E + T)\cdot E_m, \quad (13)$$

where BC_m is the basic charge per month, 217 € in the MV grid tariff, π_p is the charge of power, 4.56 €/kW, month in the Helsinki area, P_m is the highest hourly average consumed power in the month m, π_E is the energy charge, 1.75 and 0.78 €/MWh in the winter day and other times, respectively, in the Helsinki area, T is the electricity tax in Finland, 0.872 €/MWh for production sites[30], E_m is the BSS energy consumption in the month m.

E. Battery Lifetime Model

In order to investigate all costs of providing FCR, the battery lifetime model, which is able to estimate the fading of performance for the battery, is required. The degradation of the parameters of batteries can be modelled according to the idle times keeping a constant SOC and charging/discharging cycles. The two components can be referred to as calendar and cycle ageing, respectively.

Battery ageing degrades both battery energy capacity and power capability. However, as discussed in [22], [31], the ageing has a lower effect on the power than on the energy capacity of the battery. In addition, the power capability of the battery is often over-dimensioned for FCR provision. For those reasons, the impact of ageing on the power capability of the BSS is ignored in the rest of this paper.

Although the degradation model of Lithium batteries may change slightly based on their chemistries, this paper is using the models developed in [22], [31]. Using these models, the percentage of calendar capacity fade (C_{cal}) can be calculated as follows:

$$C_{cal} = 0.1723\cdot \sum\nolimits_i e^{0.007388\cdot SOC_i}\cdot m_i^{0.8}, \quad (14)$$

where SOC_i represents the SOC level and m_i represents the total time, expressed in months, that battery keeps the specific SOC and zero output power. To calculate (14), the periods having zero output power will be divided into i different SOC level using methods like *histcounts* in MATLAB.

The percentage of cycle capacity fade (C_{cyc}) can be calculated as follows:

$$C_{cyc} = 0.021\cdot \sum_k e^{-0.01943\cdot SOC_k} cd_k^{0.7162}\cdot nc_k^{0.5}, \quad (15)$$

where nc_k is the number of cycles with having cycle depth equal cd_k and $SOCk$ represents the average SOC level of that cycle depth. In order to calculate (15), the rainflow counts method for fatigue analysis, implemented in MATLAB, can be used.

The battery lifetime is defined as the time, which the battery loses a certain percentage, e.g. 20 %, of its capacity, called end-of-life (EOL). Assuming salvation value for battery equal to 60% of initial capital cost (ICC) [32] and zero interest rate, the degradation cost (C_d) of the battery for the studied time becomes:

$$C_d = 0.4\cdot ICC\cdot \frac{C_{cal} + C_{cyc}}{EOL}. \quad (16)$$

F. Optimum Operation

The profit of a BSS operating in an FCR market is calculated in (1) - (16), according to the technical requirements of the FCR market (Section II), power system operating point (frequency deviation), energy and flexibility market price (energy price, imbalance price, and the FCR

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capacity fee price), and BSS properties and operation.

By combining (1) - (16), the best SOC recovery methods, the bidding price (π_{bid}), the bid capacity (P_{bid}) and the minimum and maximum optimum range of SOC ($SOC_{opt,min}$, $SOC_{opt,max}$), can be calculated as follows:

$$
\begin{aligned}
&Max.\ \ \text{Profit}\left(P_{bid}, \pi_{bid}, SOC_{opt,\min}, SOC_{opt,\max}\right) \\
&\qquad = \sum_h \left(R_{eng,h} + R_{cap,h} - P_{cap,h} - C_{\mathrm{rec},h}\right) - \sum_m C_{trf,m} - C_d \\
&\text{s.t.} \\
&\quad 0 \le P_{bid} \le P_{bid,\lim} \qquad\qquad (17)\\
&\quad P_{bid,\lim} = \begin{cases} 0 & \pi_{bid,h} \le \pi_{FCR,h} \\ P_{bid,\max} & \pi_{bid,h} > \pi_{FCR,h} \end{cases} \\
&\quad SOC_{\min} \le SOC_h \le SOC_{\max} \\
&\quad SOC_{opt,\min} \le SOC_{opt,\max}
\end{aligned}
$$

In order to maximise the profit, the BSS operator needs to send the hourly FCR bid, including the bidding capacity and price, in a day-ahead market, by solving (17) over the next day. However, there is no information about the frequency deviation and flexibility market prices in a day ahead.

The frequency deviation is resulted due to real-time mismatch of productions and consumptions. In other words, the error in forecasting the demand and supply leads to the frequency deviation. Therefore, it is not possible to forecast the amount of frequency deviation in a day-ahead. In the same way, the imbalance market prices are varied based on a real-time mismatch and changed considerably due to unexpected events. Besides, the FCR market is very young and is not yet completely settled down; therefore, the capacity fee price in daily market does not follow a predictable pattern, as shown in Section IV.

In these circumstances, the optimum operation must be decided regardless of a given frequency deviation and market prices. Here, the historical data of frequency deviation and market prices are used to find the optimum operation. To consider the effect of the random distribution of frequency deviation, the profit should be calculated over a long period, e.g one years before the target day. In other words, the historical data of frequency deviation and market price is used to optimise the decision for the future market.

IV. Simulation Set-up

As part of the Finnish demonstrator in the EU-SysFlex project, a large-scale BSS, owned by Helen Ltd, is investigated to show the potential of distributed flexibility resources for the provision of frequency services. This BSS includes two parts, which are connected to a 10 kV medium voltage distribution grid in the Helsinki area. Each part has a 300 kWh battery bank connected to a three-winding transformer through a 600 kW converter. Fig. 3 shows the block diagram of the BSS installed in Helsinki.

This BSS has been operated as an FCR provider for periods in 2018 using different SOC recovery methods. The working performances, e.g. no-load loss and efficiency is calculated from the measurement. However, in order to compare different methods and investigate the optimum operation of this BSS, this paper simulates the BSS operation for a longer period by using historical data of frequency measurement and markets price. Fingrid open data platform shares the historical data of the Nordic synchronous system with a 10 Hz sample rate, hourly based FCR capacity price, and hourly up- and down-regulation price in [33]. In addition, the historical hourly record of the day-ahead energy market (pool market) of the Nordic synchronous system can be found in Nord pool database [34].

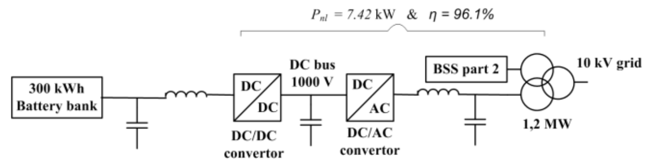

Fig. 3. The block diagram of the BSS installed in Helsinki. This BSS consists of two similar parts, while just one of them detailed in diagram.

The historical frequency data has 10 records per second, while the TSO looks at average minute records of FCR providers. Therefore, in order to accelerate calculation, the average frequency of each minute is used for simulation. Table I lists the important statistics of frequency deviation records in the Nordic synchronous system from 2015 to 2019. In this table, under frequency refers to the frequency less than 49.99 Hz, over frequency refers to the frequency higher than 50.01 Hz, and dead-band refers to the frequency between these two boundaries. When the frequency passes one of the boundaries, one event is counted. The total number of events during these years was 546821.

Fig. 4 shows the cumulative probability of events having a duration longer than a specific time. Fig. 4 shows that about 10 % of events having a duration longer than 15 minutes and about 5 % of events have duration larger than 30 minutes.

TABLE I
THE IMPORTANT STATISTIC OF FREQUENCY DEVIATION RECORDS IN THE NORDIC SYNCHRONOUS SYSTEM FROM 2015 - 2019

		Under-Frq	Dead-band	Over-Frq
Time Share (%)		40.4	19.8	39.8
Event Duration (Min)	Mean	5.73	1.76	5.77
	Standard Deviation	12.86	2.89	12.92
	Longest Event	304	900	265

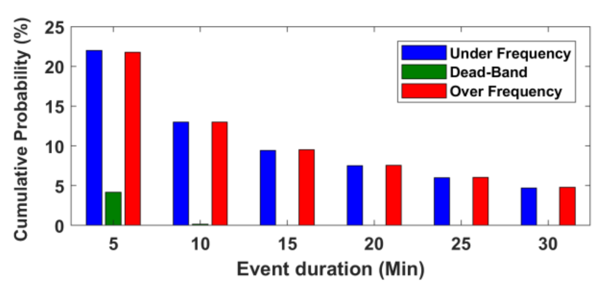

Fig. 4. The cumulative probability of events having duration longer than specific time.

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These long events make some challenges for BSS to provide FCR service and leads to some penalty.

Regarding the market price, Table II lists important statistics of markets prices for the same period (2015-2019). This table shows although the hourly price is zero for some hours, the average FCR-N capacity fee in the hourly agreement (20.36 (€/MW,h)) is higher than the yearly agreement (13.5 €/MW,h [27]). Therefore, the hourly agreement has the potential of earning more revenue with less availability time.

Furthermore, in lifetime model, the initial cost of the battery, without charging and control equipment, is considered 200 €/kWh based on the average price reported in [7], while whole BSS investment cost is about two times more than this amount.

TABLE II
THE IMPORTANT STATISTIC OF MARKET HOURLY PRICES IN THE NORDIC SYNCHRONOUS SYSTEM FROM 2015 - 2019

	Mean	**Std**	**Min**	**Max**
FCR-N Capacity fee/penalty (€/MW,h)	20.36	20.22	0	500
Pool market (€/MWh)	36.14	15.03	0	255.02
Down-Regulation (€/MWh)	31.75	20.13	-1000	249.97
Up-Regulation (€/MWh)	41.04	39.62	0.32	3000

V. SIMULATION RESULTS

In this section, the optimization problem (17) is solved for different SOC recovery methods, using BSS properties, e.g. no-load loss and efficiency, and historical data, e.g frequency deviation and market prices, as explained in section IV. Analytical analysing of the convexity of this problem is beyond the focus of this paper. Fig. 5 shows the relation between the annual profits of BSS for different SOC recovery bound, in the dead-band recovery method. Here, the problem (17) is solved by using the constrained particle swarm optimization (CPSO) developed in [35].

Although the implemented CPSO may not be the best choice to solve this large optimisation over long historical data, the performance was acceptable. The proposed methodology has been implemented in MATLAB and solving (17) by CPSO takes about half an hour for each SOC recovery method using a Core I7 PC, which is an acceptable time for the daily market.

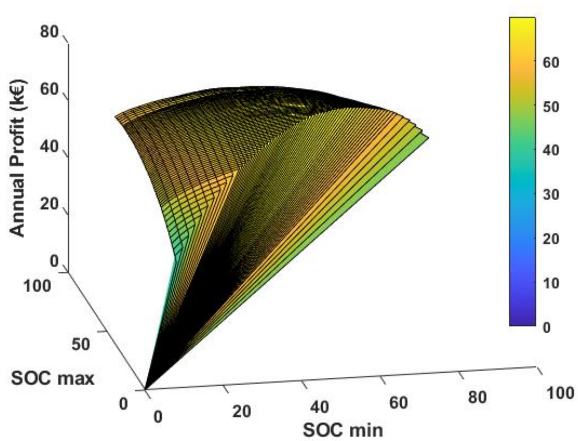

Fig. 5. The relation between the annual profits of BSS for different SOC recovery bound, in dead-band recovery method.

Table III lists the optimum bidding strategy, control methodology, and the average annual profit of the BSS installed in the Helsinki area, calculated using last year historical data (last 365 days) for the first two months of 2019. This method uses the historical data for representing the next day frequency deviation and flexibility market price since it is not possible to forecast these parameters in a day ahead as explained in Section III.

However, to analyse the robustness of the method against future uncertainties in frequency deviation and price, a comparison is performed. In this comparison, the optimisation problem (17) is solved for exact data of the next day, assumed that there is an ideal estimator, instead of solving the optimisation over last year. Table IV shows the average annual optimum settings and profit in different scenarios using the first two months of 2019 as the ideal estimators. Comparing these results with Table III, show that the order of the most profitable methods and the optimum settings remain almost the same as reported in Table III, which indicates the robustness of using historical data in the proposed methodology.

Table III shows that without having any SOC recovery (Method 0), the average annual BSS profit will be about 38 k€, which makes a payback period about 6 – 8 years. At the same time, the battery lifetime model over last 4 years shows that providing FCR-N leads to about 10 % decay ($C_{cal} \approx$ 1% $C_{cyc} \approx$ 9%), which means the battery will last about 8 years assuming an end of life (EOL) at 20% of the capacity. However, it is expected the other parts of BSS last for a longer period. It is

TABLE III
THE OPTIMUM STRATEGY AND AVERAGE ANNUAL PROFIT/LOSS (K€) OF DIFFERENT METHODS, BASED ON LAST YEAR HISTORICAL DATA

	Method 0	Method 1	Method 2	Method 3	Method 2 & 3
π_{bid}	0	0	4.46	0.7	8.37
P_{bid}	540	540	540	540	540
$SOC_{opt,min}$	-	49.16	56.65	4.35	62.91
$SOC_{opt,max}$	-	64.75	84.69	83.69	78.80
R_{cap}	86.57	101.11	85.85	86.58	86.55
P_{cap}	-20.57	-6.02	-19.54	-20.55	-19.85
R_{eng}	-2.35	3.91	-1.26	-2.36	-1.49
C_{trff}	-22.52	-20.43	-22.51	-22.52	-23.01
C_{rec}	0.00	-6.68	-0.02	0.01	-0.1
C_d	-2.34	-2.01	-2.32	-2.34	-2.33
Profit	**38.79**	**69.88**	**40.21**	**38.82**	**39.77**

TABLE IV
THE AVERAGE OPTIMUM SETTINGS AND ANNUAL PROFIT USING THE FIRST TWO MONTHS OF 2019 AS THE IDEAL ESTIMATOR

	Method 0	Method 1	Method 2	Method 3	Method 2 & 3
π_{bid}	0	0	6.20	2.1	8.37
$SOC_{opt,min}$	-	47.14	53.16	4.56	65.91
$SOC_{opt,max}$	-	61.58	86.01	74.69	85.80
Profit	**42.28**	**77.57**	**45.04**	**44.65**	**45.18**

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worth mentioning that the maintenance time is not considered in this implementation and the profit in practice could be slightly less than the calculated one.

The dead-band SOC recovery, method 1 in Table III, recovers SOC whenever the frequency is in the dead-band area, which is distributed in different hours of a day. Therefore, this method has the potential to keep the SOC in the optimum boundary over all periods and to increase dramatically the capacity revenue and decreases the capacity penalty. In addition, by avoiding high SOC in the BSS, it decreases slightly the degradation cost of BSS. Furthermore, since the SOC recovery is usually in the opposite direction of FCR-N regulation, it can decrease the grid tariff cost. Consequently, the SOC recovery in dead-band has the potential to increase the profit by 80%, as shown in Table III. However, the energy used for SOC recovery will be a burden against the FCR-N regulation (as shown in Fig. 8) and therefore will be not allowed in the new technical requirements of FCR-N market in Finland.

As listed in Table III, the other SOC recovery methods do not have the same potential to improve the profit of providing FCR-N. The second method performs SOC recovery instead of providing FCR-N regulation when the price is less than π_{bid}, whose the optimum is 4.46 €/MW,h, in the simulated case. It means this method escapes low capacity revenue, to avoid high capacity penalty. However, since the market is hourly based, it cannot be distributed in different hours and therefore, the improvement is rather small in the Finnish market, which has equal capacity penalty and reward. As expressed in Table III, it would improve the BSS profit by 4%.

The third method, perform SOC recovery whenever the power system needs more regulating power in the direction, which matches with SOC recovery direction. In this case, the BSS provide FCR-N larger than the bid and therefore it will not get any capacity reward for the extra part. In this situation, due to the internal loss of BSS and demand tariff, this method will improve slightly the profit (less than 1%).

In order to explain better the different methods, Fig.6 shows the frequency of the Nordic synchronous system for January 7 2019, and Fig.7 demonstrates the FCR-N price in the hourly market. Fig.8 and Fig. 9 show respectively the injected power and SOC of BSS installed in the Helsinki area, using different SOC recovery methods.

Fig. 8 shows that after each frequency event when the frequency goes back to the dead-band, method 1 starts to inject power in the reverse direction of the last frequency event to recover the SOC. While this behaviour helps the BSS to avoid a penalty, it recreates pressure on the system immediately after frequency restoration. Therefore, the new technical requirements forbade this recovery method.

On January 7 at hours 2-6, 8-9, and 12-21, the FCR price was lower than 4.46 € (the optimum $\boldsymbol{\pi_{bid}}$ in method 2); as shown in Fig. 7; therefore, method two did not provide FCR-N for these hours. However, since the SOC was in the optimum range, between 56.65 and 84.69 (Table III, column 4), the BSS, using method 2, neither perform SOC recovery. During hour 7, the frequency is higher than 50.1 Hz for some minute that could activate method 3. However, since the BSS in that time has SOC in the optimum range, between 14.82 and 83.89 (Table III, column 5), there will be no SOC recovery in method 3 and its behaviour is similar to method 0, in this case.

VI. CONCLUSION

This paper proposes an optimized bidding strategy and online control methods of BSS to participate in the PFC market by maximising the BSS profit over battery lifetime. For this purpose, the profit of a BSS providing frequency regulation is formulated as a multi-variable non-linear constrained optimization problem. This profit model was developed considering 1) the BSS model including constraints

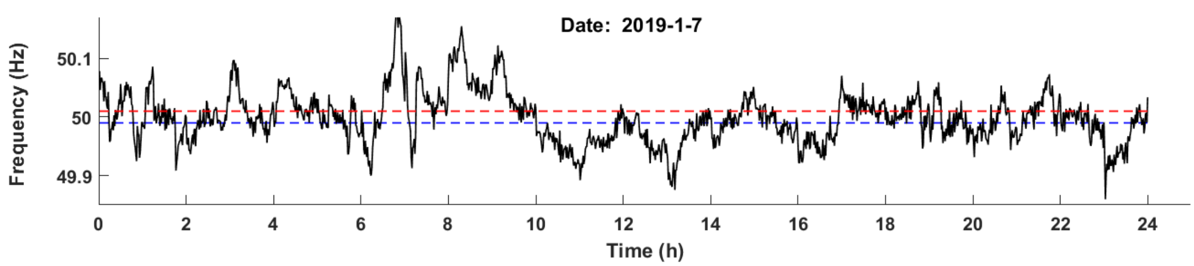

Fig. 6. The frequency of the Nordic synchronous system on January 7, 2019.

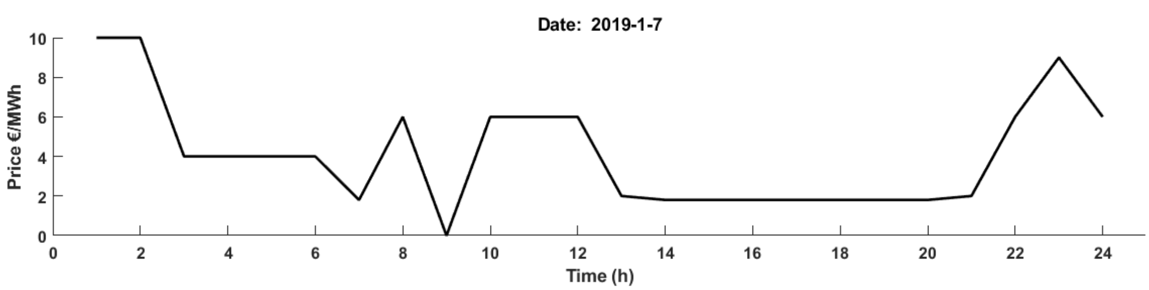

Fig. 7. The FCR-N Price on January 7, 2019.

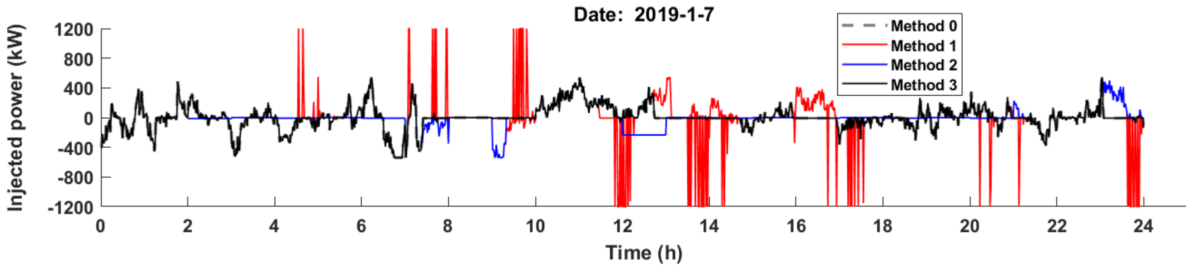

Fig. 8. The injected power of the BSS installed in Helsinki area on January 7 2019

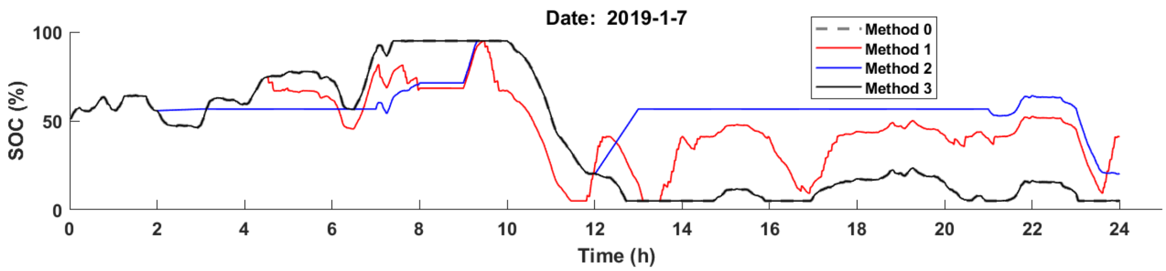

Fig. 9. The SOC of the BSS installed in Helsinki area on January 7 2019

and loss, 2) FCR market technical requirements including capacity dimensioning and SOC recovery obligations, 3) pool market and imbalance market regulations to calculate the exact reward/cost of energy exchange, 4) distribution tariff, and 5) battery lifetime model to calculate degradation cost. The simulation results in the Helsinki area, using historical data demonstrate that prohibition of the SOC recovery in the dead-band dramatically decreases the BSS profit. The results indicate that the best SOC recovery method, which in line with the new regulation, is reserve time for SOC recovery during lower market price.

The simulations show that the payback period of a BSS providing FCR-N regulation in Finland is longer than six years while the battery lifetime is this application is about eight years. It is worth mentioning that the proposed method can be replicated in other frequency markets of different countries or used for upcoming flexibility products, such as fast frequency reserve to handle low inertia situation, by changing the values of model's parameters.

VII. Future Work

This research will continue to implement the bidding strategy and online control methods in the large-scale BSS, installed in the Helsinki area. In addition, the research activity can be continued in the following direction:

(1) Extend the methodology to model fast frequency reserve product, recently introduced in the Nordic flexibility markets as a solution to the inertia challenge.

(2) Find the optimum bidding strategy and online control method for several battery sets, work together.

(3) Find a more efficient optimisation method than CPSO. Especially in the case of several battery sets, the performance of the optimisation method would be more important.

VIII. Acknowledgment

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