Efficient market-based storage management strategy for FCR provider with limited energy reservoir

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***Abstract*—We present a market-based storage state of charge management strategy for primary frequency control providers with limited energy reservoirs such as battery energy storage systems. The strategy is the result of research work motivated by relatively recent regulatory condition updates in Continental Europe which stipulate that frequency containment reserve providers cannot rely on dead-band utilization and delivery overfulfillment to manage their reservoirs. In addition, we show how the devised strategy allows an appropriately sized battery system to withstand the realization of a worst-case scenario, even if the unit is providing multiple reserve products at once and is allowed to recover its state of charge only via the intraday market.**

***Index Terms*-- ancillary services, balancing, BESS, FCR, storage**

I. Introduction

The role of energy storage technologies in the power systems has been rapidly growing as the rising share of intermittent renewable energy sources increases the need for system flexibility. To that end, storage is seen as an invaluable resource able to provide fast-acting ancillary services to system operators in decarbonized electricity systems. Consequently, there has been a significant growth of battery-based grid-scale storage during the recent years worldwide. However, their intrinsic differences when compared to conventional balancing resources must be accounted for and reflected in regulation.

In order to both facilitate and regulate integration of storage systems in ancillary service markets, especially for provision of frequency containment reserve (FCR), the EU System Operation Guideline [1] stipulates specific rules applicable to limited energy reservoirs (LERs), i.e. storage units that can be depleted within two hours of operation. Namely, the minimum activation period (T_{minLER} criterion) to be ensured by FCR providers qualified as LERs is 15–30 min during the system alert state with a specific value to be proposed by all TSOs of each synchronous area. While the Continental Europe (CE) TSOs lean towards a 30-min T_{minLER} at least for newly installed storage power plants, the final proposal is still under development as of mid-2023.

Furthermore, CE TSOs have already developed a number of additional properties of FCR [2]. Here, the definition of a LER has been clarified as an FCR provider that cannot maintain full reserve activation for at least two hours without performing corrective actions for reservoir management. Furthermore, the TSOs have disallowed overfulfillment or dead-band utilization, which means LERs should rather use existing market-based or similar measures for their reservoir recovery, intraday market being one of the most feasible possibilities.

Another important addition is the introduction of Reserve Mode, whereby LERs that are technically capable to should change their mode of FCR provision to react to only short-term frequency deviations when the reservoir is near exhaustion [2]. Reserve Mode allows for more beneficial usage of LERs during power system alert state, however, the technical intricacies of it have not been sufficiently harmonized yet.

LERs as FCR and frequency restoration reserve (FRR) providers are of particular interest for the Baltic power system, which is scheduled to desynchronize from IPS/UPS and connect to the CE synchronous area by 2025 [3]. By this time, the Baltic TSOs ought to be able to cover their FCR and FRR needs themselves while historically the primary frequency control has been ensured by the neighboring Russian power system [4], [5]. Hence, large-scale battery energy storage system (BESS) projects are under development in the Baltics to ensure FCR and FRR adequacy [6]–[8]. The outlined EU-level developments and regional challenges around the Baltic synchronization project have motivated the research question of this study: develop efficient market-based BESS operational management strategy subject to a set of technical and regulatory constraints related to ancillary service markets and specific reserve products as well as to electricity wholesale markets for storage recovery.

Even though a number of different strategies for FCR-providing BESS management can be found in the literature, the recent EU regulatory advances and the regional intricacies of the Baltic power system introduce the need for a more sophisticated methodology to conform to a number of binding requirements towards LERs. Notable previous studies include, for instance, FCR-providing BESS management algorithms developed for the German case described in [9]–[11] which use three degrees of freedom for storage management: overfulfillment,

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dead-band utilization and scheduled intraday (ID) transactions (with a 30-min gate closure time (GCT)). Reference [9] also uses provision rate adjustment, but finds it inconsequential.

On the other hand, [12] explores three methods of state of charge (SOC) recovery in a Finnish context: dead-band utilization (which they admit as incompliant with the new regulations), day-ahead (DA) bidding in time intervals when FCR capacity has not been sold and overfulfilling day-ahead trades when it is favorable to the balance of the power system.

In the Baltic context, a recent study [13] also considers overfulfillment and dead-band utilization as viable SOC recovery strategies along with ID transactions. An important additional drawback is that the ID GCT time is not considered, which is 60 min in the Baltics [14].

In contrast, we fill the gap of the previous studies by proposing and validating an active energy reservoir management strategy for an FCR providing BESS respecting the prohibition of delivery overfulfillment, dead-band utilization and subject to a specific T_{minLER} in line with the recent EU regulation. Moreover, the strategy successfully implements market-based storage recovery exclusively in the ID market (i.e. a stand-alone BESS) which means that intentional imbalance is disallowed, and it is also applicable to a LER providing both FCR and FRR. Consequently, our proposed management strategy respects all the regulatory requirements that a stand-alone frequency reserve providing BESS will be subjected to in the Baltic power system in the near future as well as in the EU in general. The strategy has been implemented in a mathematical simulation tool to validate its performance. Hence, the tool also allows testing the BESS operational strategy under various market settings (e.g. varied T_{minLER}, ID GCT etc.) and parameters (e.g. BESS size) to validate the BESS ability to deliver the contracted services.

II. SOC Management Strategy

The SOC management strategy is only a part of the overall management model necessary for a LER participating in balancing markets. The other two major components deal with the transition to and from Reserve Mode when nearing storage exhaustion during the alert state and the preparation of FCR and FRR bids, particularly the voluntary FRR energy bids which, due to short lead time, are the most dependent on the current energy level of the storage. However, to limit the scope of this paper, only the SOC management strategy is described in detail.

The main goal of the strategy is to prepare ID bids, while delivering the reserves, in order to assure a sufficient SOC level in line with the undertaken reserve (FCR and/or FRR) obligations. The overall philosophy of the strategy envisions a robust approach, i.e. the BESS must strive to be prepared for the realization of a worst-case scenario at any future point in time.

A. Assumptions and Simplifications

We assume that the FCR provider is a single BESS with a LER which can only use market-based mechanisms for restoring the energy content of its reservoir (i.e. no alternative generation or load neither in the reserve provider's portfolio nor contracted bilaterally which could be used to charge/discharge the BESS; intentional imbalance to manage storage disallowed). Ultimately, this means that the BESS can manage its SOC only by participating in the ID market as it has a much shorter lead time than the DA market and thus allows for more flexibility.

To achieve the most effective storage management under the laid out conditions, the optimum decision-making time on whether an ID trade offer needs to be submitted would be at the last possible moment before the GCT. However, for the sake of robustness, a certain bid preparation time should be added before each ID GCT by which the decision is made.

The relationship between various time-related variables employed in the management strategy is explained in Fig. 1, where $t_{\mathrm{ID,decision}}$ – moment in time for ID offer decision; $t_{\mathrm{ID,GCT,next}}$ – the closest ID GCT; $t_{\mathrm{ID,start}}$ and $t_{\mathrm{ID,end}}$ – the start and end time of the ID trading period with the closest GCT; $\Delta t_{\mathrm{prepare}}$ – user-selectable time period for bid preparation (expressed in minutes before GCT, e.g. 5 min); $\Delta t_{\mathrm{ID,GCT}}$ – ID GCT (in minutes before delivery start, e.g. 60 min in Baltics [14]); Δt_{MTU} – market time unit duration (assumed 15 min [4]).

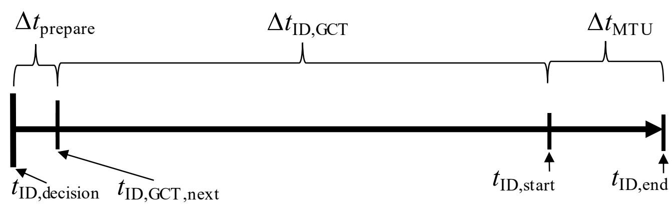

Figure 1. Relationship between the time-related variables

To minimize over-correction risks, ID trades are prepared only for the shortest possible delivery periods, i.e. at each decision time only one potential MTU is considered for delivery. On the other hand, this means that the need for corrective trade has to be evaluated before each ID GCT; with a 15-min MTU this equals to 96 decisions a day.

Based on analysis of the EU regulatory framework, we derive the following main requirements for the SOC management strategy of a BESS to provide FCR with a LER qualification:

- Capability to provide a prolonged full FCR activation at least until the T_{minLER} criterion is satisfied during the system alert state.
- Capability to provide uninterrupted prolonged FCR up to 25% of the total committed reserve power in one direction during the system normal state.
- Recovery of sufficient storage level to be able to again fulfill the T_{minLER} criterion no later than 2 hours after the end of a prior system alert state.
- The previous three requirements need to be met also when the BESS provides FRR alongside FCR. However, the committed FRR must be able to be fully activated at any given time for any duration regardless of the T_{minLER} criterion and post-alert state recovery status. This is because there are no special properties defined or exemptions allowed for an FRR provider with a LER.

B. Algorithm

The main steps of the devised algorithm are generalized in Fig. 2 and henceforth explained.

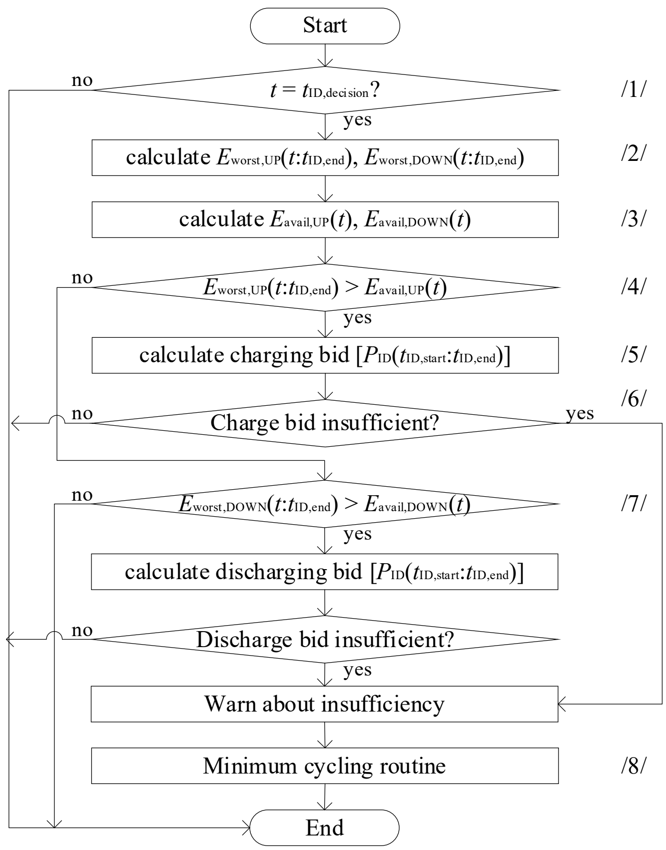

Figure 2. Main steps of the energy recovery algorithm

1) Check if the current timestep equals ID decision time. It depends on the closest ID GCT and bid preparation time:

$$t_{\text{ID,decision}} = t_{\text{ID,GCT,next}} - \Delta t_{\text{prepare}}. \tag{1}$$

If it does, the remaining part of the algorithm is executed, otherwise the process can end for this time instance (it is then launched anew at the next time step).

2) Calculate the worst-case up-regulation (discharging) energy for the time interval from the current ID decision time to the end of the ID delivery period for which trading with the closest GCT is open, i.e. from t to $t_{\text{ID,end}}$, where, as per Fig. 1:

$$t_{\text{ID,end}} = t + \Delta t_{\text{prepare}} + \Delta t_{\text{ID,GCT}} + \Delta t_{MTU}. \tag{2}$$

Evidently, the necessary look-ahead horizon has a duration equal to the sum of $\Delta t_{\text{prepare}}$, $\Delta t_{\text{ID,GCT}}$ and Δt_{MTU}.

In general, the worst-case energy consists of the sum of fully activated FCR and FRR up-regulation reserves (according to the sold capacity) as well as the full delivery of prior ID trades:

$$E_{\text{worst,UP}}\left(t : t_{\text{ID,end}}\right) = \sum_{t_x = t}^{t_{\text{ID,end}}} \left(\left(\begin{array}{l} P_{\text{FCR,cap}}\left(t_x\right) + P_{\text{FRR,UP,man}}\left(t_x\right) + \\ + P_{\text{FRR,UP,vol}}\left(t_x\right) + P_{\text{ID}}\left(t_x\right) \end{array} \right) \cdot \frac{\Delta t}{\left(1\text{ h}\right)} + \Delta E_{\text{s.d.}}\left(t_x\right) \right), \tag{3}$$

where $P_{\text{FCR,cap}}$ – FCR capacity at the particular time; $P_{\text{FRR,UP,man}}$ and $P_{\text{FRR,UP,vol}}$ – FRR up-regulation capacity due to mandatory and voluntary FRR bids respectively; P_{ID} – capacity to fulfill priorly scheduled ID trade (a negative value for charging trade); $\Delta E_{\text{s.d.}}$ – expected self-discharge losses of the BESS. t_x denotes a timestep between the current time t and the look-ahead horizon end time $t_{\text{ID,end}}$, the number of these steps depends on the selected granularity of the calculations denoted by Δt.

The loss expectation component assumes maximum self-discharge losses (i.e. as occurs when the SOC is at its maximum):

$$\Delta E_{\text{s.d.}}\left(t_x\right) = k_{\text{s.d.\%}} \cdot SOC_{\max} \cdot \frac{\Delta t}{\left(24\text{ h}\right)}, \tag{4}$$

where $k_{\text{s.d.\%}}$ is the self-discharge losses as a percentage of the SOC during one day, $SOC_{\max}$ is the permissible depth of charge.

It must be noted that the worst-case energy estimation (3) is valid for a conventional (non-LER) FCR resource. For LERs, there are special considerations since, as previously discussed, a LER does not have to endure full activation for the whole look-ahead horizon. Instead, in a worst-case scenario it has to deliver *nearly 50% activation* for 10 min and *nearly 100% activation* for 5 min (which would trigger the alert state [1]), followed by a *full activation* for 30 min (or 15 min) during the alert state to fulfill the T_{minLER} criterion (similarly as in [11]). Furthermore, if the alert state ends when the criterion is met, the LER still needs to be able to provide FCR continuously during the normal state, i.e. up to a 25% activation. For a safe and predictable LER operation transition from Normal to Reserve Mode after fulfilling the criterion, we add a requirement of another 5 min of full activation in the worst-case energy need estimation.

The outlined combination of worst-case FCR energy is trivial to calculate if the LER has an invariable capacity obligation (due to FCR market results) throughout the entire look-ahead duration. However, in principle, it is possible for the FCR capacity obligation to be different in each MTU within the horizon. This creates a combinatorial problem as there are numerous ways how the alert state and its preconditions could be temporally placed in the look-ahead horizon implying a multitude of potential FCR activation trajectories. Fig. 3 provides two examples, but the total number of alternatives depends on the calculation time granularity.

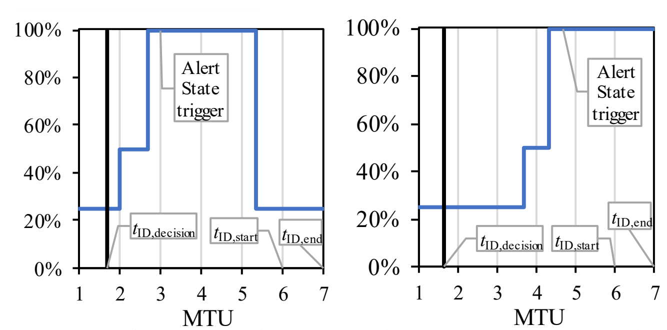

Figure 3. LER worst-case FCR activation temporal alternative examples

The worst-case up-regulation energy for a LER FCR provider can thus be expressed as:

$$E_{\text{worst,UP}}\left(t:t_{\text{ID,end}}\right)=$$
$$=\sum_{t_x=t}^{t_{\text{ID,end}}}\left(\begin{pmatrix}P_{\text{FRR,UP,man}}\left(t_{\text{x}}\right)+\\+P_{\text{FRR,UP,vol}}\left(t_{\text{x}}\right)+P_{\text{ID}}\left(t_{\text{x}}\right)\end{pmatrix}\cdot\frac{\Delta t}{(1\text{h})}+\Delta E_{\text{s.d.}}\left(t_{\text{x}}\right)\right)+ \qquad (5)$$
$$+E_{\text{LER,FCR,UP}}\left(t:t_{\text{ID,end}}\right)$$

where

$$E_{\text{LER,FCR,UP}}\left(t:t_{\text{ID,end}}\right)=$$
$$=\max\left(\begin{array}{l}\sum_{t_{\text{x}}=t}^{t_{\text{ID,end}}}\left(P_{\text{FCR,cap}}\left(t_{\text{x}}\right)\cdot\frac{\Delta f_{\text{s1}}\left(t_{\text{x}}\right)}{\Delta f_{\text{f.a.}}}\cdot\frac{\Delta t}{(1\text{h})}\right),\ldots,\\\sum_{t_{\text{x}}=t}^{t_{\text{ID,end}}}\left(P_{\text{FCR,cap}}\left(t_{\text{x}}\right)\cdot\frac{\Delta f_{\text{s}N}\left(t_{\text{x}}\right)}{\Delta f_{\text{f.a.}}}\cdot\frac{\Delta t}{(1\text{h})}\right)\end{array}\right), \qquad (6)$$

where $\Delta f_{\text{f.a.}}$ is the frequency deviation at which the FCR provider has to be fully activated and $\Delta f_{\text{s1}}(t_{\text{x}})\ldots\Delta f_{\text{sN}}(t_{\text{x}})$ are the frequency deviation alternatives.

The worst-case FCR activation alternative for a LER is thus identified by taking the one corresponding to the largest required energy as per (6). The found value is then input in (5).

However, a full enumeration as in (6) is only necessary if indeed the sold FCR capacity differs between the MTUs under consideration. Otherwise, if the FCR capacity is uniform, the worst-case LER FCR energy can be estimated using any of the alternatives (e.g. the right-side alternative in Fig. 3).

Once the worst-case up-regulation energy is estimated, the worst-case down-regulation energy requirement also needs to be assessed. The principle is the same as for the up-regulation in (3)–(6). The only differences are that now we look at the mandatory and voluntary FRR down-regulation bids (unlike FCR, FRR product is not symmetric), and that the self-discharge losses ($\Delta E_{\text{s.d}}$) are not considered as they do not worsen the situation in worst-case down-regulation scenario.

For both up- and down-regulation worst-case energy need considerations, a LER could, in principle, calculate the necessary energy as a non-LER (e.g. as in (3)). This would result in more active SOC management via ID trading, thus allowing a LER to accumulate more energy and exceed the T_{minLER} criterion (if desired). The priorly described approach, on the other hand, corresponds to conservative SOC management, the primary goal of which is to ensure meeting the minimum requirements a LER is subjected to (with a small safety margin) whilst taking advantage of the reduced FCR requirements for LERs.

3) The third step of the algorithm envisions calculating the energy available in the BESS for both up- and down-regulation. This primarily depends on the energy content in the reservoir at the current time t, its storage capacity and charge/discharge efficiency. The respective values can be calculated by:

$$E_{\text{avail.UP}}(t)=\left(SOC(t)-SOC_{\min}\right)\cdot\eta_{\text{disch}}, \qquad (7)$$

$$E_{\text{avail.DOWN}}(t)=\left(SOC_{\max}-SOC(t)\right)/\eta_{\text{ch}}, \qquad (8)$$

where $SOC(t)$ is the current energy content, $SOC_{\min}$ – the permissible depth of discharge, η_{disch} and η_{ch} – discharging and charging efficiency, respectively.

4) When both the worst-case energy and available energy are calculated for the respective activation directions, we check if the worst-case up-regulation energy exceeds the available one. If so, a charge (buy) ID bid is prepared. Otherwise, we check energy sufficiency in the other (down-regulation) direction.

5) The first step in preparing a charge bid is identifying the maximum capacity available for its execution in the respective delivery period:

$$P_{\text{ID,max}}\left(t_{\text{ID,start}}:t_{\text{ID,end}}\right)=-\left(\begin{array}{l}P_{\text{ch.max}}-P_{\text{FCR,cap}}\left(t_{\text{ID,start}}:t_{\text{ID,end}}\right)-\\-P_{\text{FRR,DOWN,man}}\left(t_{\text{ID,start}}:t_{\text{ID,end}}\right)\end{array}\right), \qquad (8)$$

where $P_{\text{ch.max}}$ is the total charging capacity of the BESS. At this point we do not consider voluntary FRR energy market bids since FRR energy market has a shorter GCT compared to ID (25 vs 60 min), thereby at the ID decision time no FRR obligations from the energy market should have been undertaken yet.

Finally, we calculate the power corresponding to the delivery of the required energy within Δt_{MTU}. The maximum of the two values corresponds to the charging bid that can be made:

$$P_{\text{ID}}\left(t_{\text{ID,start}}:t_{\text{ID,end}}\right)=$$
$$=\max\left(\begin{array}{l}P_{\text{ID,max}}\left(t_{\text{ID,start}}:t_{\text{ID,end}}\right),\\-\left(E_{\text{worst,UP}}\left(t:t_{\text{ID,end}}\right)-E_{\text{avail.UP}}(t)\right)\cdot\frac{1\text{h}}{\Delta t_{\text{MTU}}}\end{array}\right). \qquad (9)$$

6) Next, we check if the prepared buy bid is sufficient to meet the worst-case up-regulation requirements. If it is found to be insufficient, namely

$$\left|P_{\text{ID}}\left(t_{\text{ID,start}}:t_{\text{ID,end}}\right)\right|\cdot\frac{\Delta t_{\text{MTU}}}{1\text{h}}<E_{\text{worst,UP}}\left(t:t_{\text{ID,end}}\right)-E_{\text{avail.UP}}(t), \qquad (10)$$

then a warning is issued to the BESS operator. In principle, however, such a situation could only occur if the reserves to be provided by the BESS are oversized or if a worst-case scenario has already begun, in which case it is not necessarily a concern for the BESS operators since LER conditions give them ample time to recover post-alert state.

7) If a charge (buy) bid was not found to be necessary, we check if a discharge (sell) trade is needed to have the BESS ready for a worst-case down-regulation scenario realization.

The following steps are sufficiently similar as in the up-regulation case and thus will not be elaborated here.

8) The overall BESS management model should also include a specific subroutine for cases when BESS has been idle for a prolonged period and sequential ID trades to ensure minimum cycling conditions might have to be scheduled. However, due to space limitations, this has been left out of scope of this paper.

III. Validation

In the following example, we show the performance of the devised BESS SOC management strategy in a counterfactual scenario which includes prolonged activation of the committed FCR and FRR in the same direction. This allows validating the ability of the proposed approach to indeed withstand the occurrence of a worst-case scenario. While the real-life realization of such a scenario is a low-probability event, it would however be a high-impact non-compliance if the BESS failed to deliver reserves in accordance to its obligations.

We assume a BESS with 80 MW charge/discharge capacity, 160 MWh rated storage, 0.95 charge and discharge efficiencies, reservoir limits 10% and 90%. The BESS has to provide 8 MW of FCR and 32 MW of FRR in each direction. The selected parameters have been derived from the estimated reserve needs in the Latvian power system after desynchronization from the IPS/UPS in 2025 and from the specification of BESS that is being discussed for installation in Latvia [15].

In terms of reserve activations, for FCR we assume a six-hour frequency deviation profile as depicted by the brown line / right axis in Fig. 4 (NB: FCR providers observe a ±10 mHz dead-band followed by a proportional response reaching a full activation at ±200 mHz deviation). This profile is entirely artificial as its only purpose is to demonstrate that the devised BESS management strategy can ensure the reserves as expected. The FRR activations are likewise simulated to enforce a worst-case scenario realization (i.e. full activation for the entire six hours).

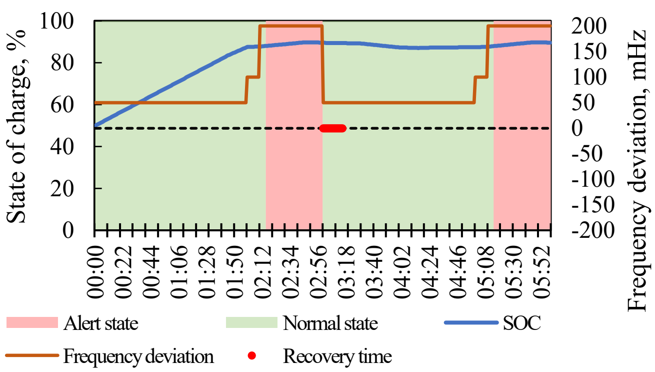

Figure 4. Simulated frequency deviation and LER SOC evolution

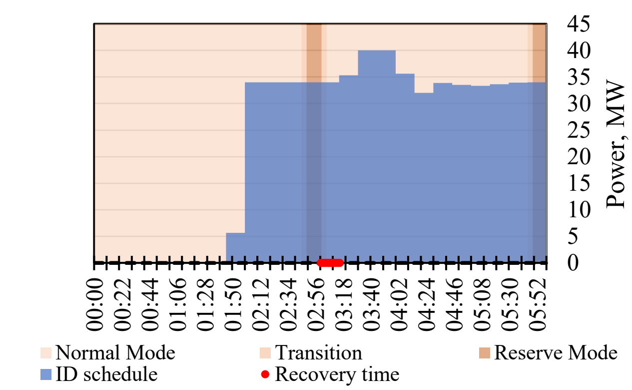

Figure 5. The schedule of corrective ID trades and FCR provision mode

In the simulated scenario, the BESS is able to continuously provide a 25% FCR activation during the normal state of the power system together with a full FRR activation without any issues. At 2:15 an alert state is declared due to frequency deviation exceeding 50 mHz for 15 minutes and 100 mHz for 5 minutes. The LER starts transition to Reserve Mode only at 2:44 when the 30 minute T_{minLER} criterion has been fulfilled. At 3:00 the alert state ends due to the frequency deviation dropping slightly below 50 mHz, at which point the 2-hour countdown for LER recovery starts. However, the LER already completes the recovery at 3:16, which means that it only required 16 min to be completed.

This is due to the robust nature of the storage management algorithm. It is also partly because of the fact that scheduled future ID deliveries are taken into account when evaluating the recovery conditions, provided that there is no risk of violating the SOC constraints at any point in the considered future time horizon. At 5:15 another alert state is declared and again the LER only starts transition to the Reserve Mode once 30 min of full activation have been endured.

From Fig. 4 it can be seen how the SOC trajectory approaches the upper constraint of 90% but does not violate it, instead remaining near it. Moreover, thanks to the scheduled ID deliveries (Fig. 5), the LER can even guarantee continued capability to provide the required FCR and FRR despite the SOC presently being close to the constraint.

IV. Conclusions

The validated market-based BESS SOC management strategy enables robust and reliable LER participation in FCR provision, meeting all the additional properties and regulatory provisions that FCR providers with LERs are subjected to in Continental Europe. It is also suitable for LERs providing both FCR and FRR. The devised strategy can be applied to prospective BESS installations in the Baltic power system after synchronization with CE and also elsewhere in the EU as it follows the most recent regulations to be adopted by the Member States. Moreover, the tool allows testing the impact of important technical parameters and market settings to aid in decision-making.

The crux of the offered approach is anticipating and preparing for the emergence of a worst-case scenario. Due to paper size limits, only a part of the overall BESS operational management strategy has been presented which, among other aspects, also manages the LER's transition between Normal/Reserve Mode and estimates the voluntary FRR energy bids. Hence, elaboration of the additional model components and features remains a venue for future work.

Furthermore, the mathematical model developed to simulate and validate the outlined strategy could be used in future work to study the impact of BESS technical parameters on their reserve provision capabilities as well as the impact of market regulations on BESS performance. The potential topics of future studies include BESS and reserve sizing, pros and cons of qualification as a LER, duration of the T_{minLER} criterion, recovery duration, market lead time etc. Moreover, the model can be extended to also consider diverse economic criteria to ultimately provide a comprehensive cost-benefit assessment of a LER-qualified BESS with varied control strategies.

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