Value-Stacking Battery Services Considering Frequency Markets and Grid-Based Voltage Support

Sigurd Sandvoll Vassmyr[a], Sigve Næss Walnum[a], Kasper Emil Thorvaldsen[a,b], Jonatan Ralf Axel Klemets[b]
[a]Department of Electric Energy, Norwegian University of Science and Technology - Trondheim, Norway
[b]Energy Systems, SINTEF Energy Research - Trondheim, Norway
Email: sigurd.s.vassmyr@ntnu.no, sigve.n.walnum@ntnu.no, kasper.e.thorvaldsen@ntnu.no, jonatan.klemets@sintef.no

***Abstract*—Battery Energy Storage System (BESS) can provide frequency support to the power system by adjusting active power flow, but this may negatively impact local voltage. To mitigate this, the BESS can simultaneously inject or absorb reactive power to regulate voltage levels. This work analyzes the reactive power compensation necessary for a BESS to participate in frequency markets while upholding local voltage levels during reserve activation. Using a LinDistFlow framework, a case study on the IEEE 33-bus system is performed for one month of operation for a grid-connected BESS that maximizes profit while upholding the voltage levels in the grid, and reserves reactive power to counteract worst-case voltage impacts. To have sufficient reactive power to counteract voltage impact during activation, the BESS reduces frequency market bids by 34.8%. This consideration impacts the profitability of the BESS, capturing the need to address these service costs with the distribution system operator (DSO).**

***Index Terms*— Battery energy storage system (BESS), Flexibility, Frequency markets, Reactive power compensation, Voltage support**

NOMENCLATURE

Sets

I : Set of buses, indexed by i
L : Set of transmission lines, indexed by i, j
H : Set of hours, indexed by h
R : Set of simulated grids, indexed by r

Parameters

$P^D_{i,h}$: Active power demand at bus i in hour h [MW]
$Q^D_{i,h}$: Reactive power demand at bus i in hour h [MVAr]
R_{ij}: Resistance between bus i and j [Ω]
X_{ij}: Reactance between bus i and j [Ω]
η: Battery charge/discharge efficiency (95%)
S^{max}: Max apparent power of battery [MVA]
SOC^{start}: Initial SOC
SOC^{min}: Minimum SOC allowed
SOC^{max}: Maximum SOC allowed
C_h: Spot price at hour h [EUR/MWh]
$C_h^{\text{FCR-N}}$: Price for reserving capacity at hour h [EUR/MW]
$C^{\text{vol,ch}}$: Volumetric Grid tariff for charging [EUR/MWh]
$C^{\text{vol,dch}}$: Volumetric Grid tariff for discharging [EUR/MWh]
C^{cap}: Capacity Grid tariff [EUR/MW]
B: Bus connected to BESS, $B \in I$
$\overline{V}, \underline{V}$: Voltage bounds [p.u.]

Variables

$p_{ij,h,r}$: Active power flow between nodes ij in hour h
$q_{ij,h,r}$: Reactive power flow between nodes ij in hour h
p_h^{res} : Reserved capacity for FCR-N market in hour h
p^{peak} : Monthly peak active power consumption
p_h^{flow} : Active power flow to/from BESS in hour h
$v_{i,h,r}$: Voltage at bus i in hour h for grid r
SOC_h : State of charge in hour h
p_h^{ch}, p_h^{dch} : Active power charge/discharge in hour h
$q_{h,r}^{ch}, q_{h,r}^{dch}$: Reactive power charge/discharge in hour h , grid r
$c^{\text{vol}}, c^{\text{cap}}$: Volumetric/Capacity grid tariff

I. INTRODUCTION

A. Motivation and Background

As the transition to a fully renewable energy system accelerates, the volatile nature of variable renewable energy sources (VRES) are causing an increasing amount of voltage and frequency challenges. With the adoption of VRES in the power system, it becomes increasingly challenging to balance demand and production, highlighting the need for more flexibility in the power system. A review article from 2020 [1] points to the distribution system operators (DSO) to take a more active role in ensuring network integrity while facilitating distributed energy resources (DER). In addition, the Norwegian transmission system operator (TSO), *Statnett*, highlights the necessity of investments in new flexible resources to balance the power system, and points to battery energy storage systems (BESS) as an important flexible asset [2].

Existing research on a distribution grid in Germany has shown that BESS can be an effective alternative to grid expansions by providing and absorbing reactive power to improve voltage levels when increasing hosting capacity for PV [3]. However, when acting purely on price-based signals, BESS has also shown to cause voltage problems when operation coincides with PV-production [4], highlighting the need for network constraints on BESS-operation. On the other hand,

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a white paper based on practical experience from a grid-connected battery in Norway [5] found it both economically and technically viable to participate in fast frequency reserve (FFR) markets while also providing voltage support to the distribution grid. Although BESS is showing great promise as a flexible resource, questions are still present regarding operational decisions, profitability, market participation and contribution to voltage fluctuations. Answering these questions are essential for increased implementation of BESS as a flexible grid-resource for both the TSO and the DSO.

B. Literature Study

Traditionally, voltage levels has been regulated using On-Load Tap Changers (OLTC), capacitor banks, Static Var Compensators (SVC), and Static Synchronous Compensators (STATCOM) [6]. However, as most VRES, including BESS, uses inverters, the reactive power capabilities of these can also be used for voltage regulation. Varma et al. proposes to use Photovoltaics (PV)-inverters as STATCOMs during nighttime for voltage regulation [7]. Cheng et al. [8] explores the use of Vehicle-to-Grid (V2G)-technology for voltage regulation, and is able to reduce the risk of both over- and under-voltage. In a different study [9], the authors utilizes BESS for voltage regulation in a grid with PV generation. The results shows that a BESS is able to regulate voltage fluctuations in the grid without significantly affecting the battery's State of Charge (SOC) and charging cycle. Another study on BESS [10] underlines how BESS can be used in weak grids as an alternative to traditional grid investments, but found that the investment is costly when only providing voltage support to the grid.

In addition to grid voltage regulation, grid-connected batteries are able provide multiple services simultaneously, a concept known as battery value stacking. Hashimi et al. [11] propose a method for value stacking by integrating energy arbitrage and Power Factor (PF) correction. The key findings indicate that PF correction is largely decoupled from energy arbitrage and does not significantly impact the revenue generated from energy arbitrage. Berg et al. [12] seek to quantify the cost of providing voltage stabilization to the DSO of an energy community with a battery, and found an increase in costs of only 0.12 % when providing voltage stabilizing services with active power. Furthermore, Tamrakar et al. [13] proposes a framework for real-time BESS dispatch to enable both energy arbitrage and power quality services. The study shows that the BESS can provide PF-corrections and voltage stabilization to the grid, with little negative impact on profits from energy arbitrage.

Grid-connected BESS can also be used in frequency markets. Hu et al. [14] found that BESS can be economically viable in many major European Frequency containment reserves (FCR)-markets, but struggles to return the investment in the Norwegian market while solely participating in either the FCR market or with energy arbitrage. The authors in [15] considers the optimal sizing and siting for a BESS participating in the frequency containment reserve for normal operation (FCR-N) market while also performing energy arbitrage in a weak distribution grid. The study shows that it is more profitable to both participate in FCR-N and do energy arbitrage than only trading on the day-ahead spot prices, and finds that a large energy capacity is more profitable when participating in the frequency market.

C. Contribution

Battery systems can provide multiple services to the grid simultaneously, giving good range of flexible use. Value stacking of BESS can be achieved with providing local voltage support while enabling energy arbitrage and participation in frequency markets. However, should frequency market activation occur from the BESS, the change in active power could lead to local voltage violations. Especially when activation occurs for longer periods of time, like activations in the FCR-N market, local voltage violations should be addressed. This can be solved through reactive power compensation, having sufficient reactive power available to cancel out the voltage impact in case of activation. To the authors' knowledge, limited research has been conducted on how reactive power compensation can be used to mitigate voltage impact from frequency market participation for a local BESS unit that offers voltage support. This work aims at addressing reactive power compensation necessary for frequency market participation and operational impact for a BESS. The main contributions are the following:

- A conceptual model of a BESS in a distribution grid is created that maximizes profit from FCR-N- and day-ahead-market participation. The model operates the BESS considering local voltage levels in the grid during operation and possible FCR-N activation, with the latter being handled with available reactive power.
- The model is demonstrated on a medium-voltage (MV) distribution grid, showcasing the changes in BESS-operation needed to successfully participate in the FCR-N market with sufficient reactive power to compensate any activation volume.

The remainder of this work is structured as follows. Section II outlines the methodology used in this study. The case study is introduced in Section III, followed by the results in Section IV. Finally, Section V presents concluding remarks based on the findings in this study.

II. METHODOLOGY

The goal of this methodology is to propose a conceptual approach for utilizing BESS in distribution grids to offer grid services. This includes enabling energy arbitrage and participation in the frequency market, while also providing local voltage support, where the latter also applies during reserve market participation. This study proposes a method for operation of BESS that considers voltage deviations resulting from activation in the frequency market, by ensuring sufficient reactive power capabilities available.

The methodology chosen to address these challenges is an optimization problem on a medium voltage grid with a BESS installed. The optimization problem considers optimal power flow, where a Linear Distribution Flow (LinDistFlow) OPF-model is being used to capture the dynamics of the grid [16], [17]. The method neglects line losses in the power flow equations (2)-(5), but still provides a good voltage estimate for radial distribution grids. The BESS can provide voltage support considering both active and reactive power, represented by the apparent power limitations of the inverter in Eq. (9). An optimization model is formulated with a linear objective and constraints that are linear, except for Eq. (9), which is quadratic, making the problem non-linear. The model simulates the grid under varying loads and optimizes profits from energy arbitrage and participation in the FCR-N market, while upholding local voltage levels.

A. Worst Case Grid Modeling

To prohibit the grid from facing voltage issues caused by activation in the frequency market, worst case scenarios are simulated each time-step to ensure that there is sufficient capacity available to mitigate voltage instabilities. This is achieved by modeling three grid scenarios that represents the highest possible active power change in the grid due to FCR-activation within the optimization problem. This change is a consequence of maximum reserve market activation, that could occur in both directions, directly affecting BESS operation. The dynamic voltage change due to OPF will then be accounted for, and captures the necessary reactive power compensation that must be available to counteract the voltage impact in the whole grid. In total, three grid scenarios are simulated for each time step, where the reserved capacity is added to the active charge or discharge for the BESS in the virtual grids.

- **Grid Scenario 1 (G1):** Actual physical grid. The BESS decides its operation and reserve capacity bid.
- **Grid Scenario 2 (G2):** FCR-N up activation equal to the bid for reserve capacity of G1, the active power of BESS from G1 changes to accommodate activation.
- **Grid Scenario 3 (G3):** FCR-N down activation equal to the bid for reserve capacity of G1, the active power of BESS from G1 changes to accommodate activation.

The virtual grids are only utilized to ensure that the voltage level remains within the operational band in case of FCR-N-activation. It is assumed that there is no net SOC change by participation in the frequency market. The optimization model considers a whole month of operation where prices and load at each time step are known.

B. Optimization problem

1) *Objective function:* The objective function described in Eq. (1) maximizes the profit from participating in the frequency and spot-price markets, while minimizing the grid tariff cost.

$$\max z = \sum_{h \in H} \left(C_h \cdot (p_h^{dch} - p_h^{ch}) + C_h^{\text{FCR-N}} \cdot p_h^{res} \right) - c^{\text{grid tariff}} \quad (1)$$

2) *Power Flow Constraints:*

$$p_{ij,h,r} = \sum_{k:j \to k} p_{jk,h,r} + P_{j,h}^{D} + \delta_{h,r}, \quad \forall h \in H, r \in R$$

$$\delta_{h,r} = \begin{cases} 0, & (i,j) \in I, j \neq B, \\ p_h^{flow}, & j = B \end{cases} \quad (2)$$

$$q_{ij,h,r} = \sum_{k:j \to k} q_{jk,h,r} + Q_{j,h}^{D} + \gamma_{h,r}, \quad \forall h \in H, r \in R$$

$$\gamma_{h,r} = \begin{cases} 0, & (i,j) \in I, j \neq B, \\ q_{h,r}^{ch} - q_{h,r}^{dch}, & j = B \end{cases} \quad (3)$$

$$v_{i,h,r} - v_{j,h,r} = 2\big(R_{ij} p_{ij,h,r} + X_{ij} q_{ij,h,r}\big)$$
$$,\forall h \in H, i,j \in I, r \in R \quad (4)$$

$$\underline{V}^2 \leq v_{i,h,r} \leq \overline{V}^2, \quad \forall h \in H, r \in R, i \in I \quad (5)$$

3) *Battery Constraints:*

$$SOC_h = \eta \, p_h^{ch} - \frac{1}{\eta} p_h^{dch} + SOC_{h-1}, \quad \forall h \in H, h \neq 1 \quad (6)$$

$$SOC_h = \eta \, p_h^{ch} - \frac{1}{\eta} p_h^{dch} + SOC^{\text{start}}, \quad h = 1 \quad (7)$$

$$SOC^{min} \leq SOC_h \leq SOC^{max}, \quad \forall h \in H \quad (8)$$

$$(S^{max})^2 \geq (p_h^{flow})^2 + (q_{h,r}^{ch} - q_{h,r}^{dch})^2, \quad \forall h \in H \quad (9)$$

$$p_h^{flow} = \begin{cases} p_h^{ch} - p_h^{dch} & r = 1 \\ p_h^{ch} - p_h^{dch} - p_h^{res} & r = 2 \\ p_h^{ch} - p_h^{dch} + p_h^{res} & r = 3 \end{cases} \quad (10)$$

4) *FCR-N market reservation Constraints:*

$$SOC_h - p_h^{res} \geq SOC^{min} \quad (11)$$

$$SOC_h + p_h^{res} \leq SOC^{max} \quad (12)$$

$$p_h^{res} \leq p_h^{ch} + P_{dch}^{max} - p_h^{dsch} \quad (13)$$

$$p_h^{res} \leq p_h^{dch} + P_{ch}^{max} - p_h^{ch} \quad (14)$$

5) *Grid Tariff:*

$$c^{\text{grid tariff}} = c^{vol} + c^{cap} \quad (15)$$

$$c^{vol} = \sum_{h \in H} p_h^{ch} \cdot C^{vol,ch} + p_h^{dch} \cdot C^{vol,dch} \quad (16)$$

$$c^{cap} = p^{peak} \cdot C^{cap} \quad (17)$$

$$p^{peak} \geq p_h^{ch}, \forall h \in H \quad (18)$$

Active and reactive power flow in all nodes in the system are given in Eq. (2) and Eq. (3), including the node connected to the BESS. Voltage drops for LinDistFlow and voltage limits are given in Eq. (4) and Eq. (5). BESS energy balance is given Eq. (6) and for initial condition in Eq. (7). Eq. (8) limits SOC boundary based on technical limits. Eq. (9) calculates apparent power and the relationship between active and reactive power for the BESS. Any FCR-N market volume is accounted for in each grid scenario, which is only dependent on the active power change from the actual grid scenario. Reactive power is not connected between grid scenarios, enabling adjustments to compensate the voltage impact from activation, limited by the apparent power capacity. Eqs. (11)-(14) ensures symmetrical reservation in the FCR-N market, and makes sure that the BESS have sufficient storage and inverter capacity available in case of activation. The grid tariff, containing a volumetric cost and a monthly demand charge cost for peak import, are defined in Eqs. (15)-(17) [18].

III. Case study

The case study examines the IEEE 33-bus system [19], [20] shown in Figure 6 over a one-month period, with the base load scaled to match the Norwegian consumption pattern for January 2024 from ENTSO-E [21]. The spot-price data and the FCR-N prices are for the same month from price zone NO3 in Norway [22]. The load has been scaled to simulate a weak grid with frequent occurrence of voltage below 0.9 p.u., as shown in Figure 4. In this study, electricity prices, FCR-N reservation prices, and load demand are deterministic and known for the whole period, showcased in Figure 5. The BESS has an storage capacity of 4 MWh, the inverter is rated for 1 MVA both ways, and a charge/discharge efficiency of $\eta = 95\%$.

The volumetric grid tariff when the BESS is charging are based on the prices from the Norwegian DSO *Tensio* for high voltage large costumers at 3.5 EUR/MWh [23]. During discharging, the volumetric tariff is set to 1.2 EUR/MWh by the TSO [24]. The monthly demand charge capacity-based grid tariff is assumed linear, set at 5128 EUR/MWh/h based on the highest single-hour peak import level during the month [23].

To analyze the impact of providing voltage support to the grid while also participating in the FCR-N and day-ahead markets, several cases are investigated. In all cases, the BESS is located at the outermost bus, Bus 18, in the system in Figure 6. The Base Case (BC) considers trading in the spot- and FCR-N market without considering the local voltage bounds. Case 1 (C1) offers local voltage support during normal operation to uphold voltage limits, but does not consider any possible voltage problems from FCR-N market activation. In Case 2 (C2), the BESS offers local voltage support, and makes sure sufficient capacity is available for reactive power compensation to stabilize voltage levels in case of FCR-N activation. The method does not include FCR-N activation, but aims at establishing a worst-case model for operating a BESS while participating in frequency markets while providing grid services.

IV. Results & Discussions

The results illustrates the impact of considering local voltage during frequency market participation, both on operational decisions and revenue potential from value stacking services.

A. Operational impact on local voltage

The operation of the BESS is significantly influenced when considering the worst case activation in C2. Figure 1 presents boxplots of the voltage levels across different cases at bus 18 in normal operation and in the worst case activation when FCR-N down regulation is requested in scenario G3. During normal operation in BC, bus 18 experiences a total of 219 hours of undervoltage, whereas no undervoltage occurs during normal operation in C1 and C2. In the worst-case scenario G3, the voltage at bus 18 drops dramatically for C2, as shown in Figure 1. In BC and C1, the voltage can drop below 0.82 p.u., whereas in C2, it remains above 0.9 p.u. at all times. Using reactive power compensation, C2 manages to uphold the voltage level during normal operation, using available reactive power to negate any voltage impact caused by FCR-N down regulation. This shows that the voltage levels are under control given any FCR-N activation.

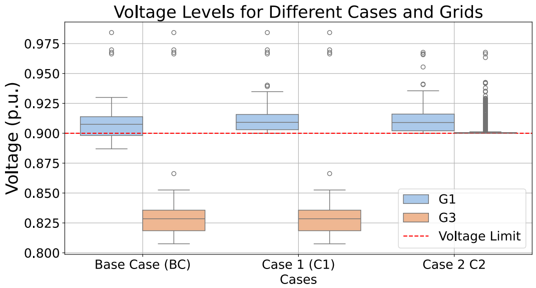

Fig. 1: Voltages at bus 18 for actual grid and worst case scenario

Figure 2 presents the voltage levels at bus 18 for normal operation and worst-case operation in C2. G3 represents the grid for FCR-N down-regulation, while G1 is the actual grid where no activation is assumed. When FCR-N regulation causes the BESS to increase intake of active power, potential for local undervoltage is dramatically amplified. Reactive power compensation is performed to ensure that the voltage level is satisfactory at all times in G3, and the model ensures sufficient reactive power available for G3. As a result, G3 is stable at 0.9 p.u. voltage for most hours, whereas G1 has higher voltage levels, which is an expected result without FCR-N activation.

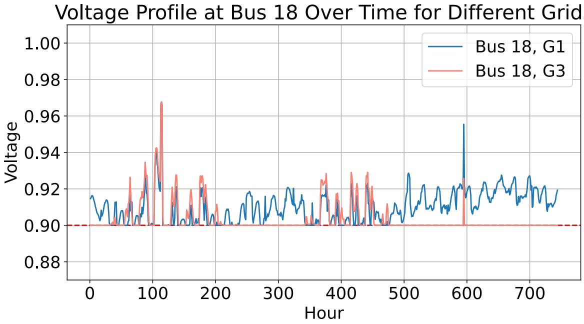

Fig. 2: Voltages in G1 and G3, Case 2

B. Changes in Market Participation and Revenue

Figure 3 illustrates the FCR-N bids in the different cases, as well as the reserved reactive power compensation quantity in C2. When local voltage is considered and activation impact is neglected in C1, the BESS maintains voltage levels above 0.9 p.u. during normal operation. The bidding strategy in the FCR-N market is only restricted by the voltage levels under normal operation, resulting in a bidding strategy similar to the BC. However, when activation is taken into account in C2, the distribution on the left-hand side in Figure 3 reveals major changes in the FCR-N bidding strategy compared to BC and C1. Reactive power compensation in case of activation limits FCR-N participation for C2 due to the apparent power limitations of the inverter. On the right-hand side of Figure 3, the reserved reactive power for C2 is shown, which is causing the decrease in FCR-bids. The BESS must reserve a total of 541.23 MVAr over the entire month to compensate the voltage impact when participating in the FCR-N market, which is neglected in C1. The ratio between reserved active power in the frequency market and reserved reactive power is on average 0.89 for C2. This means that the BESS must reserve 1.12 kVAR reactive power per kW bid into the frequency market on average, which captures the X/R-ratio of this grid and how it values reactive power compensation.

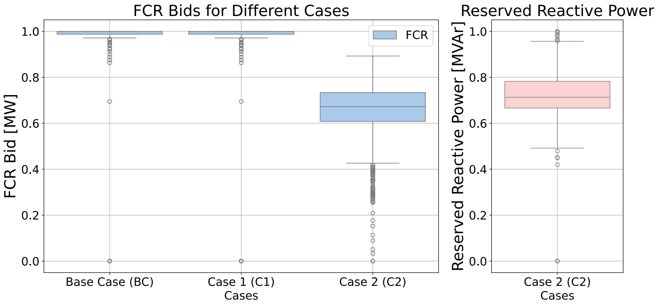

Fig. 3: FCR-N bids for different cases, and Reserved Reactive Power in Case 2

TABLE I: Overview of economic and operational results

Case	**Total income [EUR]**	P^{ch} $[MWh]$	P^{dch} $[MWh]$	Q^{dch} $[MVARh]$	P_{FCR}^{res} $[MW]$	p^{peak} $[MWh/h]$
Base Case	14389.898	3.8753	4.4950	1.3180	734.7480	0.01246
Case 1	14389.895	3.8753	4.4950	37.6206	734.7479	0.01246
Case 2	10306.99	17.2018	16.7281	36.3729	480.7539	0.04532

Table I shows that BC and C1 acquires almost the exact same revenue, while the revenue drops by approximately 28.4 % when reactive power compensation is included in C2. The table also shows that the BESS operates almost identically in the first two cases, and the small changes are primarily due to respecting the voltage limits in C1, resulting in a clear difference in the total amount of reactive power discharged from the BESS. The revenue decrease for C2 is mainly because the BESS cannot bid the maximum amount in the FCR-N market from reactive power compensation, and increased cost from peak import of electricity. This causes a decrease of FCR-N participation by 34.8 %, which limits the revenue potential of the BESS. The reactive discharge is almost the same between C1 and C2, indicating that the reactive discharge is largely unaffected by the operation of the BESS. The slightly lower reactive discharge in C2 is caused by the difference in energy arbitrage participation, as the battery can provide some active power in C2, due to higher spot-market participation, to mitigate voltage problems, reducing the total reactive discharge over the month.

C. Discussion

In C2, while revenue decreases compared to the previous cases from FCR-N participation, the energy arbitrage volume increases. With limited capacity to fully utilize FCR-N participation and the compensation required when bidding, making use of the spot-price variations is prioritized more. In Figure 7, the SOC of the BESS in all cases are showcased, clearly indicating that the battery system in C2 is more active. When the BESS must consider the local voltages in case of activation, it reserves reactive power to avert potential voltage problems. As a result, this causes the BESS to reserve less capacity in the frequency market. Furthermore, to compensate for the losses in profit, the battery performs more energy arbitrage, even though it is less profitable than participating purely in the frequency market. All cases sees a very low peak charge compared to the power capacity of the BESS. This indicates that the magnitude of capacity tariff makes it more profitable to wait for the largest spikes in spot-price, rather than constantly cycling the battery. The capacity tariff is constraining how much the battery is utilized, and reduction in the capacity tariff would yield more active battery operation, especially for C2 which is limited in FCR-N activation due to reactive power compensation. The slight difference in peaks comes from C2 prioritizing energy arbitrage more, as FCR-N participation is constrained.

The FCR-N participation in BC and C1 results in a significantly higher risk of voltage violations. However, the probability of activation is up for discussion. Figure 1 clearly indicates that the system would experience voltage issues in the event of activation that leads to higher intake of active power. As the BESS is tasked with providing voltage support, the extra revenue gained in C1 compared to C2, is of little value if the voltage drops to unacceptable levels when the reserves are activated. If the DSO wants to use BESS to offer voltage support, but also allow value stacking of services to increase revenue, then it is important to ensure the services doesn't affect or limit each other. This also brings up the resulting remuneration the BESS operator should expect from offering voltage support, to reflect part of their revenue losses.

V. CONCLUSION

This work investigated how a grid-connected BESS can be utilized on a distribution grid to offer voltage support to the DSO, while simultaneously value staking from energy arbitrage and frequency market participation to the TSO. A Non-Linear Program (NLP) was formulated, where a LinDistFlow-OPF method was utilized to capture the dynamics of the grid. Voltage impact from frequency market activation was considered by capturing the grid impact in case of active power change, using available reactive power to compensate the resulting voltage change to ensure acceptable voltage levels.

This study analyzed Battery Energy Storage System (BESS) operation over a month in a distribution grid, finding limited revenue decrease from FCR-N participation when only providing voltage support. However, considering voltage from FCR-N down activation led to a 28.4% revenue drop and a 34.8% reduction in FCR-N participation. The need for reactive power to manage voltage changes caused the BESS to shift from purely reserving capacity in the frequency market to performing more energy arbitrage. This analysis highlights the potential for value stacking grid services and the importance of sufficient reactive power to compensate for active power changes from frequency markets.

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APPENDIX

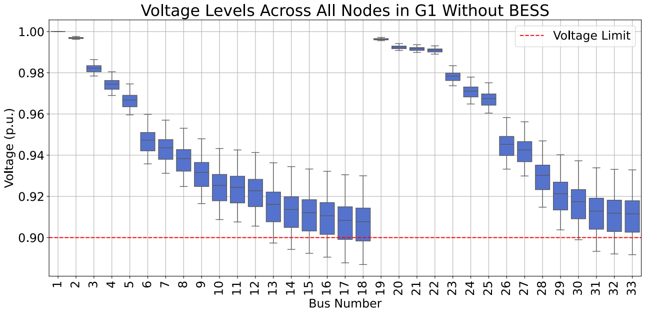

Fig. 4: System voltages without connected BESS

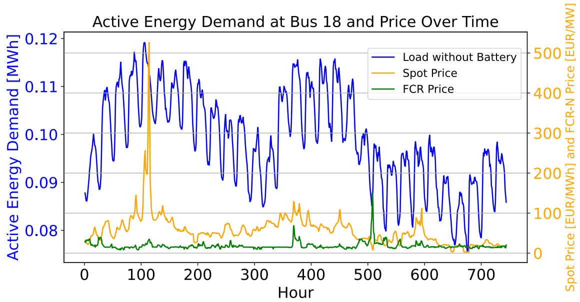

Fig. 5: Load, spot price and FCR-N price in bus 18

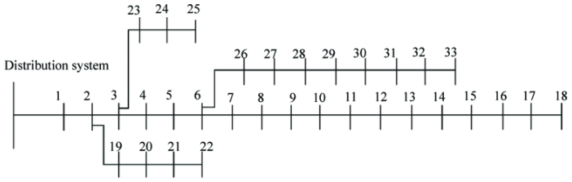

Fig. 6: IEEE 33-bus system, from [20]

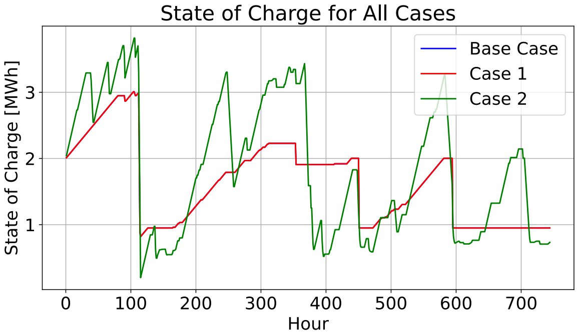

Fig. 7: SOC for all cases.