# Voltage Fluctuations of Battery Storage Systems Providing Fast Frequency Response Services in the UK

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***Abstract*— Within the UK there has been a significant increase in large scale Battery Energy Storage Systems (BESS) that provide services such as Fast Frequency Response (FFR) to National Grid ESO, for the GB system. At present, BESS units are installed by developers at substations with spare capacity, and their size and locations are not being centrally planned, and due to network connection costs, most developers are connecting the BESS units to the distribution network rather than to the transmission network. A concern has been identified that during FFR operation, multiple BESS units in an area would all operate nearly simultaneously, leading to large dynamic power swings in the systems creating problems for voltage Quality of Supply (QoS). This paper examines how the simultaneous operation of multiple BESS units in adjacent substations, can create adverse effects on the distribution system voltage that may not be apparent when considering operation of BESS units individually. The paper develops a simple test network which is representative of two substations on the Distribution Network in the UK; then uses DIgSILENT Powerfactory to examine the system voltage profile for BESS operation for several import-export and export-import cases.**

***Keywords—Voltage Stability, Battery Storage, Voltage Disturbance, Frequency Response and Renewable Penetration.***

## I. Introduction

### A. Background

Battery energy storage schemes are increasingly seen as performing a key role in managing the transition to a zero-carbon renewable grid, by National Governments, Transmission System Operators (TSO) and Distribution Network Operators (DNO). The use of BESS in electrical networks is seen as a way of providing several flexible services, that can improve overall grid stability and performance for future energy scenarios with low inertia and a high percentage of Inverter Based Generation (IBG)..

Whilst the large range of services offered by a BESS are potentially of great benefit to DNOs and TSOs, network operators also face several challenges in system planning, as BESS units inherent flexibility makes planning and analyzing their behavior in a large electrical network complex. This complexity is due to the four-quadrant capability of a BESS as well as their ability to rapidly switch between different services, potentially switching from full active and reactive power import to full active and reactive power export within a <1s timeframe.



### B. Contributions to Knowledge

The contribution to knowledge presented in this paper is an attempt to frame some of the issues and challenges of large-scale deployment of BESS units within the UK GB network, in relation to voltage profile and QoS. The paper presents a structured way of analyzing voltage QoS issues, during BESS operation for FFR events, using a simple test network, representative of two interconnected 132/33/11 kV substations, with a configuration common within the UK.

### C. BESS Roles within the UK GB System

The UK TSO (National Grid ESO) operates within a very dynamic regulated electricity market and have currently requested several new services to the market, aimed to ensure that the UK GB electrical system remains stable and within the required operating limits [1]. The primary service is known as Dynamic Containment (DC), which is a form of FFR; and, in addition to this some newer services have recently been added, known as Dynamic Regulation (DR) and Dynamic Moderation (DM). The DM service is intended to allow rapid deployment of power to meet short term power imbalances within 1s, whilst the DC service is intended to provide rapid power delivery to meet major power imbalances (post fault), within 1s. The DR service is much slower acting and intended to meet shortfalls in demand and generation over a 10s time period. A summary of the services can be seen in Table 1 and the DC and DM services seen in Figure 1.

Within the UK, one of the problems faced by large scale BESS deployment is that location and sizing of the BESS units, is left to free market opportunities and are not centrally planned. Therefore, developers are locating BESS units at any available substation with sufficient spare capacity. Furthermore, because of the high connection costs for the transmission network and long lead in times, many developers are choosing to develop smaller BESS units and connect them to the distribution network. This can therefore place a significant burden on the host DNO in terms of analyzing the dynamic response to BESS services such as FFR, as multiple BESS units could operate simultaneously and negatively affect customers voltage Quality of Supply.

TABLE I. NATIONAL GRID FREQUENCY RESPONSE SERVICES

| **Requirement** | **Dynamic Regulation (DR)** | **Dynamic Moderation (DM)** | **Dynamic Containment (DC)** |
|---|---|---|---|
| Speed of Response | 1 s | 10 s | 1 s |
| Service | Pre-Fault | Pre-Fault | Post Fault |
| Delivery Range | ±0.1 Hz to 0.2 Hz | ±0.015 Hz to 0.2 Hz | ±0.015 Hz to 0.5 Hz |
| Deadband | ±0.015 Hz | ±0.015 Hz | ±0.015 Hz |
| Initial linear range (delivery %) | ±0.015 Hz to 0.1 Hz | ±0.015 Hz to 0.2 Hz | ±0.015 Hz to 0.2 Hz |
| First Knee Point | ±0.1 Hz | None | ±0.2 Hz |
| Second linear range (delivery %) | ± 0.1 Hz to 0.2 Hz | None | ±0.2 Hz to 0.5 Hz |
| Full Delivery Point | ±0.2 Hz | ±0.2 Hz | ±0.5 Hz |
| Max Ramp Start | 0.5 s | 2 s | 1 s |

Furthermore, it is a requirement of DNOs that voltage disturbance on the public network is contained to the limits defined within the ENA ER P28/2 standard [1], which is in turn derived from various parts of the BS EN 61000 series of standards and specifically IEC 61000-3-7 [2]. The impact of multiple BESS units installed throughout a local region all responding to the same, or similar frequency response triggers raises several concerns on maintaining a satisfactory voltage profile on the DNO network during system disturbances, which is limited to a Step Voltage Change (SVC) of ±3%.

One of the problems faced in planning for voltage disturbances on the DNO network, is that the UK regulatory market for these services is flexible and competitive, meaning that different BESS units on the system are likely to be providing different services, and that the need for these services are unpredictable, which means that there are a number of potential scenarios where a BESS could potentially be charging, and be required to halt and move to a full export mode. Further complications could potentially arise with asset owners' revenue stacking multiple National Grid services in addition to the DC/DM/DR services.

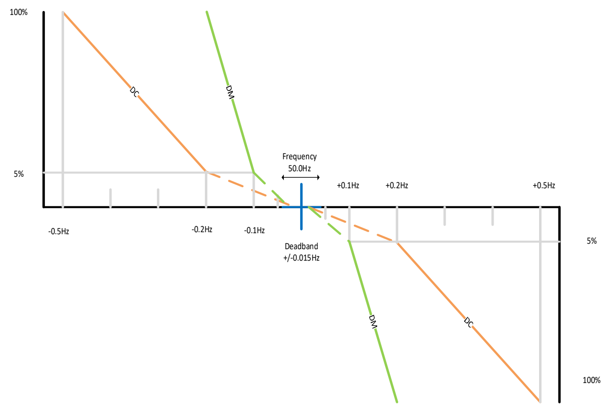


*Figure 1 DC and DM Services*

## II. BACKGROUND

### A. Literature Review

BESS units represent an interesting technical problem for power system analysis, because when considered as a slow acting unit, the analysis methods and theory are well known and understood in terms of simple active and reactive power flows [4], [5] & [6].

In shorter time periods of around a few seconds, the behavior can be analyzed with simple RMS methods, whilst when performing very fast acting so-called synthetic inertia or FFR services, the behavior of the control systems becomes significant and the use of EMT methods may become necessary, particularly when considering interaction between related control systems of adjacent BESS units or BESS units acting as Grid Forming Inverters [7] and [8].

A general literature review carried out, indicated, that there is an extensive amount of literature related to battery energy storage systems in relation to voltage stability of renewable energy sources, inertia, frequency stability and FFR type services, such as the IEEE [9], [10], CIGRE [7] & [11], NREL, NERC [12] & [13] and individual researchers [14], [15] & [16].

Several research activities have been carried out on optimal location of BESS units within a system [16] & [17]. However, to date limited analysis of voltage QoS due to multiple BESS operation in a whole system network appears to have been carried out. One possible reason for this lack of literature on the subject is that in the majority of countries BESS deployment has been either standalone large-scale projects, or at a smaller scale microgrid level, as opposed to a large volume of distributed independent storage units, and have the units have been assessed as individual projects.

## III. BACKGROUND THEORY

### A. Overview

The general concept of a static and dynamic load flows is covered extensively in a number of different textbooks, such as [4], [5] & [6]. As noted earlier, one complication with a BESS is that it can act as both a load and a generator. If the BESS is initially importing power, when it receives a signal to export, the BESS unloads, and starts exporting power, and becomes a generator; similarly, if the BESS is exporting power, it may receive a signal to begin importing power and would need to reduce generation to zero and begin acting as load. As the ramp occurs, the BESS gradually changes from one operating mode to another, there will be an instant when there is zero power flowing down the line, when the BESS is in a no-load condition.

### B. Circuit Theory

If the upstream DNO system is represented as a Thevenin equivalent, with an ideal voltage source is shown behind an impedance $Z_{Source}$, a model of a line $Z_{Line}$ and a model of a load $Z_{Load}$ are shown, with two busbars Vs and Vr. The active power flow between the busbars for the BESS operating as a generation is given by equation (1 and depends on the differing reference voltage. The reactive power flow between the two busbars is given in equation (2) and depends on the differing voltage magnitude between the two busbars.

The system voltages can be expressed in terms of simple voltage drops down the various branches of the radial network. In networks with a high grid X/R ratio, the reactance of the external grid is high, and resistance of the external grid is low; and in networks with a low X/R ratio, the reactance of the external grid is low, and the resistance of the external grid is high.

The differing characteristics of the grid impedance, impact the behavior of the system and the grid element, as the voltage dropped across the source Thevenin impedance will vary, and it is this variation that influences the overall voltage drop experienced at the load terminals. Formally this can be expressed by considering the total current flowing in the system in relation to the source voltage (3) and total impedance as (4).

$$P_r = \frac{V_s V_r}{X} sin\delta \quad (1)$$

$$Q_r = \frac{V_s V_r cos\delta}{X} - \frac{V_r}{X} \quad (2)$$

$$\underline{I} = \frac{E}{\underline{Z_T}} \quad (3)$$

$$\underline{Z_T} = Z_{Source}\angle\emptyset_1 + Z_{Line}\angle\emptyset_2 + Z_{Load}\angle\emptyset_3 \quad (4)$$

## IV. Test Network

### A. Base Model

To represent the dynamics of a DNO network, a simplified representative model of a typical UK system was developed. The upstream system consisted of an incoming 400 kV Grid Element, with a fixed fault rating of 20kA, an X/R ratio of 20, and 2x 400/132 kV, 280 MVA, Z = 18%, Transformers connected to the 132 kV busbar of Substation 1. Substation 1 consists of 2 × 132/33 kV, 90 MVA, Z = 12.5% transformers; 2 × 33 kV NERs; 2 × 33/11 kV, 25 MVA, Z = 10% transformers; 20MW static 11kV load and 5MW asynchronous machine load. In addition to the basic configuration 2 × 50 MW BESS units are connected to each of the 132 kV busbars, and 2 × 25 MW BESS units are connected to each of the 33 kV busbar. Substation 2 is identical to Substation 1, but is supplied a via a single circuit, 25 km, 132 kV cable, in order to represent a substation further out on the transmission network, with lower fault levels and X/R ratios.

All transformers are provided with a typical On Load Tap Changer (OLTC) of ±10%, in 1.25% step taps, with the OLTC tome constant set to occur outside of the BESS power ramp operation. The cable line and parameters are set artificially to give is based on a DIgSILENT standard library configuration to give a fault level of approximately 50% of Substation 1 132 kV Busbar. Maximum and minimum fault level cases are achieved by setting the various transformers out of service. The primary (33/11 kV) transformers are all left in service. The calculated fault levels for each of the main busbars is shown in Table II, and the test network is shown in Figure 2.

TABLE II. Model Fault Levels

| **Busbar** | **Maximum Fault Level** | **Minimum Fault Level** |
|---|---|---|
| 132kV Bus #1 | 14.5 kA | 8.1 kA |
| 132kV Bus #2 | 6.4 kA | 4.9 kA |
| 33kV Bus #1 | 19.5 kA | 12.1 kA |
| 33kV Bus #2 | 14.6 kA | 10.1 kA |
| 11kV Bus #1 | 21.7 kA | 18.2 kA |
| 11kV Bus #2 | 19.8 kA | 16.9 kA |

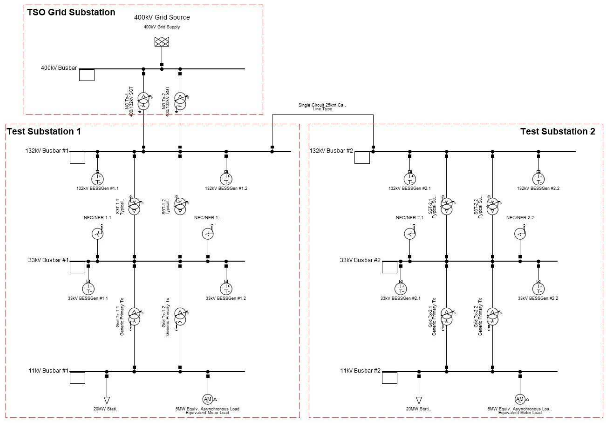

*Figure 2 DIgSILENT Test Model*

### B. Scenarios

To analyze the system response to the BESS operation during a FFR event, several different scenarios were considered:

1. Substation 1 – 132 kV BESS operation in isolation at minimum fault case for import and export cases
2. Substation 2 – 132 kV BESS operation in isolation at minimum fault case for import and export cases
3. Substation 1 – 33 kV BESS operation in isolation a minimum fault case for import and export cases
4. Substation 2 – 33 kV BESS operation in isolation for at minimum fault case for import and export cases

In each scenario the BESS units are triggered at 1s simultaneously from an initial starting value and then ramped up to full power over a 1s duration in a linear rate. Due to the large volume of study cases, the results for the minimum fault level cases are shown, and the maximum fault level cases are omitted.

### C. Scenario 1 – BESS Operation at 132kV on Substation 1

In this scenario 1a, all four 132 kV BESS units are initially importing 50 MW and 0 MVAr. The two 132kV BESS at Substation 1 are triggered to correspond to an underfrequency event and ramped to full export within 1s. In Scenario 1b, the BESS units are exporting 50MW and 0MVAr and are triggered to respond to an overfrequency event and ramped to full import power within 1s. Both scenarios consider system minimum fault levels.

Several interesting results can be seen from the results shown in Figures 3 and 4 above. In Figure 3, the voltage rises on all the main busbars at Substation 1 as would typically be expected, but a corresponding slightly larger magnitude voltage disturbance is also seen at Substation 2. This is due to the direct connection between the two systems, and the lower relative system strength of Substation 2.

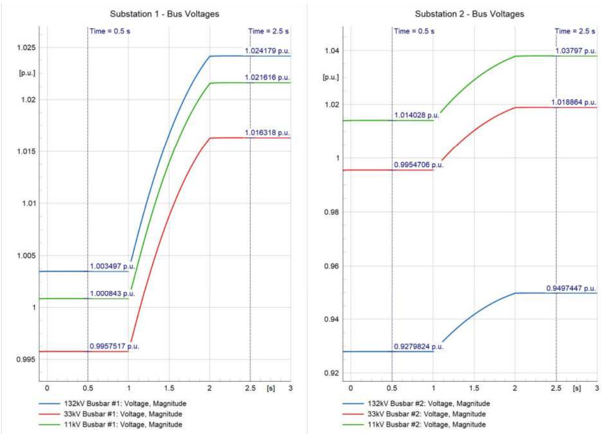


*Figure 3 Scenario 1a Results – Import to Export*

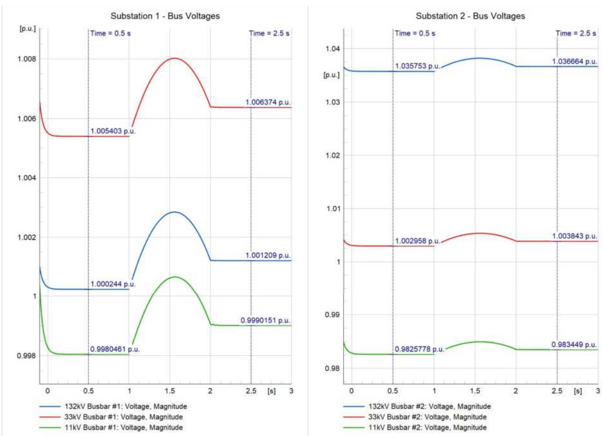


*Figure 4 Scenario 1b Results – Export to Import*

At Substation 1, the voltage also unexpectedly rises very fractionally. On inspection this is due to the output of the BESS at Substation 1, rising to meet the demand of the BESS at Substation 2, leaving only a small power flow to the 11 kV connected static and motor loads. However, a small transient voltage swell occurs Substation 1 during the power ramp, before settling once the ramp has completed. A summary of the key voltage variations can be seen in the Table III.

TABLE III. SCENARIO 1 RESULTS

| **Busbar** | **Import to Export Voltage Variation** | **Export to Import Voltage Variation** |
|---|---|---|
| 132kV Bus #1 | +2.06% | +0.096% |
| 132kV Bus #2 | +2.17% | +0.091% |
| 33kV Bus #1 | +2.05% | +0.097% |
| 33kV Bus #2 | +2.34% | +0.089% |
| 11kV Bus #1 | +2.07% | +0.097% |
| 11kV Bus #2 | +2.39% | +0.087% |

### *D. Scenario 2 – BESS Operation at 132 kV on Substation 2*

In this scenario, the operation configuration is similar to Scenario 1, but the BESS units are triggered at Substation 2. In scenario 2a, the two 132 kV BESS units at Substation 2 are initially importing 50 MW and 0 MVAr. The two 132kV BESS units at Substation 2 are triggered to correspond to an underfrequency event and ramped to full export within 1s. In Scenario 2b, the BESS units are exporting 50MW and 0MVAr and are triggered to respond to an overfrequency event and ramped to full import power within 1s. Both scenarios consider system minimum fault levels.

The output of voltages at the main busbars are shown Figures 5 and 6. The results for this study case are largely as expected, and for the import to export case, show a significant voltage rise at Substation 2, where the BESS operates, and a much lower voltage rise at the upstream Substation 1. During the export to import case, a large voltage sag occurs at Substation 2, where the power ramp occurs, although of lower magnitude than the equivalent import-export case. As with Scenario 1, a noticeable voltage swell occurs on Substation 1 during the power ramp. A summary of the key voltage variations can be seen in the Table IV.

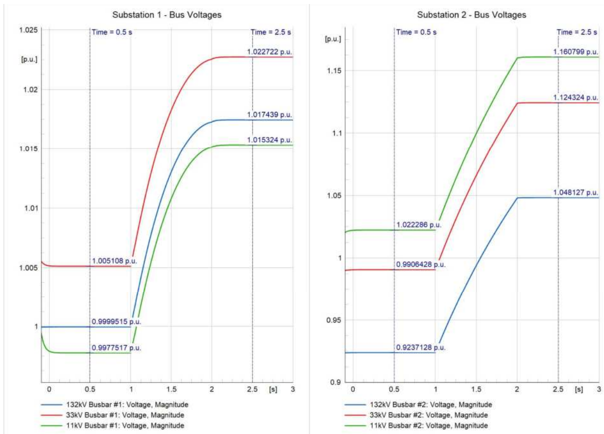


*Figure 5 Scenario 2a Results - Import to Export*

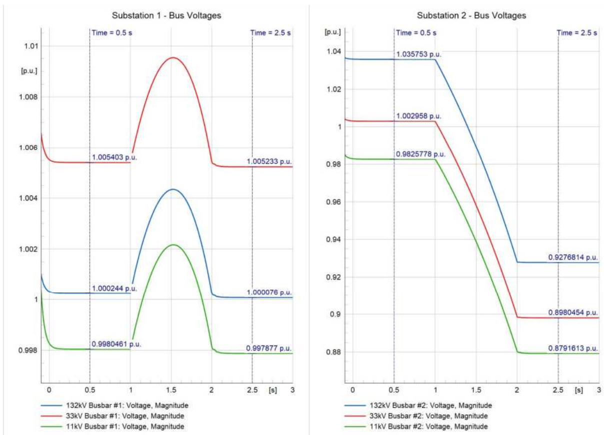


*Figure 6 Scenario 2b Results - Export to Import*

TABLE IV. SCENARIO 2 RESULTS

| **Busbar** | **Import to Export Voltage Variation** | **Export to Import Voltage Variation** |
|---|---|---|
| 132kV Bus #1 | +1.74% | -0.017% |
| 132kV Bus #2 | +12.44% | -10.80% |
| 33kV Bus #1 | +1.76% | -0.0168% |
| 33kV Bus #2 | +13.37% | -10.49% |
| 11kV Bus #1 | +1.76% | -0.017% |
| 11kV Bus #2 | +13.85% | -10.34% |

## E. *Scenario 3 – BESS Operation at 33kV on Substation 1*

In scenario 3a, the 33 kV BESS units at Substation 1 are initially importing 25 MW and 0 MVAr. The two 33 kV BESS units at Substation 1 are triggered to correspond to an underfrequency event and ramped to full export within 1s. In Scenario 3b, the BESS units are exporting 50MW and 0MVAr and are triggered to respond to an overfrequency event and ramped to full import power within 1s. Both scenarios consider system minimum fault levels.

The output of voltages at the main busbars are shown in Figures 7 and 8. The results for this study case are largely as expected, and for the import to export case, show a significant voltage rise at Substation 2, where the BESS operates, and a much lower voltage rise at the upstream Substation 1.

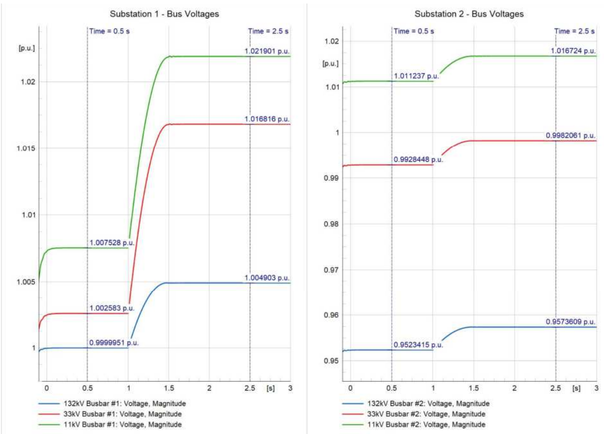


*Figure 7 Scenario 3a Results - Import to Export*

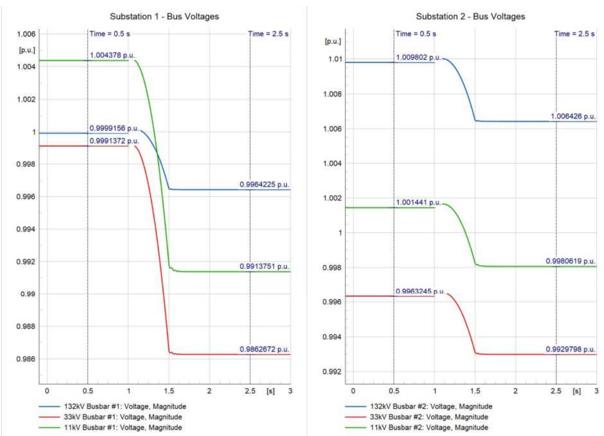


*Figure 8 Scenario 3b Results - Export to Import*

During the export to import case, a large voltage sag occurs at Substation 2, where the power ramp occurs, although of lower magnitude than the equivalent import-export case. As with Scenario 1, a noticeable voltage swell occurs on Substation 1 during the power ramp. A summary of the key voltage variations can be seen in the Table V.

TABLE V. SCENARIO 3 RESULTS

| **Busbar** | **Import to Export Voltage Variation** | **Export to Import Voltage Variation** |
|---|---|---|
| 132kV Bus #1 | +0.49% | -0.35% |
| 132kV Bus #2 | +0.50% | -0.34% |
| 33kV Bus #1 | +1.42% | -1.29% |
| 33kV Bus #2 | +0.54% | -0.33% |
| 11kV Bus #1 | 1.44% | -1.30% |
| 11kV Bus #2 | +0.55% | -0.33% |

## F. *Scenario 4 – BESS Operation at 33 kV on Substation 2*

In scenario 4a, the 33 kV BESS units at Substation 2 are initially importing 25 MW and 0 MVAr. The two 33 kV BESS units at Substation 2 are triggered to correspond to an underfrequency event and ramped to full export within 1s. In Scenario 4b, the BESS units are exporting 50MW and 0MVAr and are triggered to respond to an overfrequency event and ramped to full import power within 1s. Both scenarios consider system minimum fault levels.

The output of voltages at the main busbars are shown in Figures 9 and 10. As with the previous study cases, the results for this study case are largely as expected, and for the import to export case, show a significant voltage rise at Substation 2, where the BESS operates, and a much lower voltage rise at the upstream Substation 1.

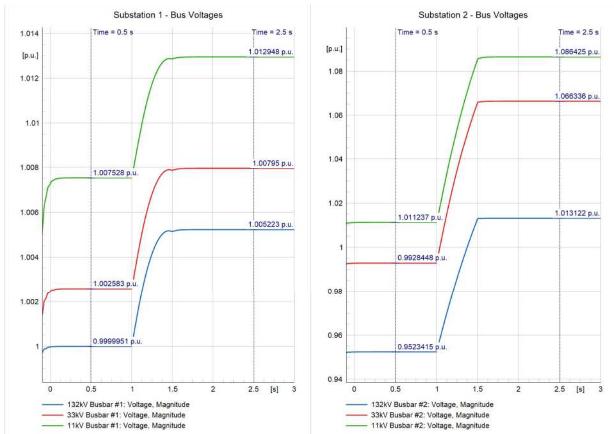


*Figure 9 Scenario 4a Results - Import to Export*

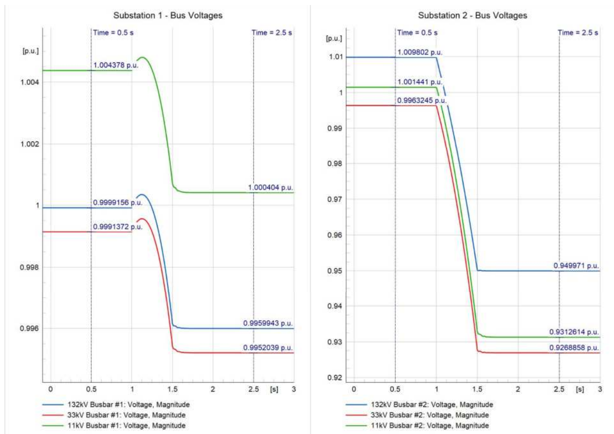


*Figure 10 Scenario 4b Results - Export to Import*

During the export to import case, a large voltage sag occurs at Substation 2, where the power ramp occurs. Which slightly unexpectedly occurs on the 132 kV busbar as well as the 33 kV and 11 kV busbars. A small voltage disturbance occurs on Substation 1 during the ramp, but this is < 0.5% and of little significance. A summary of the key voltage variations can be seen in the Table VI

TABLE VI. SCENARIO 4 RESULTS

| Busbar | Import to Export Voltage Variation | Export to Import Voltage Variation |
|---|---|---|
| 132kV Bus #1 | +0.52% | -0.39% |
| 132kV Bus #2 | +6.08% | -5.98% |
| 33kV Bus #1 | +0.54% | -0.39% |
| 33kV Bus #2 | +7.34% | -6.94% |
| 11kV Bus #1 | +0.54% | -0.40% |
| 11kV Bus #2 | +7.52% | -7.02% |

## V. CONCLUSIONS & FURTHER WORK

It has been shown in the analysis that, as expected, BESS power ramps can cause a significant effect on the bus voltages at the local substation and the surrounding substations. As can be shown by simple circuit theory, the magnitude of the voltage disturbance, at the busbars is determined by the system strength and the magnitude of the power change. Using the test network, it was identified, that BESS units of typical size of 2 × 25 MW at 33 kV or 2 × 50 MW at 132 kV could produce significant voltage disturbances on even relatively strong networks. These disturbances led to voltage changes that significantly exceeded the ±3% SVC limit required by the ENA P28/2 standard.

When considering the relationship between upstream and downstream substations, it was shown, that power ramps on upstream substations would cause a similar magnitude of voltage disturbance on all busbar voltage levels of a downstream substation. This could lead to cumulative voltage disturbances from upstream substations aggregating into significant voltage disturbances on downstream substations and distribution networks with customers directly connected. It was also identified that power ramps on downstream substations would generally produce a much smaller disturbance on upstream substation due to the higher fault level, however transient voltage swells could occur during the power ramp, which may cause nuisance behavior if of sufficient magnitude.

The analysis carried out in this paper has scope for a large amount of further development, as this is an active area of research. Further analysis could be carried out considering some of the IEEE test network such as the 14-Bus and 39-Bus model, or on larger real systems such as the Reduced GB model operated by National Grid ESO. Several key questions remain open in relation to voltage fluctuations associated with distributed BESS units. Key open questions are summarized below:

1. Is considering multiple BESS units all ramping from maximum import to maximum export, or vice versa, a credible scenario? Should this be limited to just one BESS per nearby node undergoing a full power swing, and all remaining BESS units starting from a 0MW position?
2. How should a DNO account for multiple BESS units all providing similar services, given that the voltage disturbance will be largely cumulative on downstream substations?
3. If the BESS ramp occurs at a non-unity power factory. How should the MVAr flow be considered if the generator moves from export to import or vice versa, given that PF is defined differently between generators and loads?
4. Considering that FFR type services are a critical system support is it appropriate to consider the system voltage fluctuations at minimum fault level?
5. Do ramp rates of BESS units significantly alter the network voltage response in relation to transient voltage swells?
6. What consideration should be given between different DNO checking and coordinating voltage disturbances across DNO area interfaces and boundaries, or from BESS units installed on the Transmission network?

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