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Assessment of Voltage Fluctuations for Battery Storage Systems Providing Frequency Response Services

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Abstract: This paper investigates voltage fluctuations caused by the operation of Battery Energy Storage Systems (BESS) which provide Frequency Response (FR) and Fast Frequency Response (FFR) services; using the United Kingdom (UK) mainland Great Britain (GB) system as a test case. This paper provides an overview of current FR / FFR services currently used in the UK, and a summary of their typical modes of operation. Using DIgSILENT Powerfactory, the paper introduces a simple frequency disturbance generator to mimic typical frequency disturbances that occur in real electrical network; and then subsequently uses a representative test distribution network, to show how voltage disturbances associated with BESS units can develop across the electrical network. The paper provides a contribution to knowledge by creating a systematic approach for assessing voltage disturbance and flicker concerns for BESS units using a simple control algorithm, and novel frequency disturbance generator.

Keywords: Voltage Stability, Battery Storage, Voltage Disturbance, Frequency Response and Inverter Based Generation.

1. Introduction

Battery Energy Storage Schemes (BESS) are increasingly seen as performing a key role in managing the transition to a zero-carbon renewable grids by Transmission System Operators (TSO) and Distribution System Operators (DSO). A BESS can provide many services but are frequently used to provide post disturbance Fast Frequency Response (FFR), and continually operating Frequency Response (FR) balancing services. These services are seen as a way of improving overall grid stability and performance for future energy scenarios, which are typically based on low inertia and a high percentage of Inverter Based Generation (IBG). Whilst the large range of services offered by BESS units are potentially of great benefit to TSOs, their operation, can also negatively affect distribution systems voltages and Quality of Supply (QoS), due to the frequent power swings associated with their operation. This has been shown in [1], to cause potentially large voltage fluctuations in the network, that could lead to unacceptable voltage disturbances to customers.

This is concern is influenced by four main factors. Firstly, a BESS has the ability to operate in all four-quadrant capability of active and reactive power flow. Secondly, a BESS has the ability to operate rapidly, moving from import to export within a rapid <1s timeframe. Thirdly, multiple large BESS units, is that the power ramps will all occur simultaneously and in-phase, leading to large voltage change in the network. Fourthly, BESS units are operated as a continual balancing service to meet temporary shortfalls in power, their continual ramping and operation of the BESS can lead to problems of ongoing voltage disturbances of short term and long flicker (Pst and Plt) IEC 61000-3-7 [2].

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At present, some countries use a central planning strategy to determine the location and rating of the BESS units, whilst other countries with deregulated electricity markets such as the UK, Ireland, Australia and parts of the USA have adopted a more general strategy of allowing developers to connect to any available substation. In deregulated countries such as the UK, this has resulted in multiple BESS units connected near each other, with only individual assessments carried out, rather than a wide area assessment of the interaction between units. A concern has been raised by the DSO / TSO, that if there are multiple BESS units all providing similar services, then potentially they could all respond simultaneously leading to a cumulative voltage disturbance on the network.

The contribution to knowledge presented in this paper covers a few different areas. Firstly, the paper provides an overview of the current issues facing BESS units providing FR/FFR services, in relation to power quality. Secondly, a generic model a of a 2-slope response controllers is developed for use with control of the BESS units. Thirdly, a generic model of an AC voltage source and disturbance model is developed to allow easy assessment of likely impacts of frequency fluctuations on BESS response and system flicker.

2. Typical BESS FFR and FR Services

BESS FR/FFR services vary from country to country and are triggered based on different criteria. Some BESS units operate on moving average Rate of Change of Frequency (RoCoF) based assessment, whilst others are operated based on measurement of the system frequency, which is usually a much slower response. At present one of the challenges represented by BESS units, is that there are very few agreed principles or standards available, and these primarily focus on steady state planning requirements or on slower acting services **[3]**.

The UK GB system represents an interesting example as the 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 **[4]**. Two main fast acting services are currently in use within the UK: Dynamic Containment (DC) which is a form of FFR intended to provide post-fault rapid support for large frequency deviations, and a slower Dynamic Regulation (DR) service, which is intended to operate continuously to help provide shortfalls of power due to frequency deviations. A future third service known as and Dynamic Moderation (DM) is intended to be added, which is similar to the DR service, but operates over a 1s time period. A summary of the services can be seen in Table 1 and Figure 1 below. Other smaller islanded networks such as the Republic of Ireland follow similar principles (known as the DS3 service).

Table 1. Frequency Response and Fast Frequency Response Services in the UK GB system

Requirement	DR	DM	DC
Speed of Response *	10 s	1 s	1 s
Service	Pre-fault	Pre-fault	Post-fault
Delivery Range	data	data	Data
Deadband	±0.015 Hz	±0.015 Hz	±0.015 Hz
Initial Linear Range (Delivery %)	±0.015 Hz to 0.2 Hz	±0.1 Hz to 0.2 Hz	±0.015 Hz to 0.5 Hz
Knee Point	None	±0.1 Hz	±0.2 Hz
Second Linear Range (Delivery %)	±0.015 Hz to 0.2 Hz	±0.015 Hz to 0.1 Hz	±0.015 Hz to 0.2 Hz
Full Delivery Point	±0.2 Hz	±0.2 Hz	±0.5 Hz
Max Ramp Start	2 s	0.5 s	1 s

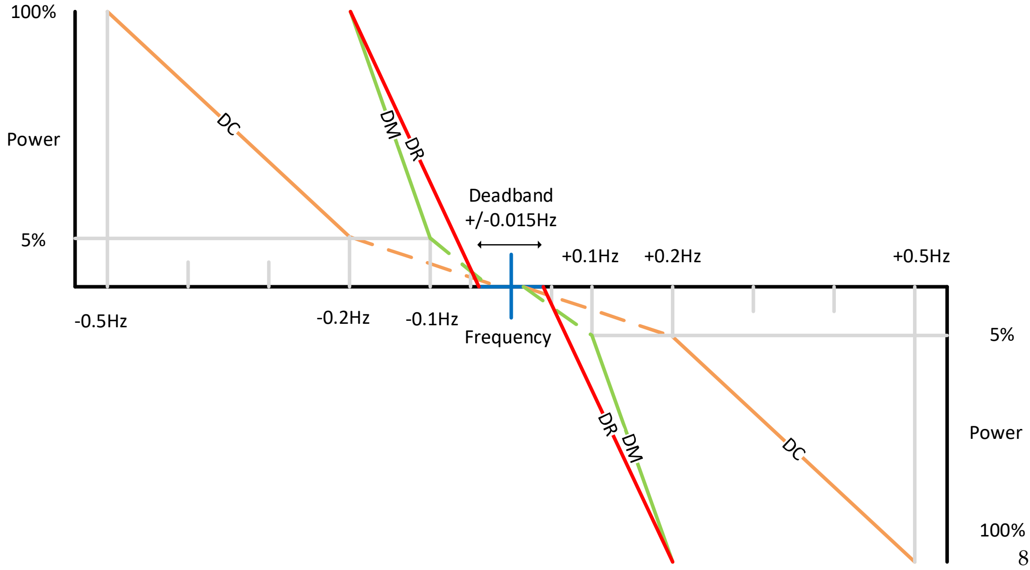

Figure 1. Frequency Response Services in the UK GB System

3. Background

3.1 Overview

As noted earlier, BESS units are very flexible and can operate in several different quadrants and modes. At present, BESS units tend to operate in distinct operating modes or services, depending on the asset owner. Typical services include power arbitrage (behind the meter load shifting), continually acting MVAr control services to DSO / TSOs, or as FR / FFR type units. In principle, multiple services could be revenue stacked together, but this has so far been resisted by larger network operators due to the complexity of modelling and predicting the unit behavior. For the purposes of this paper BESS units providing FR / FFR type services are reviewed.

3.2 Literature Review

A key issue with BESS units is that they can operate as both a generator and a load and can swap between operating modes and quadrants quickly. As the BESS changes from import to export, or export to import, there will be an instant when there is zero power flowing down the line, with the BESS is in a no-load condition. 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 [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 services, such as so-called synthetic inertia or FFR, 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 or units operating as Grid Forming Inverters [7], [8] and [9].

A general literature review carried out, indicated, that there is an extensive amount of high level literature related to battery energy storage systems in relation to frequency stability , voltage stability of renewable energy sources, inertia and FFR type services, such as the IEEE [10] & [11], CIGRE [3], [7] & [8], NREL, NERC [9], [12] & [13]. However, as noted in Section 2, there are at present very few unified and accepted standard practices for integrating BESS units into a system network [3].

To date limited analysis of voltage QoS due to multiple BESS operation in a whole system network appears to have been carried out [1]. 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.

3.2. BESS Power Swings

A key concept associated with a BESS unit, is that it can operate in any of the 4 quadrants associated with active and reactive power. Furthermore, depending on the control mode implemented, it can simultaneously alter both its active and reactive power settings from one quadrant to another. At present operation of BESS units with the UK GB system providing FR / FFR services is based on receiving a frequency input signal to control the active power output (MW), BESS unit remains in Constant Q operation mode, with the reactive power output (MVAr) remaining constant. It is noted however the reactive power output needs to alter slightly during a power swing, as the controller will try and maintain a nominal MVar setpoint at the system Point of Interface (PoI) between the BESS and the host DSO / TSO.

Whilst Constant Q operation mode of the BESS, is the most common mode with the UK, it is also possible to also operate the BESS in a voltage control mode with the reactive power (MVAr) output managed through a QV droop response type curve. In QV control mode, the BESS MVAr output is regulated to maintain the local bus voltage within the target levels. This can be seen diagrammatically in Figure 2 below.

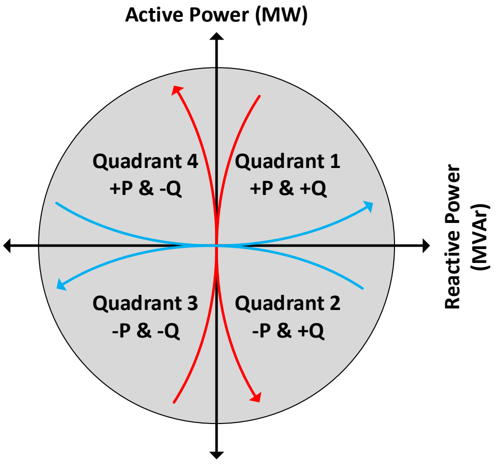

Figure 2. Battery Storage 4 quadrant operation

3.3. Voltage Disturbance and Flicker

The voltage disturbance on a network is given by the RMS change in the system voltage during the disturbance. In IEC 61000-3-7 [2] voltage limits are defined either as Rapid Voltage Changes (RVC) for short duration transient disturbances or as a fluctuating load resulting in disturbance emissions for short term duration Pst, over a 10-minute period or long-term duration Plt over a 2-hour period.

The assessment of the magnitude of the voltage disturbance is covered extensively in various textbooks and relies on simple circuit theory to assess [5] & [6]. The assessment of flicker for Pst and Plt values, is slightly more complex and depends on the size, duration, and frequency of the system disturbances. IEC 61000-3-7 [2], adopts the use of shape factors to account for disturbances associated with step changes, pulses and ramps. The standard provides a detailed assessment method for analyzing the magnitude of voltage disturbances and frequency of occurrence as being acceptable for human perception.

For practical assessments of flicker a flicker meter can also be used as defined in the IEC 61000-4-15 standard [14]. The DIgSILENT Powerfactory simulation software also has a flickermeter function available, which can be used in conjunction with both RMS and EMT simulations to determine values of Pst and Plt for dynamic time-based simulations.

4. Frequency Disturbances

4.1 System Frequency Disturbances

All system networks experience frequency disturbances in response to continual load demand changes, generation fluctuations and system disturbances. The magnitude, severity and frequency of these disturbances depend on several factors such as the overall system generation, inertia, generator controllers and settings, intermittency of renewable sources etc. The UK mainland GB system (excluding Northern Ireland) can be considered as an interesting test case, due to its relatively large size and deregulated market. Currently, National Grid ESO maintain a nominal system frequency of 50 Hz, with a typical variation limit of ± 0.2 Hz and a target of absolute system frequency limits of ± 0.5 Hz [4]. The UK demand is typically in the range of 25 GW to 40 GW [15], with an inertia of 140 GVA.s [4].

National Grid ESO publish historical frequency data based on a 1s resolution for each month; this allows review of historical trends. A detailed statistical analysis of the historical frequency trends of the GB system is beyond the scope of this paper, but general trends of the number of significant frequency disturbance events in a time frame of the Pst (10-minute) and Plt (2-hour windows) can be obtained through qualitative means. A typical sample of a 1-day window in November 2022 is shown below in Figure 3.

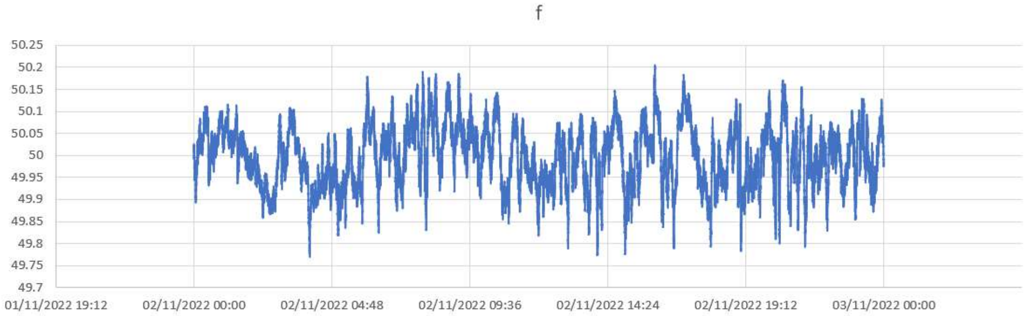

Figure 3. Great Britain (Mainland UK) Typical Frequency Data – November 2022

From a high-level qualitative analysis of various months data, the UK GB system behavior could be loosely defined as the following characteristics:

- Frequency changes, even for large disturbances are gradual events, that occur over several minutes, due to the high system capacity load and generation (MW), along with high levels of system inertia;
- RoCoF does not vary noticeably between summer and winter months;
- Step changes in frequency do not occur;
- Very significant frequency disturbances larger than ±0.5 Hz occur very occasionally, typically not more than once in every 12 months;

- Significant frequency disturbances larger than ±0.3 Hz occur occasionally, typically less than once per month;
- Frequency disturbance of greater than ±0.2 Hz but less than ±0.3 Hz occur occasionally, typically several times per month;
- Frequency disturbance of greater than ±0.1 Hz but less than ±0.2 Hz occur regularly, typically every few hours, of varying magnitude;
- Minor frequency disturbance up to ±0.1 Hz occur very regularly, typically every few minutes, of varying magnitude;
- Very minor frequency disturbance <0.015 Hz occur very regularly, typically every few seconds.

4.2 Frequency Disturbance Generator

The response of a BESS unit providing FR / FFR type services will depend on the system frequency of the host network. In most islanded networks, the system frequency changes continually, in relation to changes in system demand, generation and outages. Wit the magnitude of the system frequency change defined through calculation of the swing equation. In a real system these frequency deviations, are random in relation to real time events. In order to predict the behavior of a BESS unit, and the subsequent impact to the network voltage, it is necessary to try and replicate the response of the BESS in relation to the incoming setpoints from the controller, based on the frequency disturbance. Two methods were initially considered for this. Firstly, the historical frequency data could be downloaded, and then a simple script could be developed to use this to control the system frequency in a simulation method. Secondly, an approximation could be developed of typical system frequency disturbances to give a representative example of the system behavior. Due to the large volume of data available from National Grid ESO, and the challenges of carrying out a detailed analysis on the data, a simpler solution was adopted, of creating a system to replicate typical disturbances, through using a noise generator.

A novel frequency disturbance generator was developed, to replicate the typical behavior of the UK GB system frequency, using the DIgSILENT PowerFactory simulation package. The novel disturbance generator design was developed to help represent a real-world behavior of the system frequency, in order to create a realistic test case. The novel frequency disturbance generator design, was based on the concept of using two separate noises generator; one producing a larger magnitude slow signal to represent significant events in the system frequency, and another producing a smaller magnitude faster signal to represent smaller more frequent fluctuations in system frequency. The two signals are then, passed through moving average filter to smooth the signals out, before being summated together and then used to drive an AC Voltage Source to allow the system frequency to be disturbed. A model of the controller can be seen below in Figure 4.

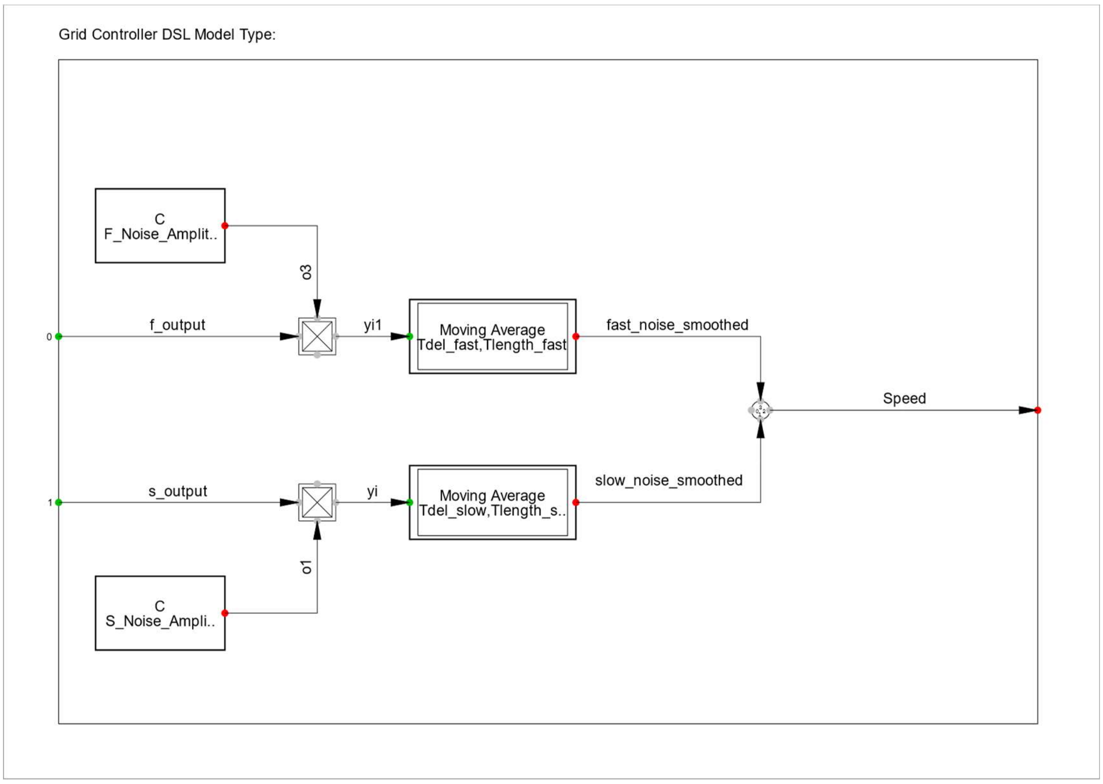

Figure 4. Frequency Disturbance Generator Controller

The slow speed noise generator was set to use a Gaussian distribution, with a mean of 0 and set at a slow speed to create a significant of around ±0.25 Hz disturbance approximately every 5 minutes, and then passed through a moving average filter with a time delay of 1 and a window length of 20. The fast speed noise generator was also set to a Gaussian distribution with a mean of 0, but set to create a much smaller, but sharper disturbance of around ±0.025 Hz every 2 seconds and then passed through a moving average filter with a time delay of 1 and a window length of 5. These values are slightly larger than those seen in typical disturbances seen in the UK GB electrical network but would be representative of future lower inertia cases. The resultant frequency disturbance can be seen in Figure 5.

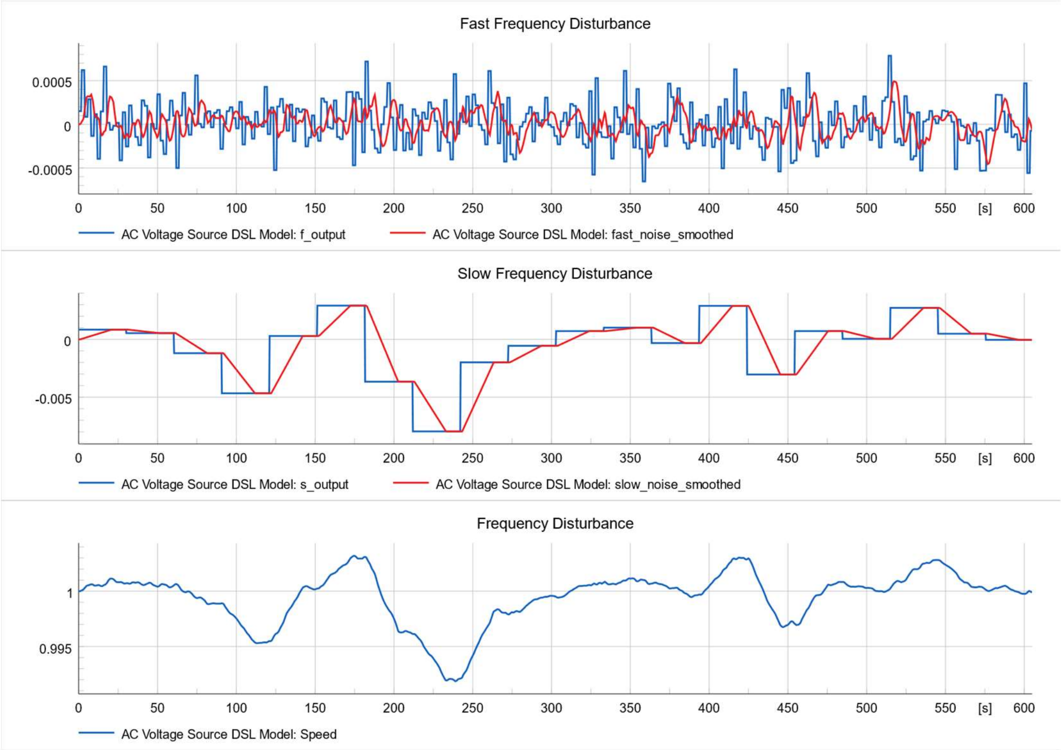

Figure 5. Frequency Disturbance Results

5. Network Model

5.1. Overview

This section of the paper introduces the network model used to carry out the analysis for the BESS behavior on the system. The section of the paper provides an overview of the test network used and the system controller used to control the BESS units. The test network used is slightly arbitrary but based on a typical UK type configuration. Consideration was given to using the IEEE 14-Bus network or IEEE 39-Bus network, but these systems were not considered too helpful, due to the large amounts of distributed generation within the network.

5.2 Test Network

A test network like the one used in [1] was utilized to analyze the behavior of the BESS units, as can be seen below in Figure 8. To represent the dynamics of a DSO network, a simplified representative model of a typical UK system was developed. The configuration is based on a typical sub-transmission network of two interconnected 132 kV substations, fed from an upstream 400kV network, with each 132 kV substation supplying a downstream 33 kV and 11 kV switchboard, to represent typical distribution customers.

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, 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 time constants set at 5s for the 132kV busbars, 10s for the 33kV busbars and 15s for the 11kV busbars. 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 2, and the test network is shown in Figure 6.

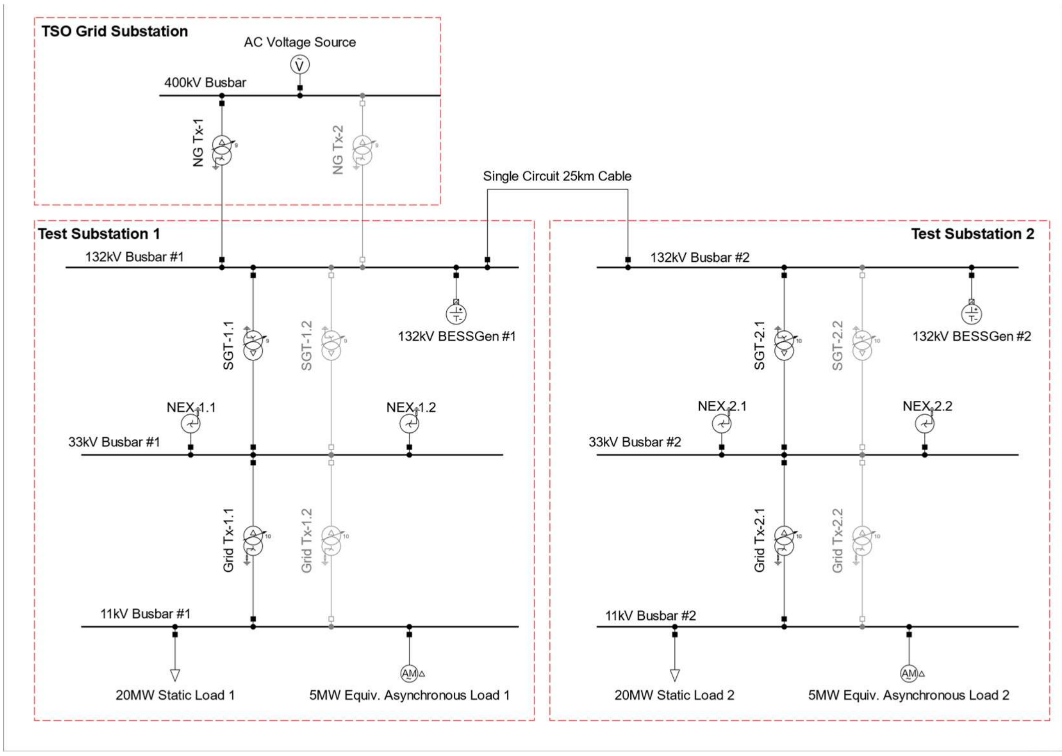

Figure 6. Representative Test Network of Part of GB System

Table 2. Test Network 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

5.3. System Controllers

The control systems used in a typical BESS installation, consists of multiple levels of control. At the field level, control algorithms in the BESS units are responsible for functions such as current control, individual inverter setpoints and protection. The second layer of control is typically implemented by a Power Park Controller (PPC) responsible for dispatching PQ setpoints to the inverters in the group and providing frequency response services. The third level is within the overall System Controller, which can be implemented via a variety of methods, in simple systems such as Solar PV, these may be passive systems with a simple target MW setpoint provided by the system aggregator.

One of the problems faced by assessment of TSO / DSO networks, is that commercial BESS units' controllers will all be different and may be 'blackboxed' to hide key data. It was therefore decided to develop a novel, generic controller to allow implementation of any of the power ramps associated with the DC/DR/DM services indicated earlier. This novel approach allows a universal approach to be adopted when considering BESS responses for a system, and any non-UK based applications to be implemented easily. Considering the response curves shown in Figure 1, although the response is symmetrical, the response curve can be fully defined by 4 simple linear equations, to represent each slope of the graph and the deadband in the middle. The equations implemented for the DM service, as this is the most onerous condition, are shown below, where equation (1) represents the slope from -0.5 Hz to -0.2 Hz, Equation (2) represents the slope from +0.5 Hz to 0.2Hz, Equation (3) represents the slope from -0.2 Hz to -0.015Hz and Equation (4) represents the slope from +0.2 Hz to +0.015Hz.

$$\text{Slope 1} = -9.5*(df+0.2) + 0.05, \tag{1}$$

$$\text{Slope 2} = -9.5*(df-0.2) - 0.05, \tag{2}$$

$$\text{Slope 3} = -0.5*(df + 0.015), \tag{3}$$

$$\text{Slope 4} = -0.5*(df - 0.025). \tag{4}$$

The controller model uses a standard Powerfactory library model of a Phase Locked Loop (PLL) to track the system frequency from the 132 kV busbars, and then produce an error signal, which is in turn fed into the control logic. The control logic consists of four equations (1 to 4) to represent each of the slope sections of the DC/DR/DM service, along with a simple logic selector gate to choose the required slope for activation. The output signals are then summated together and driven through limiters to prevent excess power overload of the BESS units occurring, and then directly given to a PI controller to drive the BESS setpoint. An implementation of the controller is shown below in Figure 7.

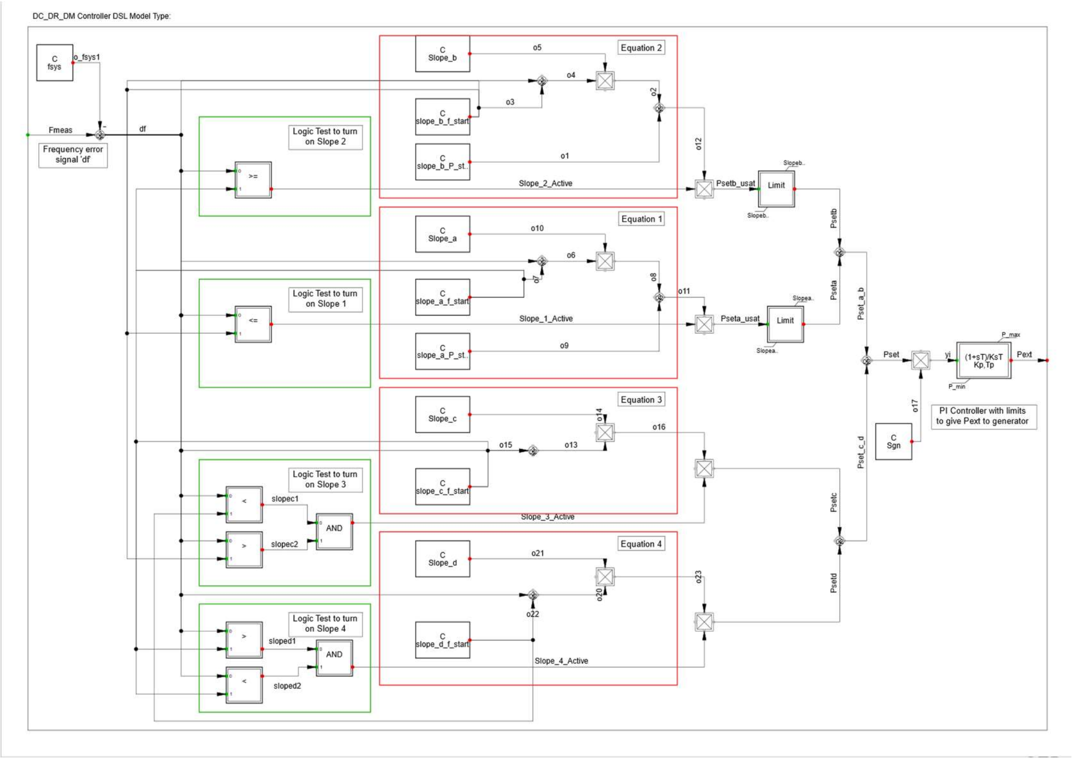

Figure 7. Battery Energy Storage System Frequency Response Controller Model

5. Analysis

5.1 Overview

To analyze the behavior of the BESS and the result impact on the test network a number of test cases were carried out considering operation of a BESS on a strong (high fault level) part of the network, as well as operation on a weaker (low fault level) part of the network, and then operation of multiple BESS units together. The BESS units were set to operate in the Dynamic Moderation configuration.

5.2 Case 1 – BESS Operation at 132kV Busbar 1

In Case 1, the BESS is operated at 132kV Busbar 1, and the other BESS at 132 kV Busbar 2 is set out of service and one of the 400/132kV SGTs was set out of service to provide a minimum fault level. The frequency noise generator input was set to produce a representative frequency disturbance pattern and the output of the system bus voltages was recorded and then assessed for the flicker value Pst. The output plots can be seen below in Figure 8, where it is noted that the bus voltage disturbance is of a similar magnitude and shape on each of the busbars, even on the remote busbars. The magnitude of the voltage disturbances is relatively small at <1%. This result is largely as expected as the upstream voltage disturbance is reflected directly onto the downstream network.

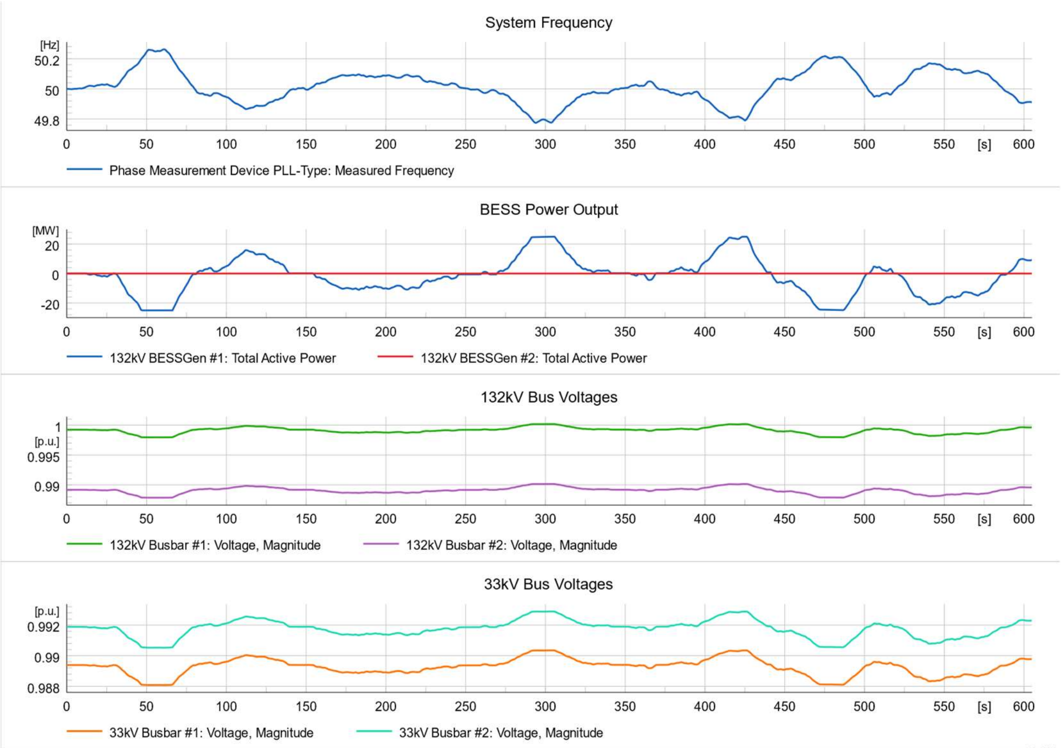

Figure 8. BESS Operation at 132kV Busbar 1 Results

Table 3. BESS Operation at 132kV Busbar 1 Results

Busbar	Short Term Flicker (Pst)
132kV Bus #1	0.0095
132kV Bus #2	0.0095
33kV Bus #1	0.0095
33kV Bus #2	0.0095
11kV Bus #1	0.0095
11kV Bus #2	0.0095

5.2 Case 2 – BESS Operation at 132kV Busbar 2

In Case 2, the BESS is operated at the 132kV Busbar 2, and the BESS at 132 kV Busbar 1 is set out of service; as before one of the 400/132kV SGTs was set out of service to provide a minimum fault level. The frequency noise generator input was set to produce a representative frequency disturbance pattern and the output of the system bus voltages was recorded and then assessed for the flicker value Pst. The output plots can be seen below in Figure 9, where it is noted that the bus voltage disturbance on the Substation 2 busbars (all voltages) is of a similar magnitude and shape, but the bus voltage disturbances on Substation 1 are significantly reduced. The values of flicker (Pst) are notably higher on the Substation 2 busbars, and the magnitudes of the voltage disturbances is also higher at around ±2%. As before this result is largely expected.

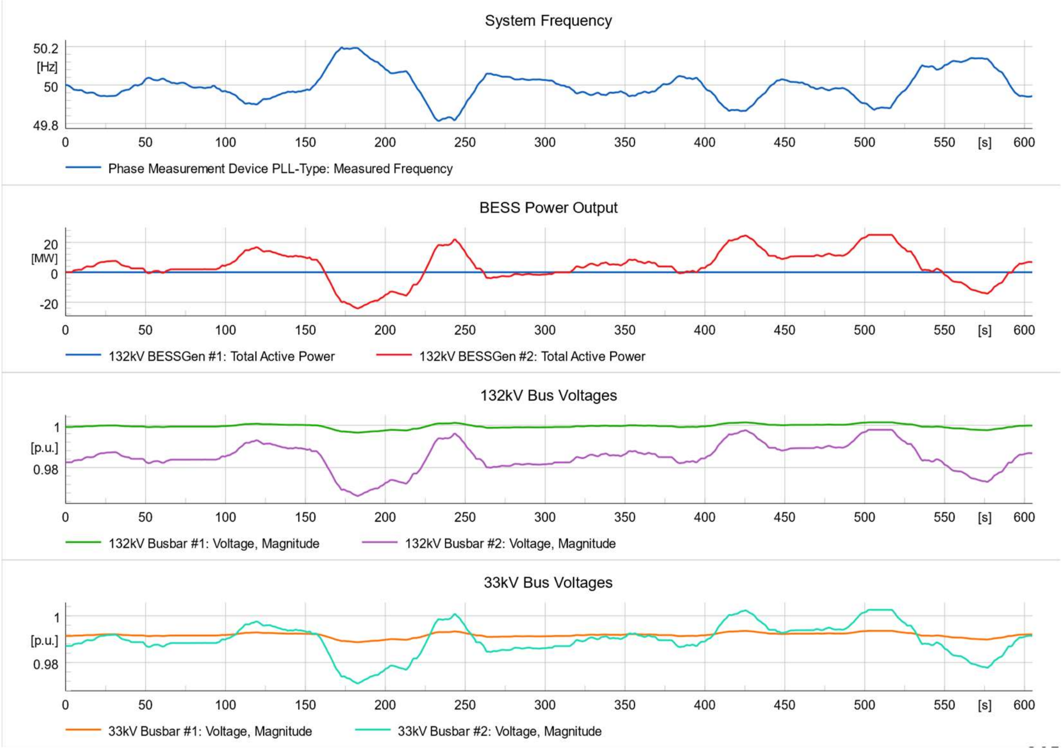

Figure 8. BESS Operation at 132kV Busbar 2 Results

Table 3. BESS Operation at 132kV Busbar 2 Results

Busbar	Short Term Flicker (Pst)
132kV Bus #1	0.094
132kV Bus #2	0.0251
33kV Bus #1	0.005
33kV Bus #2	0.0252
11kV Bus #1	0.0095
11kV Bus #2	0.0256

5.2 Case 3 – Operation of Both BESS Units

In Case 3, both BESS units are operated at the same time; and as before one of the 400/132kV SGTs was set out of service to provide a minimum fault level. The frequency noise generator input was set to produce a representative frequency disturbance pattern and the output of the system bus voltages was recorded and then assessed for the flicker value Pst. The output plots can be seen below in Figure 10, where it is noted that the bus voltage disturbance on the Substation 2 busbars (all voltages) is of a similar magnitude and shape, but the bus voltage disturbances on bus 1 are significantly less. Interestingly, although a number of medium voltage deviations of ±3% occur, the calculated overall flicker for the system is still very low.

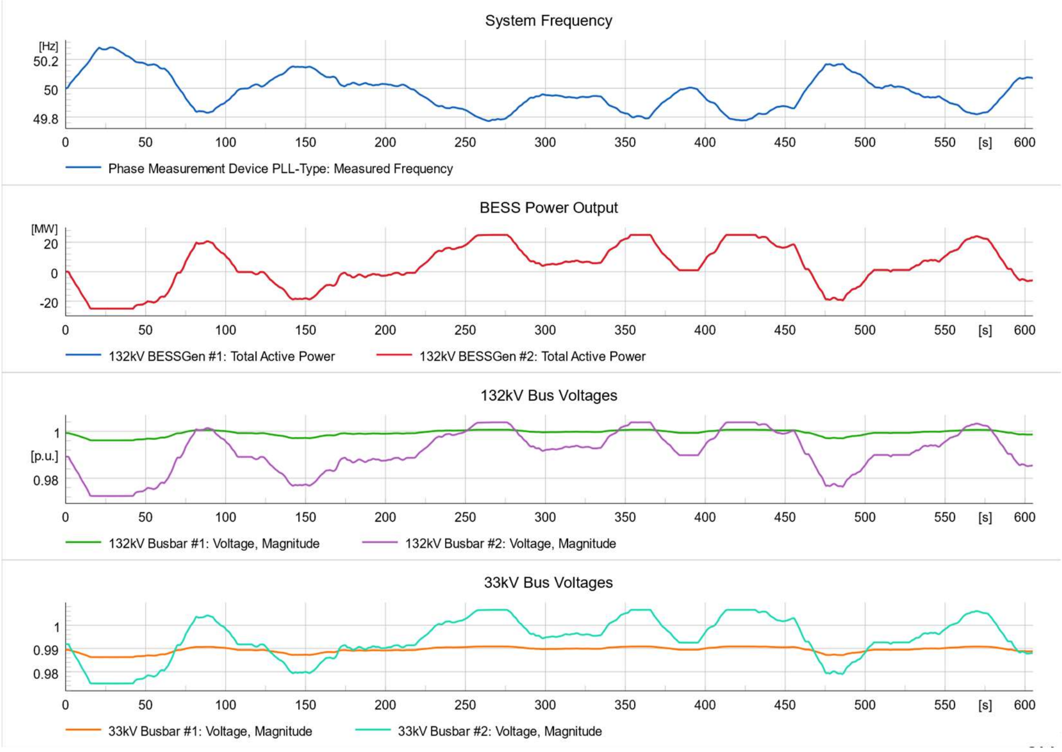

Figure 10. BESS Operation at both 132kV Busbar Results

Table 3. BESS Operation at both 132kV Busbar Results

Busbar	Short Term Flicker (Pst)
132kV Bus #1	0.0101
132kV Bus #2	0.0279
33kV Bus #1	0.0102
33kV Bus #2	0.0281
11kV Bus #1	0.0102
11kV Bus #2	0.0284

6. Conclusions & Future Research

The results of the analysis section showed that the voltage change experienced by the system was generally small, even on the weaker network (Substation 2), and the value of short-term flicker (Pst) were also small. This was due to the system frequency changes occurring relatively slowly in a network and although the BESS unit operates continually, large rapid power changes do not generally occur quickly. This also allows for the transformer OLTCs to help manage the system voltage on the switchboards. The results also showed that for a BESS operating on an upstream supply substation (Substation 1) the voltage disturbance caused by the BESS was reflected of similar magnitude on all of the downstream substations; conversely BESS operation on downstream substations were only minimally reflected on the upstream network. During operation of both BESS units, their response was identical, so the voltage disturbance on both systems was increased.

From the results the general conclusions that can be inferred that large BESS units on upstream networks will affect all nearby substations connected to the local network and the voltage disturbance will be reflected on all the downstream substations. Where there are scenarios where there are multiple BESS units within the same area, these units will operate together and provide similar power swings causing a direct summation of the voltage disturbances. This could be problematic on networks with a large number of distributed BESS units present, or where the local network already has an existing voltage flicker problem.

At present, there is considerable variation in the methods that DSO / TSO use to assess the suitability of proposed BESS units prior to connection on the system. These methods are currently very conservative, and there is a tendency to consider worst case events of a full export to import ramp, or import to export ramp, occurring over 1s, but to only consider single BESS units in isolation. This paper has shown that such events do not occur in practice, as the system frequency doesn't not change quickly, as it is constrained by a high system inertia and thus the BESS units respond more slowly over extended periods of time. This slower response means that the system transformer tap changers can help mitigate the system voltage disturbance and should not be ignored. It is therefore recommended that when assessing BESS units for connection to a host DSO / TSO a more realistic model is carried out considering typical frequency variations and controller response. This gives a much more realistic behavior of the system network and allows both operators and developers to determine system capacity and suitability for large BESS schemes.

The approach used to create the frequency disturbance is in the method contains an inherent probabilistic component as the frequency disturbance generator is random. The noise generator frequency and magnitude, and smoothing action of the filters can easily be adjusted to be consider future energy cases, where events may be larger, magnitude or occur with a greater RoCoF. A useful further work exercise would be to carry out a more detailed review of the historical frequency data and compare and baseline this against the values used in the disturbance generator.

One other area of significant interest could be the overlap of BESS units creating system fluctuations and leading to increased small signal stability problems due to the constant operation and ramping behavior of the BESS units on the network and interaction with existing machines and new synchronous condensers. Further areas of work could include modelling the behavior of Grid Forming Inverters to see how local terminal voltage control can be utilized better to help stabilize network voltage fluctuations.

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