

# Contribution of GFM BESS for System Strength | Feasibility Assessment

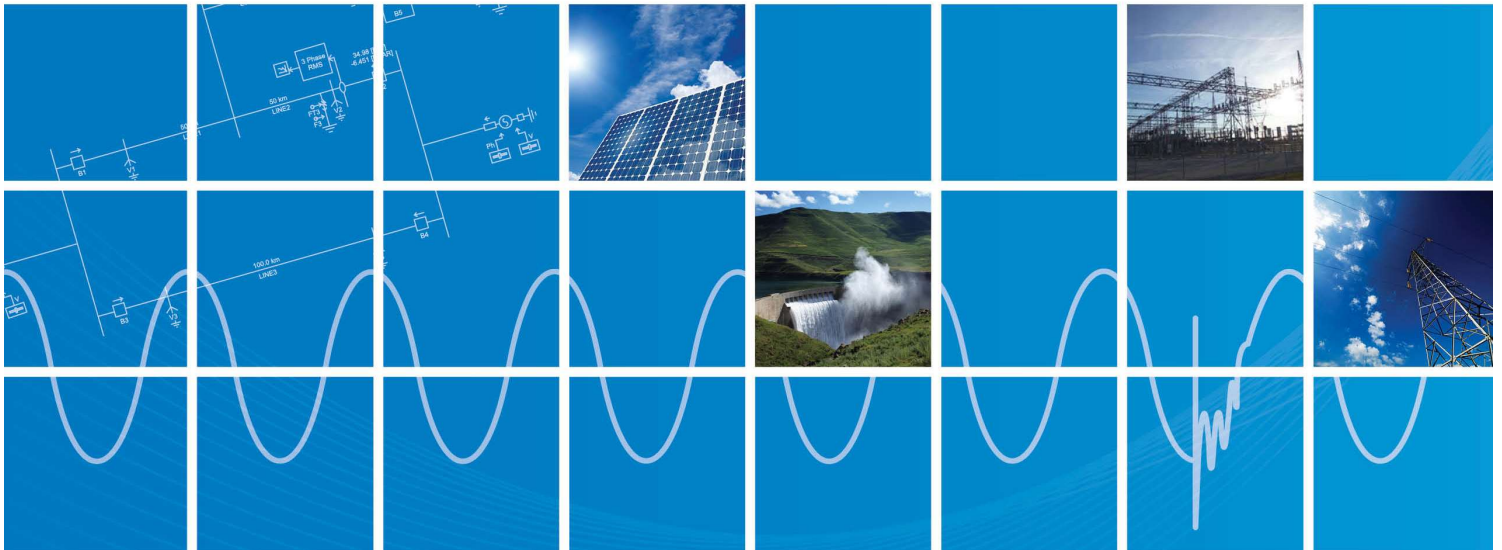


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## Document History

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## Executive Summary

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There are several BESS plants either committed or anticipated within the next two years for connecting to the South Australia High Voltage power transmission network (ElectraNet). ElectraNet assumes these BESS locations to be the most likely to connect with new GFM technologies in the next two years. Hence, these locations are the likely hosts for providers of system strength services that may be deployed in the next two years if required. ElectraNet has engaged Manitoba Hydro International (MHI) to look into the feasibility of GFM BESS capability in these locations. Performance of Utility Scale Batteries operated at these locations under Grid Forming (GFM) mode was studied for potential contribution towards System Strengthening. A summary of journey, results and inferences are presented in this report.

ElectraNet desires to understand and quantify potential contributions from the BESS plants if operated in GFM mode to determine whether the grid forming BESS meet the RIT-T threshold as a credible option. The purpose of this report is to demonstrate the technical viability of a generic grid forming BESS. Failure to demonstrate an improvement in the criteria AEMO have determined for measuring system strength (a stable voltage waveform) in this study may lead ElectraNet to determine that GFM BESS is not a viable technical option at this time.

As the system strength from a GFM BESS cannot be distinctly measured in terms of a tangible unit such as 'MVA' or a proxy 'fault level' this investigation refers to four criteria of stable voltage waveform defined by AEMO<sup>1</sup> in order to calibrate contribution of each BESS towards improvement based on those criteria. For example, the fourth criteria says that the low frequency oscillation at each SSN need to be kept within the limit of 0.1% (peak-to-peak amplitude) for stable voltage waveform. Some contingency scenarios during or post-contingency can lead to induce such oscillations of even higher amplitudes (greater than 0.5% peak-to-peak), and those scenarios were particularly selected for the purpose of initial testing of the GFM BESS model.

Under carefully selected severe contingency environments, the GFM operation mode was tested for each assumed Battery and then for multiple Batteries for their collective effort on improving System Strength. Various protection schemes were purposely omitted to create a sufficiently weak network (i.e. applying a contingency led sustained sub synchronous oscillations). This weakened network was used to gain understanding on whether a GFM BESS provides an improved response to the system (in terms of reducing the oscillatory behavior produced from the artificially weakened network) when compared with the GFL BESS.

Based on the assessment undertaken, the GFM BESS is found to exhibit improvement in System Strength mainly within the local area of connection. Under multiple GFM BESS environment the collective effort was observed to be lower than a linear sum of the individual effects in this study. This collective effort was found to depend on the import / export dispatch conditions too.

The oscillations (one of the measures of system weakness) do not appear to be linked, specifically, to the GFB models, but the site-specific tuning and with additional tuning (supported by the OEM) these oscillations (observed) should be able to be damped to an acceptable threshold. This controllable damping effect along with synthetic inertia from the GFM BESS are added features to harvest in addition to system strength.

Tie-in of a selected 275kV transmission line to a nearby 275kV bus to see the mitigating effect on voltage collapse (a non-credible contingency) is also a noteworthy observation from this study. Control tuning to mitigate interaction among the nearby GFM Batteries is beyond the scope of this study; however, a further study aimed at compensating GFM BESS interaction can demonstrate the way ahead for enhanced control techniques to tap the maximum collective potential for system strength from a group of BESS plants

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<sup>1</sup> See page 20 of [2] [system-strength-requirements-methodology.pdf \(aemo.com.au\)](https://www.aemo.com.au/system-strength-requirements-methodology.pdf)

connected to the network. The idea is to get each and every BESS plant in the network oriented to work towards a common goal of supplying system strength at the maximum level as a group.

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## Glossary of Terms and Abbreviations

Term	Definition
AG	Asynchronous Generation
BESS	Battery Energy Storage System
CP	Connection Point
GFB	Grid Forming Battery
GFL	Grid Following
GFM	Grid Forming
IBR	Inverter Based Resources
OEM	Original Equipment Manufacturer
OOS	Out of Service
PEC	Project Energy Connect
PLL	Phase Locked Loop
PRIM	Primary
RIT-T	Regulatory Investment Test - Transmission
SA	South Australia
SCR	Short Circuit Ratio
SMIB	Single Machine Infinite Bus
SSN	System Strength Node

## 1. Background

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With the increasing IBR volumes forecast for SA transmission network by AEMO's 2022 System Strength report, ([2022-system-strength-report.pdf \(aemo.com.au\)](#)) it is anticipated that almost all IBR forecast are GFL type thus weakening the system strength unless remediated.

How to recognise low system strength in this study? Signs of low system strength will be presented as undamped voltage and power oscillations, IBRs being unable to properly ride through a disturbance, increased harmonic distortion, increased nadir and peaks in POC voltages, and, under some severe contingencies, voltage collapse.

Traditionally Synchronous Condensers rectify this situation. The drive for new solutions such as Grid Forming (GFM) BESS is the low or almost zero incremental cost in implementing GFM function in an existing network connected BESS in comparison to a newly built or converted Synchronous Condenser.

How does a BESS operating in Grid Forming mode can help in this situation? A BESS traditionally operates in Grid Following (GFL) mode and follow to the network voltage waveform for its current injection into the network. So, if the network connection point has low system strength; for example, during or post contingency situation, GFL plant cannot function properly. On the other hand, GFM (grid forming) BESS defines its terminal (or PoC) voltage waveform independently and drive currents into the network irrespective of the network strength or weakness. For this reason, a GFM BESS can act somewhat similar to a Synchronous Machine.

Grid Forming (GFM) BESS is claimed to be able to maintain stable voltage waveform at a node particularly in the immediate vicinity of its connection. OEMs have tested their models on SMIB basis but not widely performed until now on a wide area network model of Giga-Watt scale.

ElectraNet is proactively planning for improved system strength within its transmission network in order to host increasing volume of Inverter Based Resources (IBR) forecast by AEMO for the years 2024-2033.

ElectraNet desires to understand and quantify potential contributions from the BESS plants if operated in GFM mode to determine whether grid forming BESS would meet the RIT-T threshold as a credible option. The purpose of this study report is to demonstrate the technical viability of a generic grid forming BESS. Failure to demonstrate an improvement in the criteria AEMO have determined for measuring a stable voltage waveform in this study may lead ElectraNet to determine that GFM BESS is not a viable technical option at this time.

### 1.1. Committed BESS projects

There are eight (8) or more locations of BESS plants either committed or anticipated within the next two years for connecting to the SA transmission network (ElectraNet). ElectraNet considers these BESS locations to be the most likely locations to connect BESS in the next two years. Hence, these are the most likely providers of system strength stable voltage waveform services that can be deployed in the next two years if required. ElectraNet has requested MHI to limit their scope to consider GFM capability in these locations only in this study.

Table 1: New and existing BESS locations near SSNs

BESS reference	Bus (kV)	Closet SSN	Operational
A <sup>2</sup>	275	Davenport	FY2026
B	275	Davenport	FY2026
C	132	Davenport	FY2026
D	132	Robertstown	FY2026
E	275/132	Robertstown/Para	FY2026
F	132	Para	FY2026
G	275	Para	FY2024
H	275	Para	FY2024

In this limited scope project, it is expected to assume that the above BESS plants can operate in GFM mode in order to examine their contribution towards system strength improvement. This assumption is purely for the study purpose only.

Due to lack of observable direct variables indicating system strength, it is adhered in this study to monitor voltage waveform at the SSNs with respect to (1) RMS magnitude (2) Phase angle (3) Waveform Distortion (4) Low frequency Oscillation; as per AEMO's four-point criteria on stable voltage waveform (See page 20 of [2] [system-strength-requirements-methodology.pdf \(aemo.com.au\)](#) and Appendix 7).

As indicated in ElectraNet's PSCR [3] (AEMO | ElectraNet System Strength RIT-T PSCR), a Network solution of connecting synchronous condensers has been proposed to remediate depleting system strength at Davenport, Para and Robertstown within the next five years.

This current study is to assess the assumed BESS plants described in the **Table 1** if operated in GFM mode for possible quantifiable contribution towards establishing stable voltage waveform (i.e. system strength at efficient level). The approach taken in this study is quite unique as can be seen from section 3.

## 1.2. System Strength Impact

Connecting large volumes of GFL IBR can bring the existing level of system strength at a node down. Traditionally, system strength is expressed in terms of fault level, a quantity directly related to stable operation via protection schemes. For South Australia this type of protection related fault level is not at a deficit. Hence, AEMO's System Strength reports [1], [5] declare that SA transmission network has sufficient (minimum level) fault level at each SSN for protection relay operation. However, [1] and [5] gave a future forecast IBR for which the existing system strength may not going to be sufficient to maintain stable voltage waveform. This is referred to as efficient level above and beyond the minimum level of system strength as vividly described in [4]; System Strength Impact Assessment guidelines published in 2023 ([AEMO | System Strength Impact Assessment Guidelines](#)).

AEMO's guidelines [4] introduces a concept termed "Available Fault Level" AFL in order to capture system strength requirements for growing volume of GFL IBR forecast. In order to apply this AFL concept, the minimum stable operation short circuit ratio (mSCR) for each IBR need to be prior determined by a PSCAD study. This mSCR value may vary between 1.2 and 3.0 depending on the performance characteristics of

<sup>2</sup> Proprietary information are not provided in this report.

each IBR. For practical use of the AFL concept, an approximate SCR value of 3.0 is typically used in previous studies.

For GFM BESS this stable operation mSCR value may even be lower than 1.2 which means net provision of system strength towards the wider network. Only way to assess this system strength contribution from a GFM BESS is to evaluate the efforts of the BESS in terms of maintaining stable voltage waveform. For that purpose, a wide-area network PSCAD model is required in the assessment.

As the system strength at efficient level from a GFM BESS cannot be distinctly measured in terms of a tangible unit such as 'MVA' or a proxy 'fault level' this investigation refers to four criteria of stable voltage waveform defined by AEMO<sup>3</sup> in order to calibrate contribution of each BESS towards improvement of those criteria at the node. For example, the fourth criteria says that the low frequency oscillation at each SSN need to be kept within the limit of 0.1% (peak-to-peak amplitude) for stable voltage waveform. Some contingency scenarios during or post-contingency can lead to induce such oscillations of even higher amplitudes (greater than 0.5% peak-to-peak), and those scenarios were particularly of interest for the purpose of initial testing of the GFM BESS model.

### 1.3. Early-stage questions

System strength was traditionally measured in terms of fault level and the minimum fault levels required at SSNs were declared by AEMO for TNSP to implement. SA transmission network has no deficit in minimum fault level. However, AEMO forecast increasing volume of IBR which may need additional system strength beyond the capacity of the current network. This is primarily a capacity to host forecast volume of IBR in the years to come (e.g. FY26 to FY31). This quantity is termed as efficient level of system strength<sup>4</sup> In terms of system strength assessment this means how much IBR volume (in MW) that can be hosted with having stable voltage waveform. For example, what is the maximum volume (MW) of IBR that can be hosted while maintaining stable voltage waveform using a 100 MVA BESS in GFM mode?

In order to host forecast IBR of 954 MW at Robertstown<sup>5</sup>, what would be the size of the GFM BESS required at Robertstown? These are the questions discussed at the early stage of this study.

In order to host forecast IBR of 498 MW at Para, what would be the size of the GFM BESS required at Para? Although the stable IBR hosting (in MW) capacity may not be prorated with rating / dispatch of a system strength providing plant it may give decision makers a rule of thumb for future planning.

### 1.4. SA Transmission Network

Relative locations of existing IBR and the System Strength Nodes (SSN) are indicated in the map of SA Transmission Network (**Figure 1**). AEMO declared SSNs are Davenport, Para and Robertstown. SA High Voltage transmission network is characterized by four major (backbone) lines running in almost parallel between North and South without many cross connections at 275 kV level between those lines as can be seen from a network map. Hence the continuity of system strength is challenged at nodes along the lines in between North and South regions while during or post-contingency scenarios involving any of those backbone lines. For this reason, it is critical to investigate feasible plants that can easily connect and supply

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<sup>3</sup> See page 20 of [2] [system-strength-requirements-methodology.pdf \(aemo.com.au\)](#)

<sup>4</sup> [AEMO | System Strength Impact Assessment Guidelines](#)

<sup>5</sup> Referring to AEMO's 2022 System Strength report, December 2022.

system strength within local nodes all along these backbone lines. Can the Batteries, anticipated or committed, (placed along the lines - Figure 1) act as system strength providers at their node of connection?

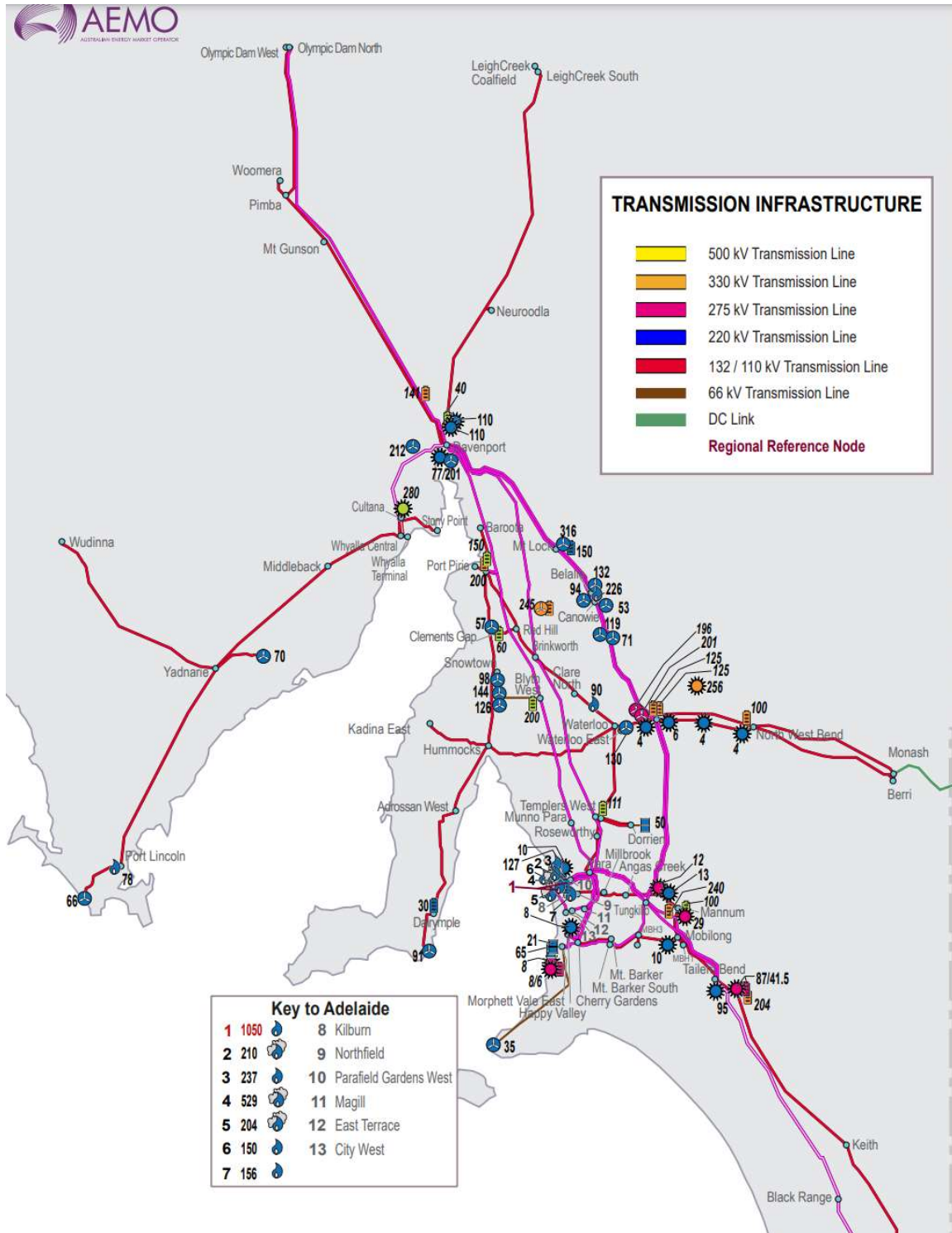


Figure 1: Approximate locations of the anticipated BESS projects are assumed to be close to existing IBR or 275kV transmission nodes

Figure 1 shows the transmission network for connecting the anticipated BESS projects from **Table 1**. Based on common sense approach, a contribution from a BESS project can be assumed larger if it is electrically closer to the node of interest. That may indicate; for example, a BESS at Mannem Bend, Mannum or Taillem Bend contributes the least amount of system strength towards the respective SSN depending on the distance.

A detail model of the new Transmission interconnector (330 kV) between Bunday and Buronga and to Wagga-Wagga was not available for this study, and hence an equivalent Thevenin's source at Bunday was assumed. This may limit the validity of assessment of contribution from a close by GFM BESS particularly on the stable voltage waveform aspect. More on this and feasible improvements are discussed in the presentation of results (see section 4).

## 2. Network Model

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### 2.1. Model Overview and simulation setup

System performance studies were undertaken using a network model for SA HV transmission. All dynamic models of existing and committed plants connected within that network area including wind farms, solar farms, BESS, HVDC systems and reactive plants are modelled in detail. All investigations are based on detailed electromagnetic transient (EMT) simulations, which were performed on the industry standard PSCAD™/EMTDC™ software version 5.0.2.

The main network is modelled as ten separate regions (projects): Eyre\_Peninsula\_EMT, Metro\_1\_EMT, Metro\_2\_EMT, North\_EMT, South\_East\_EMT, Riverland\_EMT, Mid\_North\_EMT, Eastern\_Hills\_EMT, MLNK\_PEC\_EMT, and Riverland\_EMT\_MLK. These projects are connected via the Parallel Network Interface (PNI) to facilitate parallel processing. All dynamic plant models in each region are connected via Multi-rate PNI to facilitate simulating dynamic plant models with different time steps. The main network model is simulated with a time step of 10  $\mu$ s.

### 2.2. Network Boundary

A PSCAD™/EMTDC™ model for SA, with equivalent sources at Bunday 330 kV and Southeast 275 kV was used for the assessment. The equivalent impedance values used to represent the upstream network at these boundary buses that are not included in detail within the network model are derived based on the 3PHG fault level at the respective bus. Table 2 lists the power flows into SA measured at the two boundary buses (Bunday 330 kV and Southeast 275 kV) for this study.

Table 2: Power flow provided by the equivalent source at network boundary buses.

Boundary Bus	Min Import Case		Max Import Case		Max Export Case	
	A. Power	R. Power	A. Power	R. Power	A. Power	R. Power
Bunday 330 kV	68 MW	34 MVar	600 MW	-159 MVar	-307 MW	31 MVar
Southeast 275kV	65 MW	46 MVar	592 MW	37 MVar	-357 MW	155 MVar

### 2.3. Dynamic Plant models

All dynamic plants, which are presently in-service as provided in the NEM PSCAD wide area model, are used for the study. MHI also included all committed renewable generators to the base model using the latest available PSCAD models. Generation in SA was re-dispatched to compensate for the appropriate levels of interconnector power transfer as well as line loading. Three dispatches were used to conduct this study: the minimum import dispatch, the maximum import dispatch and the maximum export dispatch. The three dispatches are presented in **Table 2**.

- **Minimum Import Dispatch** – A minimum power flow (NSW → SA) and (VIC → SA) with the generators in the study area dispatched as high as possible, while respecting the thermal transmission line limits.
- **Maximum Export Dispatch:** A maximum power flow (SA → NSW) and (SA → VIC) with the generators in the study area dispatched as high as possible, while respecting the thermal transmission line limits
- **Maximum Import Dispatch:** A maximum power flow (NSW → SA) and (VIC → SA) with the generators in the study area dispatched as high as possible, while respecting the thermal transmission line limits.

Dynamic voltage regulating devices in the study area are listed below.

- Davenport synchronous condensers
- Robertstown synchronous condensers
- Node G synchronous condenser (a new plant for select studies)
- Southeast SVC
- Para SVC

### 2.4. GFM BESS model

A generic GFM BESS model from an OEM was used. As this is an OEM model, specifics about the parameters cannot be shared. However, at a high-level the GFM BESS may be represented by typical values such as given below for example:

- H constant = 2.5 s
- Damping Gain = 0.03

A GFM BESS, is referred to as a battery technology equipped with inverters that operates as voltage source synchronised with the grid frequency and provides power to the grid based on the load angle and voltage magnitude. The stable operation of GFM BESS, in the same manner as conventional synchronous generators, must not be dependent on the system strength of the system. In fact, it increases the system strength of the nearby power system (e.g. voltage waveform stability), by generating a robust voltage waveform at its own terminal comprising the magnitude and angle at the synchronised 50 Hz frequency.

## 2.5. Network Configuration, Power Flow and Demand

The network is modelled in its system normal state, i.e., all transmission elements are in service. The pre-contingent network voltage profile across the network is maintained within the typical operating range.

The dispatch levels of the renewable energy generators under three operating scenarios prior to contingencies or outage were established for each study.

## 3. Methodology of Study and Format of Presentation

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### 3.1. Methodology

A selected list of contingencies (compiled from a list, provided by Electranet, of credible and non-credible contingencies in SA), that produced unacceptable behavior (i.e. sustained sub-synchronous oscillations or voltage collapse), were used to measure the system performance of grid following batteries against grid forming batteries. It was understood that various schemes exist in SA for the purpose of securing the system. These were purposely omitted to create a sufficiently weak network (i.e. a network where the applied contingency produced a sustained oscillation). This weakened network was used to gain understanding on whether a GFM BESS provides an improved response to the system (in terms of reducing the oscillatory behavior produced from the artificially weakened network) when compared with the GFL BESS. The focus of the study is to analyse the following:

- Investigate the impact grid forming batteries have on the system strength of the SA network.

For the purpose of this study, three-phase to ground faults were considered with Primary protection clearance times (100/120ms).

Additional investigations using the following network conditions were also conducted:

- Additional synchronous condensers
- Tying the Blyth West and Brinkworth buses together

To determine the success of system strength provision by a GFM BESS, a measure of voltage waveform stability (AEMO's four-point criteria<sup>6</sup>) is used in this study. Each GFM BESS is assessed for hosting a stable voltage waveform for the maximum volume (MW) of IBR at or in vicinity of the SSN.

The collective effort of hosting the maximum volume of increased IBR is also assessed when considering more than a single BESS (Multiple GFM BESS on the network). However, no specific tuning of the individual BESS units is considered.

### 3.2. Strategy to quantify the increased hosting capacity

One of the most difficult aspects of this investigation is to evaluate the exact quantity of increment in system strength due to the application of a particular BESS operated in GFM mode. Early stages of this project adopted traditional gradual introduction of contingencies after the first round of normal operational scenario. In that basis and with N-1 contingency it was first attempted to add IBR volumes in blocks of say 100MW until the system shows characteristic signs of losing strength (typically sub-synchronous oscillations) at the

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<sup>6</sup> See page 20 of [2] [system-strength-requirements-methodology.pdf \(aemo.com.au\)](https://www.aemo.com.au/system-strength-requirements-methodology.pdf)

respective SSN. In this approach it took quite a lot of iterative assessments in order to discover that system weakening level of added IBR; for example, at Davenport node it was necessary to add more of IBR (GFL mode) and still having to observe no signs of sub-synchronous oscillations. From that point onwards, the strategy of assessing GFM BESS's contribution towards raising the AG hosting capacity at the SSN (e.g. Davenport) has been changed to a more pragmatic results-oriented approach. Section 3.2.1 explains this new strategy.

### 3.2.1. GFM BESS Support at SSNs

A single GFM BESS was placed in-service to obtain an initial idea of how much support it can lend to three different SSNs (Davenport 275 kV, Para 275 kV and Robertstown 275 kV). Only BESS units geographically close to each SSN were considered. Three different network changes were made to evaluate this.

- 1) to evaluate the effectiveness that BESS references A and B have on **Davenport 275 kV SSN**, one of the double circuit line from Davenport – Robertstown was disconnected and the line from Munno Para – Blyth West was also disconnected.
- 2) The network model used for these studies was ill-suited to evaluate the effectiveness of BESS references D and E have on **Robertstown 275 kV SSN. This is due to the modelling of the ideal source at Bundy 330 kV**. This source is too close to Robertstown 275 kV to fairly represent the dynamic response within the area. Therefore, using this network, the method (as used to evaluate Davenport and Para) will not provide sufficient accuracy. To fairly assess this SSN, it is recommended to move the boundary bus towards Wagga-Wagga, well into NSW.
- 3) to evaluate the effectiveness of BESS references G and H have on **Para 275 kV SSN** one line from Para to PGW, one line from Para to TIPS, one line from Para to Magil and one line from Munno Para to Blyth West were disconnected.

For each case mentioned above a base case was developed. This base case contained only GFL BESS units and asynchronous generation was added at the SSN until the voltage oscillation surpassed the threshold of 0.5%, measured at the associated SSN. Next, a single GFM BESS was placed in-service (putting the GFL BESS with the same name OOS) and asynchronous generation was added to the SSN until the voltage oscillation surpassed the threshold of 0.5% measured at that SSN. The difference between these two values is an estimate of the additional generation of IBRs that can be hosted with one GFM BESS in-service. This strategy of differential approach helps facilitate the evaluation of extra AG hosting capacity (in MW) of each GFM BESS without having to wait for the establishment of the new absolute limit of AG hosting capacity arriving after PEC stage 2 completion.

### 3.3. Presentation of Results

The network contingency scenarios (network faults) studied are listed and summarized in three categories:

- Minimum Import Results
- Maximum Export Results
- Maximum Import Results

**Table 4 - Table 8** (Minimum Import Results), **Table 10 - Table 14** (Maximum Export Results) and **Table 16 - Table 20** (Maximum Import Results) respectively present these scenarios. Observations are provided in the Observation column, presenting the magnitude of the largest voltage oscillation observed at the three buses of interest (Devenport 275 kV, Para 275 kV and Riverland 275 kV). The voltage magnitude, change of phase angle and a measure of waveform distortion are also presented for the cases where these measures go outside the allowable limits (as per AEMO’s four-point criteria).

The “In-service” column refers to all the changes that deviate from the original network, including:

- **Grid-forming BESS (GFB)** – if listed in the “In-service” column, the corresponding grid following BESS is disabled.
- **Synchronous condensers** – if listed in the “In-service” column, the named synchronous condenser was added to the network.
- **Tie Blyth – Brinkworth or Transmission tie-in**– if listed in the “In-service” column, a zero-impedance line was used to connect the Blyth West bus to the Brinkworth bus. These buses have no direct connection in the original networks.

A summary of each contingency is provided at the end of each section, with the largest voltage oscillation presented (e.g. Davenport 275 kV in Scenario S1). This serves as a condensed version of the information provided in the Results tables. The “Summary” column is colour coded, for reader convenience, with; **black** representing the original network run (only GFL BESS considered), **green** representing a pass (<0.1% voltage oscillation) or improvement, and **red** representing a failure.

A further description of each summary observation is provided below:

- **Original** – this is the original case with all grid following BESS units integrated.
- **Improvement** – if the voltage oscillations have a smaller oscillation magnitude than in the original case.
- **Worse** – if the voltage oscillations have a larger oscillation magnitude than in the original case.
- **Voltage collapse** – if a voltage collapse is observed in the system. In this case voltage oscillation magnitude is not recorded.
- **Blank** – if the voltage oscillation of the original is already <0.1% (*\*Note\*: AEMO criteria – if the voltage oscillations have a peak-to-peak magnitude less than 0.5% (TNSP limit)*)

The “Network Condition” column is a list of all the changes within the network for the corresponding run.

For each scenario listed in S1 to S5, the results under contingency cases are presented in sections 4.1, 4.2, and 4.3.

### 3.4. Contingencies

The network contingency scenarios (network faults) studied are listed and summarized in **Table 3**. These 5 contingency scenarios (S1 to S5) were studied using various network conditions defined in **Table 4 - Table**

8 (Minimum Import Results), **Table 10 - Table 14** (Maximum Export Results) and **Table 16 - Table 20** (Maximum Import Results) where each unique network condition is denoted with a subsequent letter, starting at “a” (i.e. different network conditions for contingency S1 are labeled; S1a, S1b, S1c, etc.)

Table 3: Summary of selected contingencies

Test	Contingency Category	Clearance time (ms)
S1	Trip of Robertstown – Mokota 275 kV line for a 3PHG fault: <i>Prior outages: Robertstown – Canowie 275kV, Robertstown SC 1 &amp; 2, Davenport SC 1 &amp; 2</i>	100/120
S2	Trip of Davenport – Bungama 275 kV line for a 3PHG fault: <i>Prior outages: Blyth West – Munno Para 275kV</i>	100/120
S3	Trip of Robertstown – Canowie 275 kV line <b>AND</b> Robertstown - Mokota for a 3PHG fault: <i>Prior outages: Blyth West – Munno Para 275kV</i>	100/120
S4	Trip of Robertstown – Canowie 275 kV line for a 3PHG fault: <i>Prior outages: Blyth West – Bungama 275kV</i>	100/120
S5	Trip of Robertstown – Canowie 275 kV line for a 3PHG fault: <i>Prior outages: Davenport – Brinkworth 275kV</i>	100/120

### 3.5. What would expect under these contingencies?

The network contingency scenarios (S1, S2, S3, S4 and S5) were selected on the expectation that deterioration of network voltage stability would occur under these contingencies (prior outage plus faults) and would manifest either in voltage oscillations (typically near 2 Hz) or voltage collapse (extreme cases). The reason for selecting such severe contingencies is to start with a weak system giving the GFM BESS an opportunity to rectify the instability of voltage waveform. If the GFM BESS is capable of rectifying a weak system in such severe contingencies that would be a classic marker of success in contribution to system strength.

Under S1 Davenport would be completely cut off from Synchronous Condensers unless for minor contributions from indirect and long pathways and via 132 kV lines. Hence voltage instability (oscillations) would be expected the most at Davenport.

Under S2 Davenport would not be cut off from Synchronous Condensers; however, isolated from Para and connected to Wind Farms via 132 kV lines. This could trigger oscillations in voltage at Davenport.

Under S3 three of the four 275 kV lines between North and South are down and that causes congestion on the only remaining line and possibly voltage collapse.

Under S4 two of the four 275 kV lines between North and South are down and that causes congestion on the remaining two lines and may cause voltage collapse.

Under S5 two of the four 275 kV lines between North and South are down and that causes congestion on the remaining two lines and may cause voltage collapse.

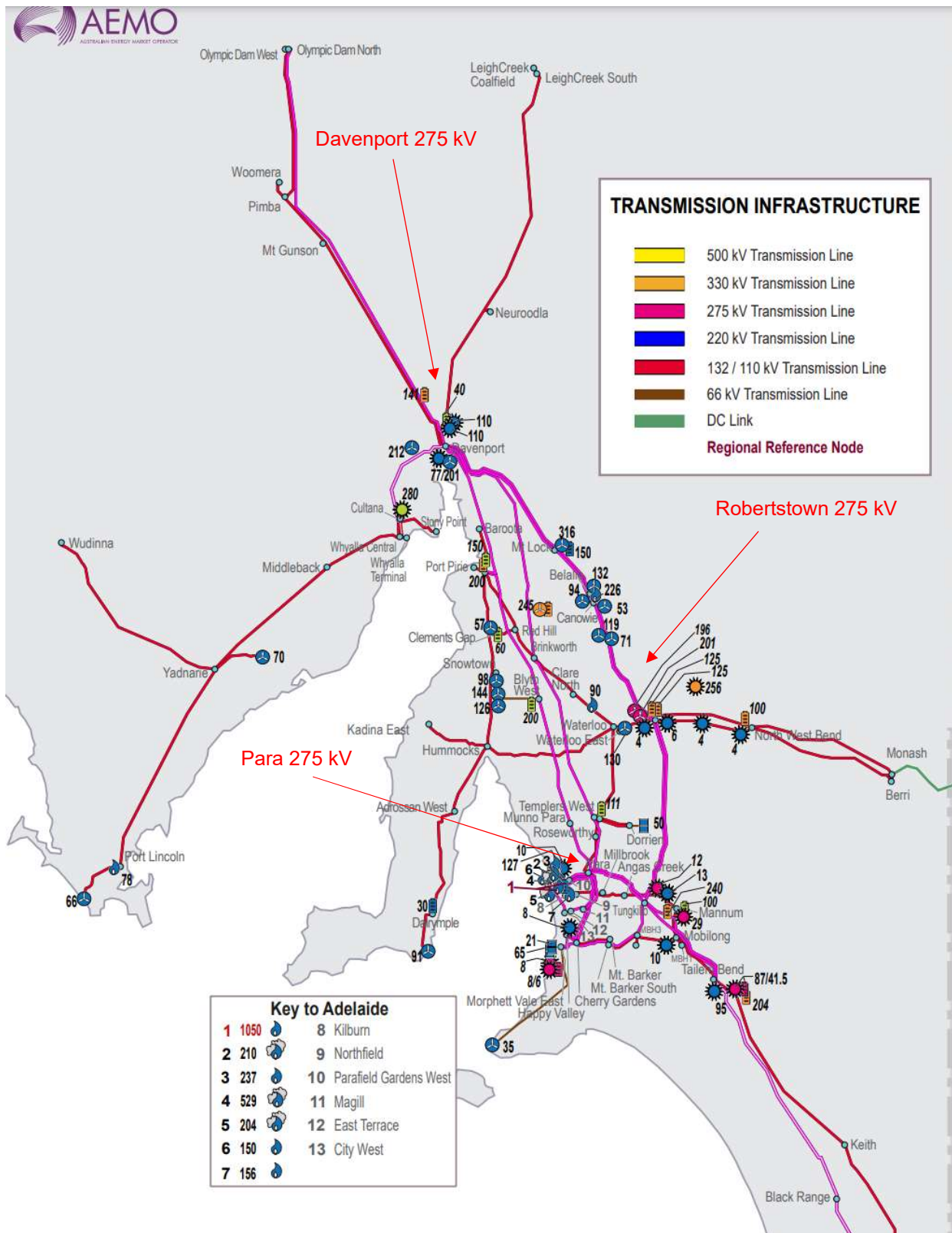


Figure 2: SA High Voltage transmission network (275kV and 132kV included)

## 4. Summary of Assessment

Summary of the Full Impact Assessment is provided in sections 4.1, 4.2 and 4.3.

### 4.1. Minimum Import Case Results

#### Results S1

Table 4: Summary of contingency analysis: Minimum Import: S1

Test	Observation (Voltage oscillation at 2.2 Hz) and any comments			
	Davenport (SSN1)	Para	Robertstown	GFM /Comments
S1a	4.37% p-p 2.2 Hz	0.37% p-p 2.2 Hz	0.31% p-p 2.2 Hz	All GFL
S1b	7.11% p-p	0.88% p-p	0.41% p-p	A GFM
S1c	7.61% p-p	0.89% p-p	0.58% p-p	B GFM
S1d	4.21% p-p	0.44% p-p	0.38% p-p	A and B GFM
S1e	4.00% p-p	0.44% p-p	0.40% p-p	A, B, C, D, E, F GFM

#### Results S2

Table 5: Summary of contingency analysis: Minimum Import: S2

Test	Observation (Voltage oscillations) and any comments			
	Davenport	Para	Robertstown	GFM / Comments
S2a	1.68% p-p multiple freq	0.77% p-p multiple freq	1.08% p-p multiple freq	All GFL
S2b	<0.1% p-p	<0.1% p-p	<0.1% p-p	A
S2c	<0.1% p-p	<0.1% p-p	<0.1% p-p	B
S2d	0.94% p-p	0.3% p-p	0.65% p-p	C
S2e	2.12% p-p multiple freq	0.88% p-p multiple freq	1.68% p-p multiple freq	D
S2f	1.21% p-p 3.1	0.42% p-p 3.1	0.97% p-p 3.1	E
S2g	<0.1% p-p	<0.1% p-p	<0.1% p-p	F, Plants are observed to trip

## Results S3

Table 6: Summary of contingency analysis: Minimum Import: S3

Test	In service / GFM	Observation (Voltage Oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S3a	All GFL	N/A	N/A	N/A	Voltage collapse
S3b	D	N/A	N/A	N/A	Voltage collapse
S3c	B	N/A	N/A	N/A	Voltage collapse
S3d	A	N/A	N/A	N/A	Voltage collapse
S3e	A,B,C,D,E,F	N/A	N/A	N/A	Voltage collapse
S3v	GFB 700, B, SC250	N/A	N/A	N/A	Voltage collapse
S3w	GFB 700, 250, B, SC250	N/A	N/A	N/A	Voltage collapse
S3x	GFB 700, 250, B, C, F	N/A	N/A	N/A	Voltage collapse
S3y	Transmission tie-in	N/A	N/A	N/A	Voltage collapse
<b>S3z</b>	Transmission tie-in, GFB 700	N/A	N/A	N/A	Voltage collapse, Stability reached after Plants are observed to trip
<b>S3aa</b>	Transmission tie-in, GFB 700, 250, F, B	N/A	N/A	N/A	Voltage collapse, Stability reached after Plants are observed to trip
<b>S3ab</b>	Transmission tie-in, GFB 700, 250, B, C, F	<0.1% p-p	<0.1%p-p	<0.1% p-p	Refer to extreme weather case (Appendix 4).

## Results S4

Table 7: Summary of contingency analysis: Minimum Import: S4

Test	In-service / GFM	Observation (Voltage Oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S4a	All GFL	N/A	N/A	N/A	Voltage collapse
S4b	A, B, C, D, E, F, G	N/A	N/A	N/A	Voltage collapse
S3ab	Transmission tie-in, GFB 700, B, C, F, G	<0.1% p-p	<0.1% p-p	<0.1% p-p	Refer to Appendix 4 extreme weather case (page 18).

## Results S5

Table 8: Summary of contingency analysis: Minimum Import: S5

Test	In-service / GFM	Observation (Voltage Oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S5a	All GFL	N/A	N/A	N/A	Voltage collapse

Test	In-service / GFM	Observation (Voltage Oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S5b	A, B, C, D, E, F, G	N/A	N/A	N/A	<b>Voltage collapse</b>

### Improvements observed (Minimum Import)

The maximum improvement potentially due to GFM mode is tabulated below based on the results from section 4.1. There is some improvement (greater than 0.5%) in reducing amplitude of low frequency oscillation under scenario S2.

Table 9: Improvements observed (Minimum Import)

Scenario	Maximum improvement (%) due to GFM		
	Davenport	Para	Robertstown
S1	0.37	-0.07	-0.09
S2	1.67	0.76	1.07

## 4.2. Maximum Export Results

### Results S1

Table 10: Summary of contingency analysis: Maximum Export: S1

Test	In-service / GFM	Observation (Voltage oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S1a	All GFL BESS	13.35% p-p 2.2 Hz	2.27% p-p 2.2 Hz	2.06% p-p 2.2 Hz	
S1b	GFB 700	9.75% p-p 2.2 Hz	1.56% p-p 2.2 Hz	1.17% p-p 2.2 Hz	
S1c	B, GFB 700	9.56% p-p 2.0 Hz	1.36% p-p 2.0 Hz	0.93% p-p 2.0 Hz	
S1d	B, E, GFB 700	9.35% p-p 2.1 Hz	1.28% p-p 2.1 Hz	0.94% p-p 2.1 Hz	
S1e	Robt SC1 & SC2	16.43% p-p 2.2 Hz	1.92% p-p 2.2 Hz	1.71% p-p 2.2 Hz	
S1f	B, Robt SC1 & SC2	11.84% p-p 2.2 Hz	1.84% p-p 2.2 Hz	1.41% p-p 2.2 Hz	
S1g	B, GFB 700, Robt SC1 & SC2	9.47% p-p 2.2 Hz	1.39% p-p 2.2 Hz	0.82% p-p 2.2 Hz	<i>sustained oscillations start at 21.6 s (6.6 s after fault)</i>
S1h	B, D, GFB 700, Robt SC1 & SC2	4.19% p-p 2.2 Hz	0.58% p-p 2.2 Hz	0.29% p-p 2.2 Hz	<i>oscillations begin increasing in magnitude at ~28 s (13 s after fault)</i>

Test	In-service / GFM	Observation (Voltage oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S1i	B, D, GFB 250, GFB 700, Robt SC1 & SC2	10.40% p-p 2.2 Hz	1.42% p-p 2.2 Hz	0.84% p-p 2.2 Hz	<i>sustained oscillations start at 22 s (7 s after fault)</i>
S1j	B, D, SC 250, GFB 700, Robt SC1 & SC2	10.02% p-p 2.2 Hz	1.21% p-p 2.2 Hz	0.70% p-p 2.2 Hz	
S1k	<i>Transmission tie-in,</i> Robt SC1 & SC2	11.90% p-p 2.3 Hz	1.76% p-p 2.3 Hz	1.26% p-p 2.3 Hz	
S1l	<i>Transmission tie-in,</i> GFB 700, Robt SC1 & SC2	0.24% p-p 2.2 Hz	<0.1%	<0.1%	<i>disturbance at 25.1 s causes an oscillation that damps to the above value before the end of the simulation.</i>
S1m	<i>Transmission tie-in,</i> B, GFB 700, Robt SC1 & SC2	0.20% p-p 2.0 Hz	<0.1%	<0.1%	<i>disturbance at 25.1 s causes an oscillation that damps to the above value before the end of the simulation.</i>
S1n	<i>Transmission tie-in,</i> B, D, GFB 250, GFB 700, Robt SC1 & SC2	0.20% p-p 2.0 Hz	<0.1%	<0.1%	<i>disturbance at 25.1 s causes an oscillation that damps to the above value before the end of the simulation.</i>

## Results S2

Table 11: Summary of contingency analysis: Maximum Export: S2

Test	In-service	Observation (Voltage oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
S2a	All GFL BESS	2.65% p-p multiple freqs	1.00% p-p multiple freqs	2.14% p-p multiple freqs	<i>oscillations at multiple frequencies for the first 10 s (post fault clearance), and damp to &lt;0.1% after that.</i>
S2b	B	<0.1%	<0.1%	<0.1%	
S2c	A	<0.1%	<0.1%	<0.1%	<i>oscillations are slightly larger in</i>

Test	In-service	Observation (Voltage oscillations) and any comments			
		Davenport	Para	Robertstown	Comments
					<i>magnitude than when Blyth West (only) is integrated.</i>
S2d	A, B	3.11% p-p 4.4 Hz	1.22% p-p 4.4 Hz	1.70% p-p 4.4 Hz	

### Results S3

Table 12: Summary of contingency analysis: Maximum Export: S3

Test	In-service	Observation (Voltage collapse) and any comments			
		Davenport	Para	Robertstown	Comments
S3a	All GFL BESS	N/A	N/A	N/A	<b>Voltage collapse</b>
S3b	B	N/A	N/A	N/A	<b>Voltage collapse</b>
S3c	A	N/A	N/A	N/A	<b>Voltage collapse</b>
S3d	C	N/A	N/A	N/A	<b>Voltage collapse</b>
S3e	E	N/A	N/A	N/A	<b>Voltage collapse</b>
S3f	D	N/A	N/A	N/A	<b>Voltage collapse</b>
S3g	GFB 700	N/A	N/A	N/A	<b>Voltage collapse</b>
S3h	GFB 250	N/A	N/A	N/A	<b>Voltage collapse</b>
S3i	Transmission tie-in	N/A	N/A	N/A	<b>Voltage collapse</b>
S3j	Transmission tie-in, GFB 700, GFB 250, B, C, F	N/A	N/A	N/A	<b>Voltage collapse</b>
S3k	Transmission tie-in, GFB 700, GFB 250, B, C, E, F	N/A	N/A	N/A	<b>Voltage collapse</b>
S3l	Transmission tie-in, GFB 700, GFB 250, B, C, E, F, SC250	N/A	N/A	N/A	<b>Voltage collapse</b>
S3m	Transmission tie-in, GFB 700, GFB 250, B, C, D, E, F, SC250	N/A	N/A	N/A	<b>Voltage collapse</b>

## Results S4

Table 13: Summary of contingency analysis: Maximum Export: S4

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S4a	All GFL BESS	<0.1%	<0.1%	<0.1%	<i>reaches &lt;0.1% oscillations at 24.5 s</i>
S4b	GFB 700	<0.1%	<0.1%	<0.1%	<i>reaches &lt;0.1% oscillations at 24.5 s</i>
S4c	B	<0.1%	<0.1%	<0.1%	<i>reaches &lt;0.1% oscillations at 23.8 s</i>
S4d	GFB 700, B	<0.1%	<0.1%	<0.1%	<i>reaches &lt;0.1% oscillations at 23.3 s</i>
S4e	GFB 700, D	<0.1%	<0.1%	<0.1%	<i>reaches &lt;0.1% oscillations at 21.8 s</i>

## Results S5

Table 14: Summary of contingency analysis: Maximum Export: S5

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S5a	All GFL BESS	<0.1%	<0.1%	<0.1%	

## Improvements observed (Maximum Export)

The maximum improvement potentially due to GFM mode is tabulated below based on the results from section 4.2. There is significant improvement (greater than 0.5%) in reducing amplitude of low frequency oscillation.

Table 15: Improvements observed (Maximum Export)

Scenario	Maximum improvement (%) due to GFM		
	Davenport	Para	Robertstown
S1	9.16	1.69	1.77
S2	2.55	0.9	2.04

### 4.3. Maximum Import Results

#### Results S1

Table 16: Summary of contingency analysis: Maximum Import: S1

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S1a	All GFL BESS	<0.1%	<0.1%	<0.1%	

#### Results S2

Table 17: Summary of contingency analysis: Maximum Import: S2

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S2a	All GFL BESS	<0.1%	<0.1%	<0.1%	

#### Results S3

Table 18: Summary of contingency analysis: Maximum Import: S3

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S3a	All GFL BESS	<0.1%	<0.1%	<0.1%	

#### Results S4

Table 19: Summary of contingency analysis: Maximum Import: S4

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S4a	All GFL BESS	<0.1%	<0.1%	<0.1%	

#### Results S5

Table 20: Summary of contingency analysis: Maximum Import: S5

Test	In-service	Observation (Stable) and any comments			
		Davenport	Para	Robertstown	Comments
S5a	All GFL BESS	<0.1%	<0.1%	<0.1%	

#### Improvements observed (Maximum Import)

The maximum improvement potentially due to GFM mode is not calculated for this case (Maximum Import) as the original state with all GFL resulted in less than 0.1% of low frequency oscillation.

#### 4.4. Special Notes from Results

The sections 4.1, 4.2 and 4.3 presented an exhaustive set of tests and the corresponding results from PSCAD simulations of the Wide Area Network with new IBR and GFBs included. Those results clearly indicated that the GFM BESS can improve system strength under many different instances within the scenarios (S1 to S5) tested and for many AG dispatch cases (three cases) by application of GFM mode on each of the considered BESS. Some cases with a combined fleet of GFM BESS did not perform any better than the individual performance. This was identified as an interference effect which deserves further investigation.

The individual performance in quantified form of each BESS under GFM operating mode was the main interest of the present investigation. For this purpose, the hosting capacity improvement (in MW) at a given SSN was assessed per each of the eight (8) BESS plants proposed (under committed and anticipated). In order to assess this special performance a separate strategy (see section 3.2) was developed in this study. Following the new strategy the GFM BESS plants were assessed at each SSN and a short summary is given in **Table 21**. The following results / trends were identified from the early-stage tests of individual BESS performance.

Table 21: Maximum IBR volume (MW) achieving stable voltage waveform at the closest SSN from the GFM BESS location.

BESS reference	Bus (kV)	Closet SSN	Improvement of Hosting IBR (MW) at the SSN
A	275	Davenport	210 MW at Davenport
B	275	Davenport	220 MW at Davenport
C	132	Davenport	10 MW at Davenport
D	132	Robertstown	(N/A) See Appendix 6
E	275	Robertstown	(N/A) See Appendix 6
F	132	Para	24 MW (SVC dynamic model active)
G	275	Para	415 MW at Para (SVC dynamics active)

## 5. Early Inferences

Based on the assessment undertaken following concepts are established.

- A GFM BESS connected in the vicinity of a SSN may be able to host stable voltage waveform for up to 220 MW (connected to Davenport 275 kV) and 415 MW (connected to Para 275 kV) of additional IBR of type 2 wind farm generation. This additional capacity is realized when the GFM BESS is connected to the same transmission level as the SSN. When the GFM BESS is connected to a lower transmission level (i.e. 132 kV) the SSN support is significantly reduced.
- Due to modelling decisions made at the commencement of these studies, the network was not suitable to confidently come to a conclusion regarding the potential requirement of GFM BESS in the Robertstown area. This is due to the connection of an ideal source at the Bundy 330 kV boundary bus. This ideal source is not sufficiently far enough from Robertstown 275 kV to observe the dynamics produced by a disturbance. To confidently extract the desired information, it is recommended to move the boundary bus to Buronga or Wagga-Wagga within NSW.
- With multiple lines OOS in the Para area, the maximum amount of additional capacity from GFL IBRs was 845 MW (**See Appendix 6**) when only GFL BESS units were considered. An additional 415 MW can be included with the existence of a GFM BESS installed at 275 kV. To gain further understanding

of the additional 498 MW of IBR at Para 275 kV, this model would require modifications. It is recommended to create the desired power flow using a steady state software and then use that information to accurately represent the desired situation.

- Having multiple GFM BESS operating in close proximity can cause interference resulting in lesser system strength than one BESS at a time (**See Appendix 2 – Improvement to Voltage Stability**).
- BESS interference due to control interactions may be reduced or eliminated by control tuning with highly focused specific implementations involving inputs from the OEMs (**See Appendix 3 –Effect of Multiple GFM BESS Models**).
- Multiple GFM BESS operating have the ability to provide sufficient support to mitigate a catastrophic event.

### 5.1. Interaction between GFM Batteries

It was observed that the combined effort of multiple BESS projects has a detrimental effect on system strength in comparison to a single BESS within the local area. This effect is due to interference of one's output with another BESS's possibly control interaction.

It is possible that this interference can be reduced by careful design of control loops, settings and similar proprietary features, that can be studied further in a future investigation.

## 6. Further Work

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To further understand the behaviour of grid forming BESS plants and their collective contribution in the South Australia HV network, some of the following studies may be relevant and proposed as potential next steps.

1. **Controller Interaction Study Using GFB Tuning as a Mitigation Technique:** Within this report there was one contingency where an oscillation was present when two GFBs were in operation. It was concluded that this is due to a controller interaction. It would be necessary to involve the OEM, however, this oscillation should be able to be mitigated through proper tuning. Such a future study's aim would be to definitively demonstrate that.
2. **Wide Area Study:** It would be beneficial to test the battery within a future grid (i.e. containing full PEC transmission upgrade). The model would need to be extended into NSW (Yass 330 kV) and into VIC (Ballarat 220 kV) to get a better understanding of the GFB operation near the state boundaries. It would also be important to observe the GFB operation under charging and discharging scenarios. This would uncover possible limitations that the GFB have and would allow for further investigations into mitigation and perhaps applying constraints on GFB dispatch.
3. **GFB to Support IBRs at the End of Long Lines:** This report indicated that a GFB can be a reliable source of system strength locally. A study extending this finding is how well can a GFB support an IBR (or IBRs) that (after a contingency) are turned radially connected via a long transmission line.

4. **SSO Study:** Being that there are type 3 WFs within South Australia, a HVDC line connected between SA and NSW and upgraded transmission lines (from PEC) it would be worthwhile to investigate how the GFB adds to stable operation in the sub-synchronous range. This would include a network frequency scan and (if warranted) PSCAD studies to further investigate any findings (from the frequency scanning) that are of major concern.
5. **Inertial Capabilities of GFB:** This study would be conducted to investigate if the GFB could be a suitable replacement for the existing synchronous machines with regards to inertia. It would involve sizing a BESS to a similar size as one unit at G and creating a loss of generation (i.e. trip the remaining unit). From this the fast injection of active power (effectively inertia) could be compared to the existing synchronous unit. It is also worthwhile to investigate how the dispatch of the GFB affects this behaviour.
6. **Blackstart Using GFB:** This study would be conducted to see the feasibility of using GFBs (only) to do a blackstart within SA. This study would contain no synchronous machines and could be initiated using the existing path or alternative paths can be investigated.
7. **Islanding:** This study would be geared towards understanding how the system operates when all interconnectors are lost under two scenarios; (1) when GFBs and synchronous machines are considered and (2) when only GFBs are considered.
8. **GFB Replacing Synchronous Condensers:** This study would be conducted to understand the effectiveness of GFBs as a substitute for synchronous condensers. It would involve best placement of the GFBs as well as size of the GFB (when operating in Id control and in Iq control).

## 7. Conclusions

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The performance of a number of Batteries already committed or anticipated on the SA High Voltage Transmission network was studied for potential contribution to System Strength if operated under GFM mode.

Under carefully selected severe contingency environments, the GFM operation mode was tested for each Battery and then for multiple Batteries for their collective effort on improvements in System Strength.

Based on the assessment undertaken, the GFM BESS exhibits improvement in System Strength mainly within the local area of connection. Under multiple GFM BESS environment the collective effort was observed to be lower than a linear sum of the individuals. This collective effort was also found to depend on the import / export dispatch conditions.

Control tuning to mitigate interaction among the nearby GFM Batteries is beyond the scope of this study; however, a further study aimed at compensating GFM BESS interaction can demonstrate the way ahead for enhanced control techniques to tap the maximum collective potential for system strength from a group of BESS plants connected to the network. The idea is to get each BESS plant in the network oriented to work towards a common goal of supplying system strength at the maximum level as a group.

The oscillations (a measure of system weakness) do not appear to be linked, specifically, to the GFB models, but the site-specific tuning and with additional tuning (supported by the OEM) the oscillations (observed) should be able to have improved damping.

Tie in Blyth West and Brinkworth lines to see the mitigating effect on voltage collapse is noteworthy (**See Appendix 4**).

Studies showed that a GFM BESS connected in the vicinity of a SSN may be able to host stable voltage waveform for up to 220 MW (connected to Davenport 275 kV) and 415 MW (connected to Para 275 kV) of additional IBR type 2 wind farm generation. This additional capacity is realized when the GFM BESS is connected to the same transmission level as the SSN and reduced when the GFM BESS is connected to a lower transmission level (i.e. 132 kV).

## 8. References

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## Attachments – Study results

### 1. Appendix 1 – GFL BESS vs GFM BESS

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The grid forming BESS has the ability to provide multiple benefits to a local network, including:

- Improving voltage stability
- Ability to provide very fast frequency response.
- Ability to provide positive system damping in the sub-synchronous range.

This study conclusively demonstrated that the grid forming BESS **improves local network stability**. When the fault is applied the grid forming BESS minimizes the voltage angle change, holding the angle to a roughly constant value. When the fault is cleared, the voltage angle close to its new stability point and therefore the system is able to reach a stable operating point. The example below shows the effect of the grid forming BESS on the voltage angle (both at the inverter and POC) and the positive effect it has on the local system (when compared to the grid following BESS).

## S2 – Min Export Case Comparison (GFB B vs GFL)

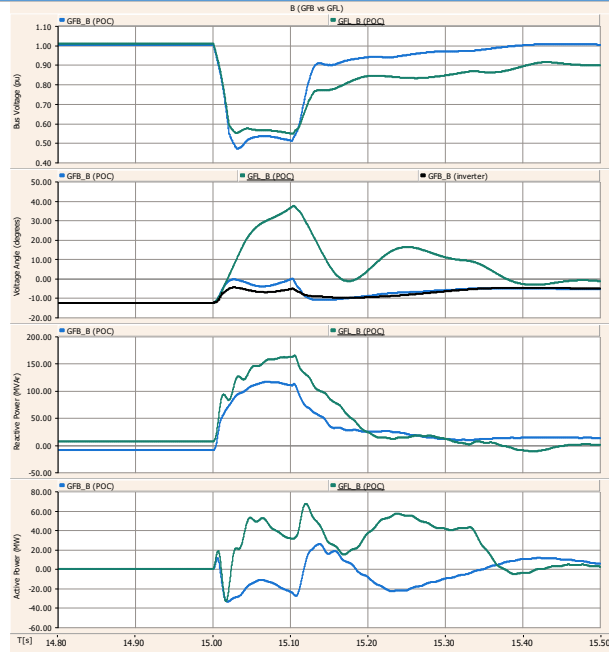


Figure 3: Time scale (14.8s to 15.5s) – GFB B vs GFL)

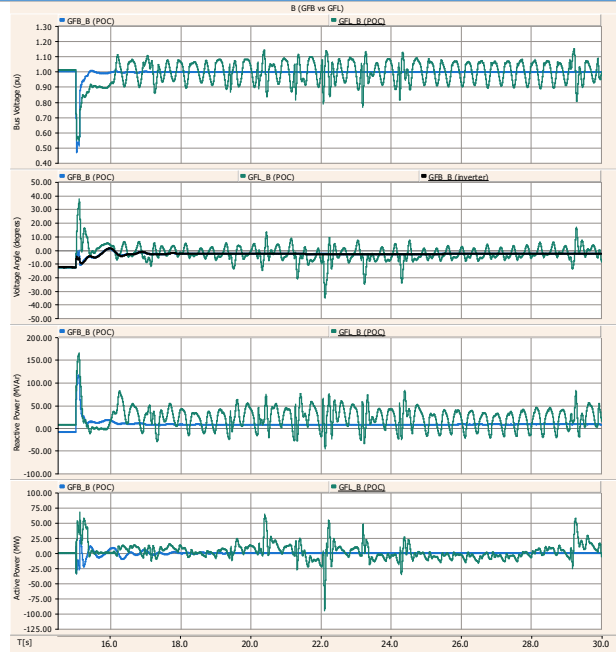


Figure 4: Time scale (14.5s to 30s) – GFB B vs GFL)

In the above example, the grid following BESS receives the voltage measurement from the grid and uses that for its controls. This N-1-1 scenario creates a weaker system, within the area of GFB B and GFB A, on account of losing two key transmission lines. Within the weaker system larger voltage angle swings are observed. By design, the GFL will receive these large angle changes and use them to follow the grid conditions. Large changes in voltage angle significantly affect the PLL within the GFL (~40° change is observed when the fault is cleared), and the controls are unable to reach a stable operating point. This occurrence gets worse as system strength weakens.

A grid forming BESS is able to provide a **very fast frequency response**. This current injection can be accomplished in cycles and can help when an inertial event occurs in a remote portion of the network. It is important to note that in order for a grid forming BESS to deliver a very fast frequency response, the BESS is required to have sufficient capacity available (i.e. BESS operating at 0 MW). Since grid following BESS units follow the system, this option is not available.

Lastly, the grid forming BESS has the ability to provide **positive system damping in the sub-synchronous range**. This is also possible within the grid following BESS. However, in the case of grid forming BESS, this is in addition to the above benefits.

## 2. Appendix 2 – Improvement to Voltage Stability

Sub-synchronous Oscillations greater than 0.1% are observed at the SSN 2 bus in a N-1-1 study:

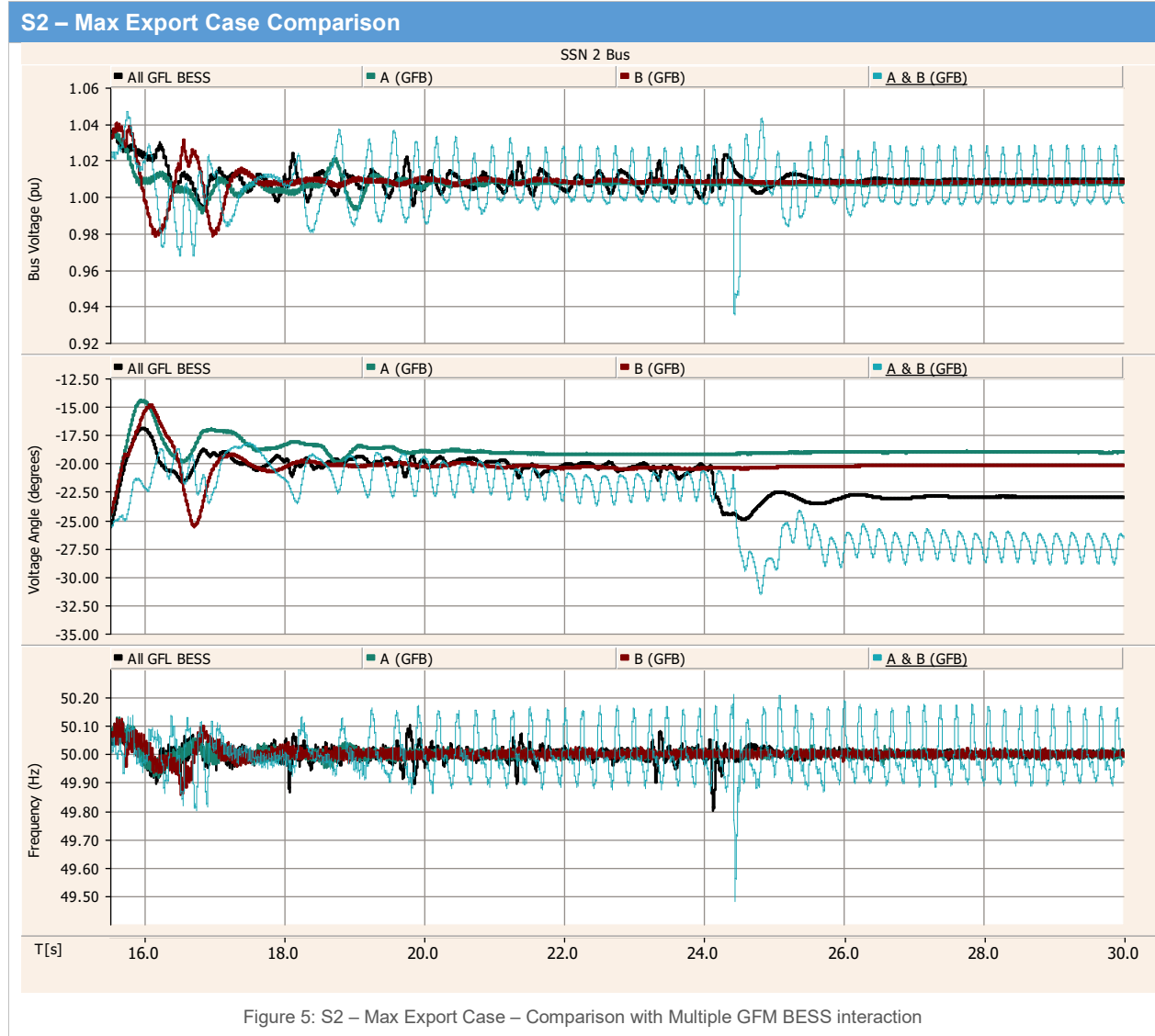
This oscillation observed when all BESS models being considered were operating in grid following mode was significantly improved when a BESS close to the line outages was operated in GFM mode. As the BESS (placed in GFM mode) moved further away from the line outages the oscillations were either mildly improved (not to any acceptable level) or not improved. This implies that the improvements to the system provided by GFM BESSs has a local effect.

### 3. Appendix 3 –Effect of Multiple GFM BESS Models

Oscillations greater than 0.1% are observed at the SSN 1 bus in a N-1-1 study:

This oscillation was observed when all BESS models being considered were operating in grid following mode.

This oscillation was reduced when either GFB A or GFB B were operating one at a time in grid forming mode. However, when both GFB A and GFB B operated in grid forming mode the oscillation became larger than when all BESS models were operated in grid following mode



The significant oscillations (when both GFB A and GFB B models operate as GFBs) are believed to be the result of improper tuning for the specific network condition. This hypothesis is supported by running the same (S2) contingency under different network conditions (minimum import). Therefore, the oscillations do not appear to be linked, specifically, to the GFB models, but the site-specific tuning and with additional tuning (supported by the OEM) the oscillations (observed above under two GFBs together) should be able to have removed via improved damping.

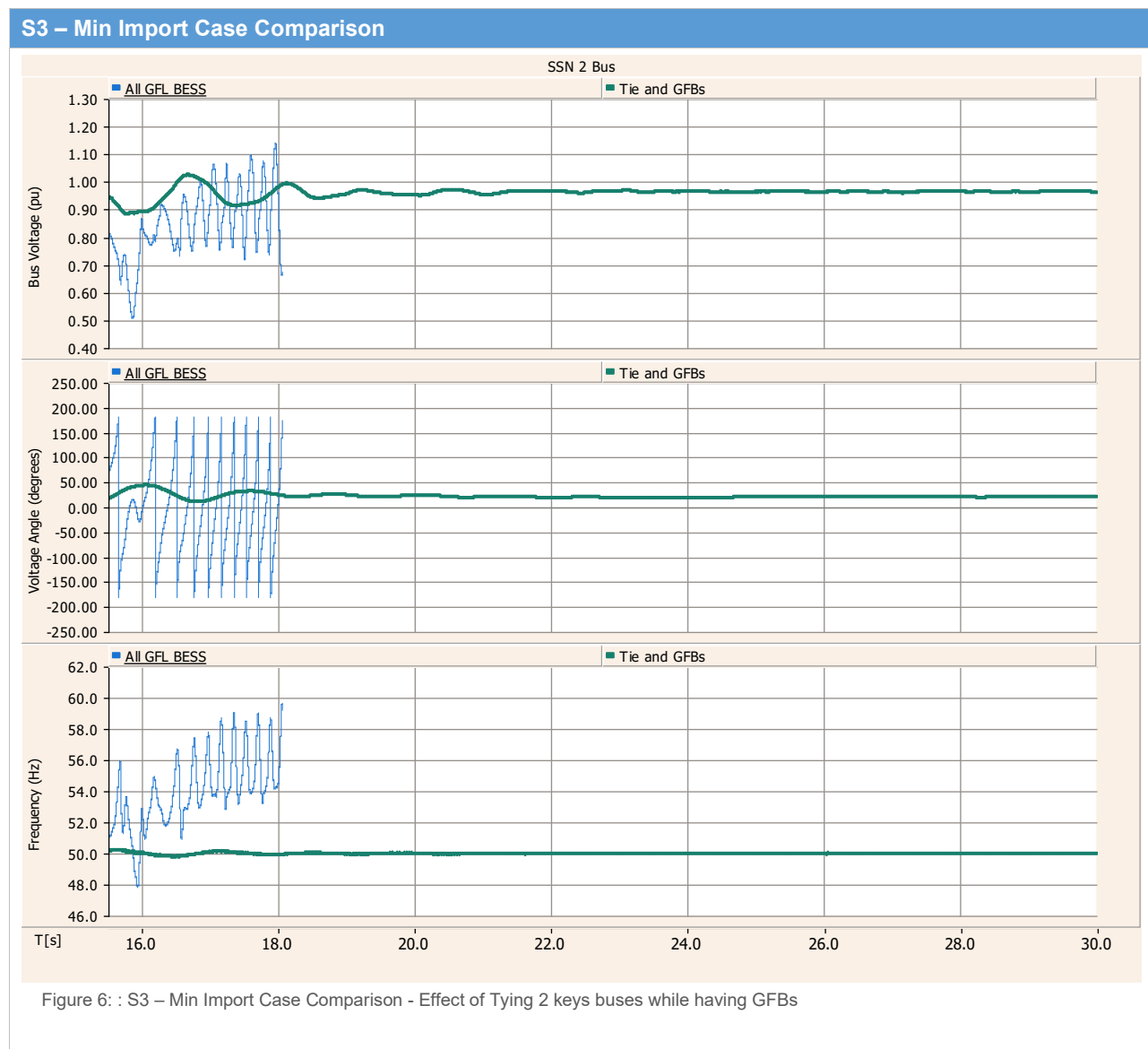
## 4. Appendix 4 – Improvement to Voltage Stability for a Non-credible Contingency

Voltage collapse was observed throughout the system for a major (N-1-2) contingency:

**This voltage collapse was able to be avoided, and stable operation was observed using the following arrangement of the network:**

- Tie two key buses.
- A future GFB, and several other GFBs in-service.

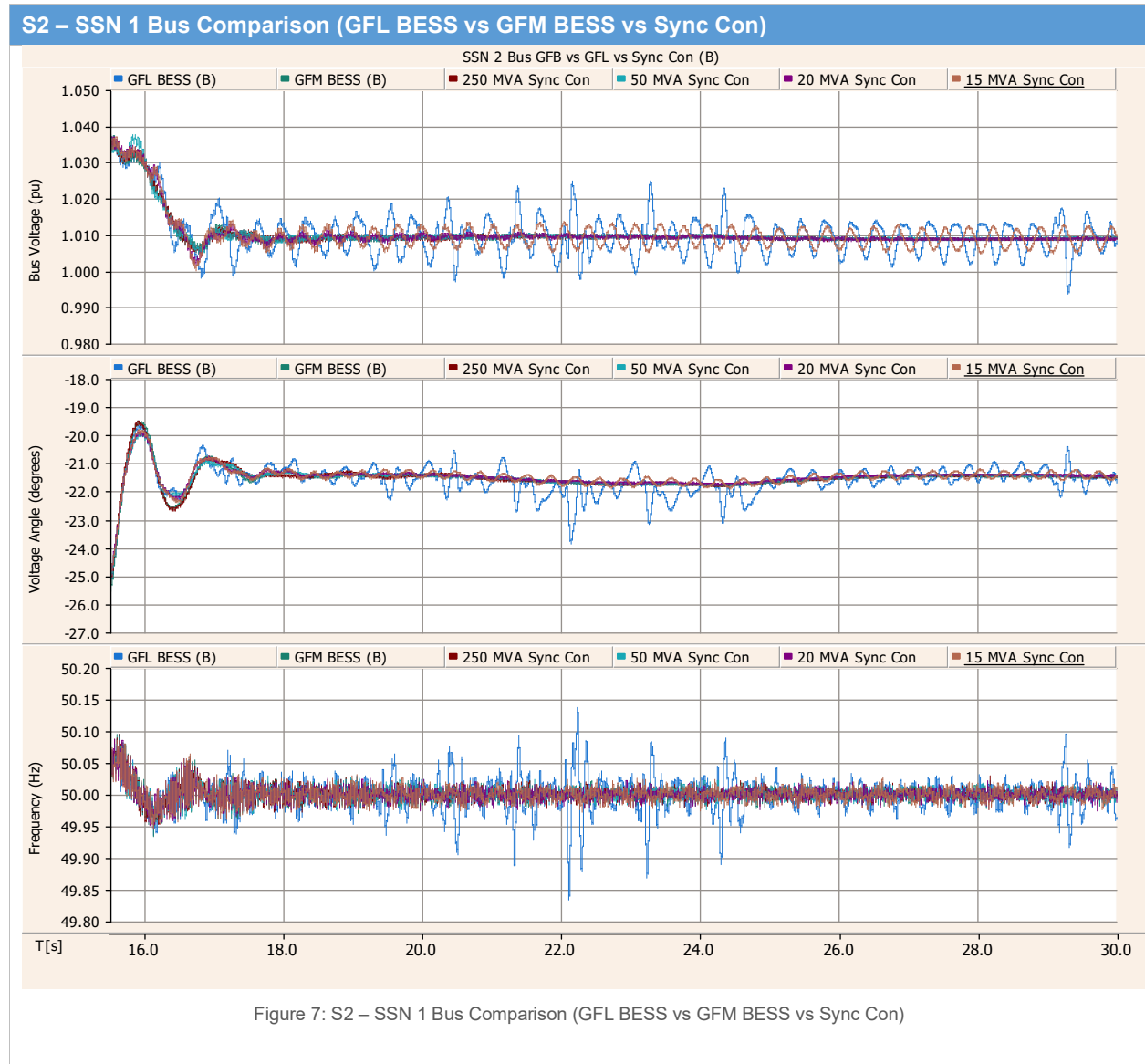
This contingency provides evidence that the operation of many GFBs within the network provides sufficient assistance to avoid a catastrophic event (see Figure 6) provided two key buses are tied in.



## 5. Appendix 5 – GFL BESS vs GFM BESS vs Synchronous Condenser

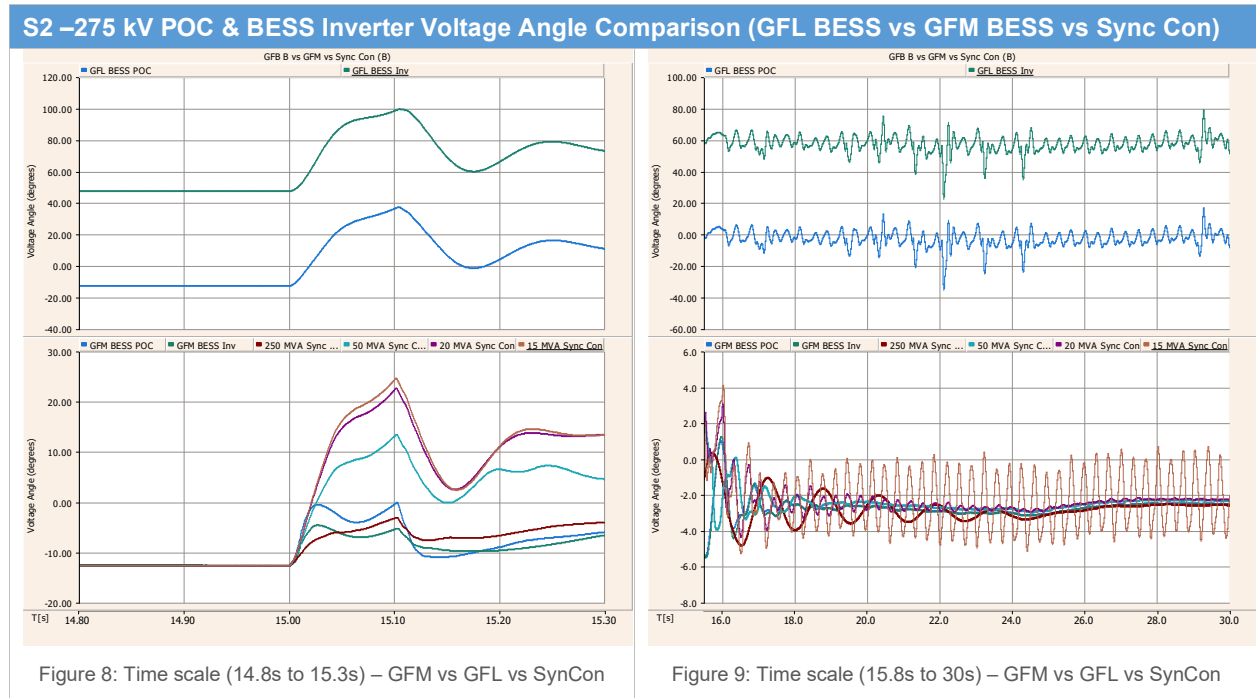
The GFM BESS was compared with the GFL BESS as well as a various sized synchronous condensers. The three different models used in this test were 1) GFL BESS (200 MW), 2) GFM BESS (200 MW) and 3) a synchronous condenser (of various sizes) connected to the 275 kV bus for a N-1-1 contingency:

At SSN 1 both the GFM BESS and a synchronous condenser larger than ~15 MVA provide similar conditions such that the oscillations (observed with the GFL BESS in-service) are no longer present. This finding strengthens the conclusion that the GFM is supplying sufficient system strength.

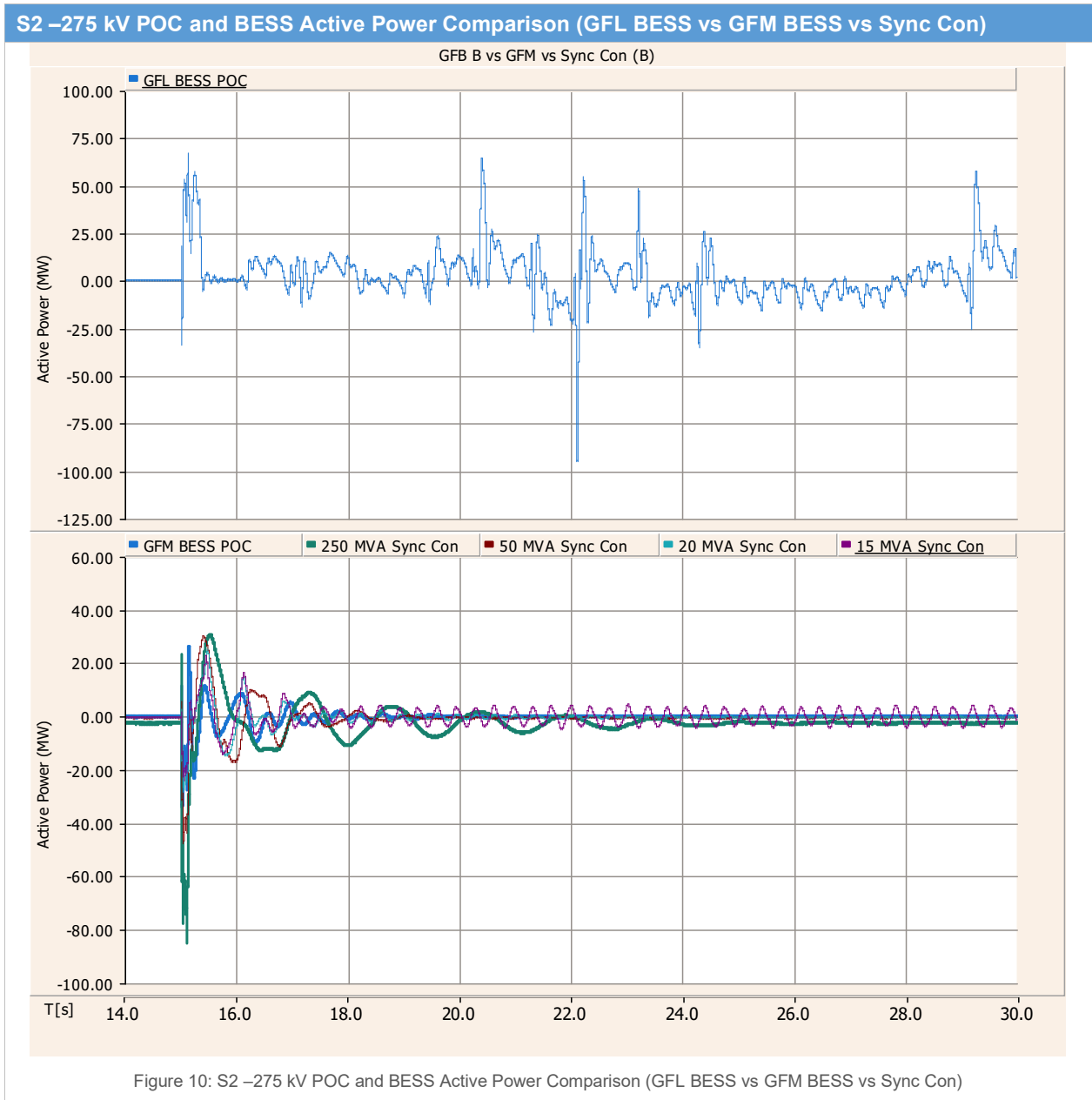


Regarding the voltage angle change, the GFM BESS performs similarly to the synchronous condenser during the fault, in that it attempts to hold the voltage angle at a constant (this is most obvious when considering the 250 MVA sync con, but as the sync con reduces in size its ability to maintain a constant voltage angle also significantly decreases). Looking further in the simulation towards steady state, the GFM BESS does not contain the low frequency (~0.6 Hz) oscillations that the 250 MVA synchronous condensers does. This

oscillation was observed to be sufficiently dampened if a 50 MVA (to the bottom threshold of ~15 MVA) synchronous condenser was considered. Therefore, the GFM BESS exhibits improved performance in this regard.



The effect of the improved convergence to a stable steady state in the voltage angle is most observable in the active power response. The synchronous condenser is observed to have significantly larger oscillations (~19.1 MW (at the most extreme) when comparing the GFM BESS to the 250 MVA sync con) after the fault clearance and these oscillations are still present at the end of the simulation (30 s) albeit at a reduced magnitude. In comparison the GFM BESS is not observed to have these low frequency oscillations (typically attributed to synchronous machines).



Lastly, looking at the reactive power during the fault, the GFM BESS performs in a similar fashion to the synchronous condenser, in that they both are injecting (relatively) stable reactive power into the network. It is worth noting that the GFM BESS does not have the small oscillations that are observed in the synchronous condenser output. Also, since the GFM BESS is fully controllable, it is possible to increase (or reduce) the amount of reactive current injection during a fault.

### S2 –275 kV POC and BESS Inverter Reactive Power Comparison (GFL BESS vs GFM BESS vs Sync Con)

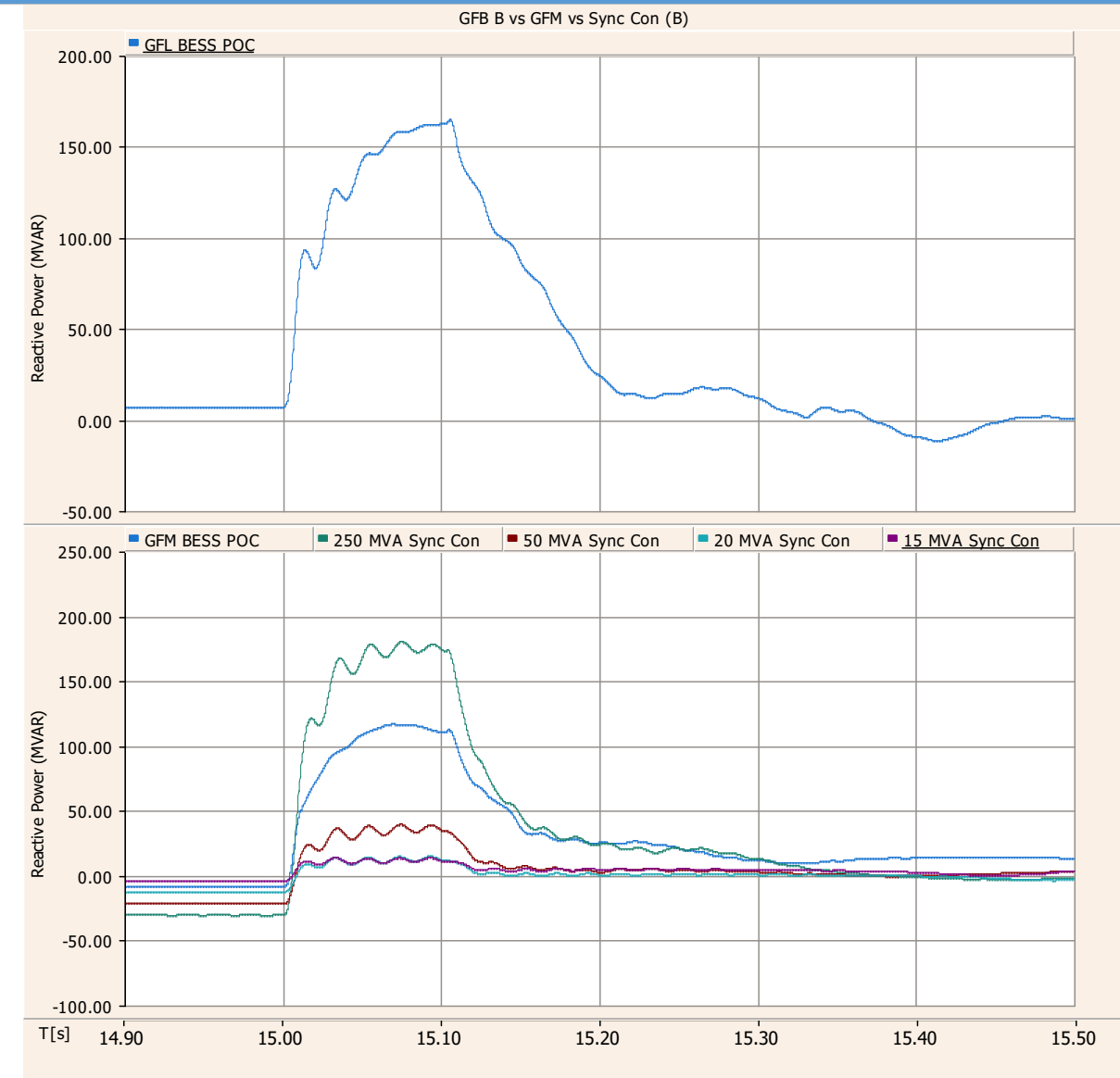


Figure 11: S2 –275 kV POC and BESS Inverter Reactive Power Comparison (GFL BESS vs GFM BESS vs Sync Con)

Therefore, based on this study, the GFM BESS can be used as a local source of system strength, and has the ability to provide support comparable to a synchronous condenser of appropriate sizing. In this case, that size was observed to be > 15 MVA. The GFM BESS also has the additional benefit of getting to a steady state point much quicker with a significant reduction in voltage angle oscillations.

## 6. Appendix 6 – GFM BESS Support at SSNs

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A single GFM BESS was placed in-service to obtain an initial idea of how much support it can lend to three different SSNs. Only BESS units geographically close to each SSN were considered. Three different network changes were made to evaluate this.

- 1) to evaluate the effectiveness that BESS A and B have on **SSN 1** a two transmission lines were disconnected.
- 2) The network model used for these studies was ill-suited to evaluate the effectiveness of BESS D and E have on **SSN 2**.
- 3) to evaluate the effectiveness of BESS G and H have on **SSN 3** four transmission lines were disconnected.

For each case mentioned above a base case was developed. This base case contained only GFL BESS units and type 2 wind farm generation was added at the SSN until the voltage oscillation just surpassed the threshold of 0.5% measured at the associated SSN. Next, a single GFM BESS was placed in-service (putting the GFL BESS with the same name OOS) and generation was added to the SSN until the voltage oscillation reached the threshold of 0.5% measured at that SSN. The difference between these two values is an estimate of the additional generation of GFL IBRs that can be supported with one GFM BESS in-service.

### **Base Case (SSN 1)**

With only GFL BESS units in-service this node (as-is in the network) can support between 650 MW and 660 MW

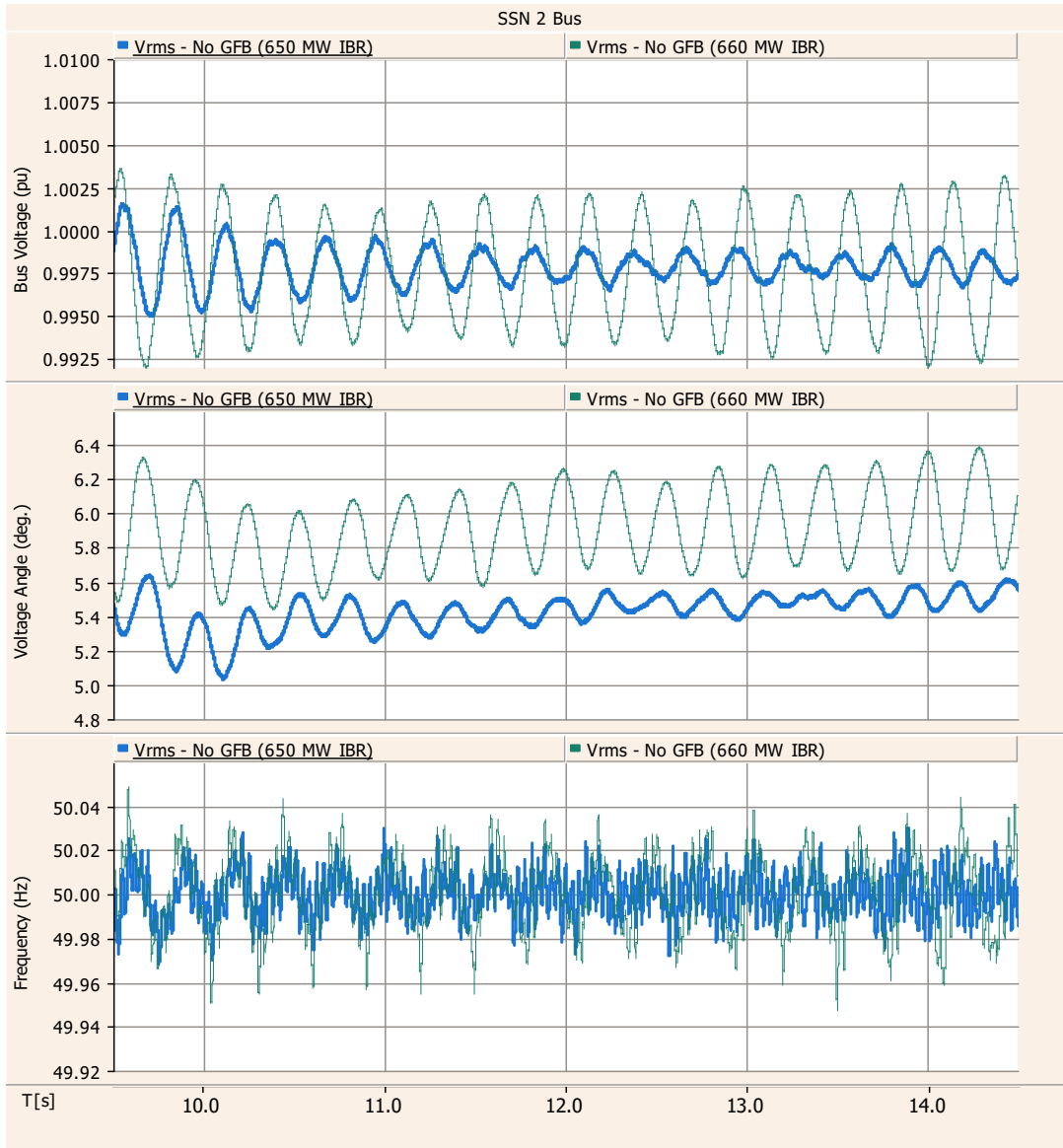


Figure 12: Base case without any GFB trying to host 650 MW of IBR at SSN 1

**BESS C in GFM in-service (SSN 1)**

With only BESS C operating as a grid forming BESS the network can support between 660 MW and 670 MW, an increase of 10 MW from the base case. The 660 MW base case (No GFB (660 MW IBR)) was added to the top graph to demonstrate the effect the GFM BESS has on the network.

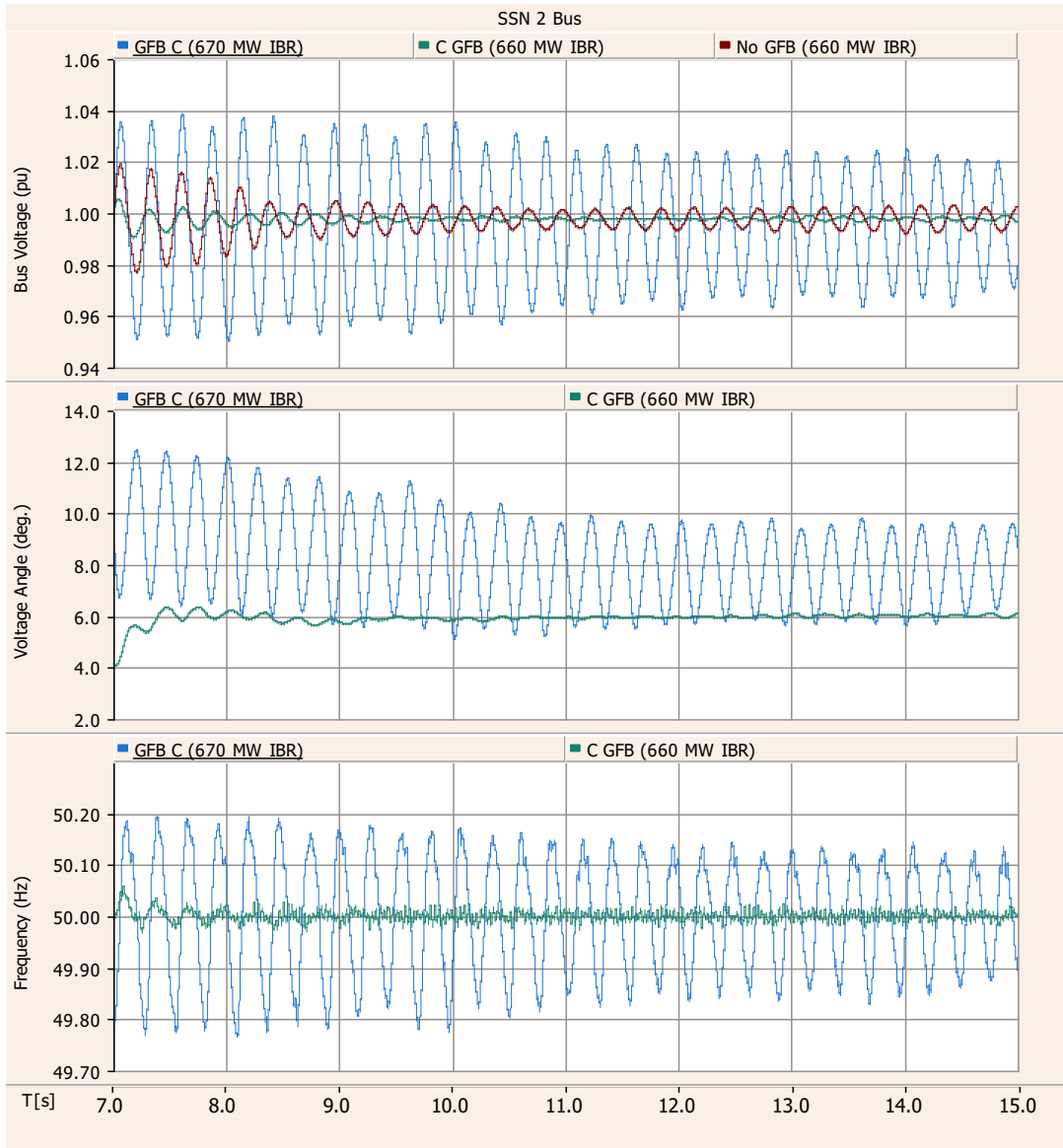


Figure 13: Effect of Clements Gap GFM BESS on trying to host 660 MW of IBR at SSN 1

### **GFM BESS A in-service (SSN 1)**

With only BESS A operating as a grid forming BESS the network can support up to 870 MW, an increase of ~210 MW from the base case. The 870 MW base case (No GFB (870 MW IBR)) was added to the top graph to demonstrate the effect the GFM BESS has on the network.

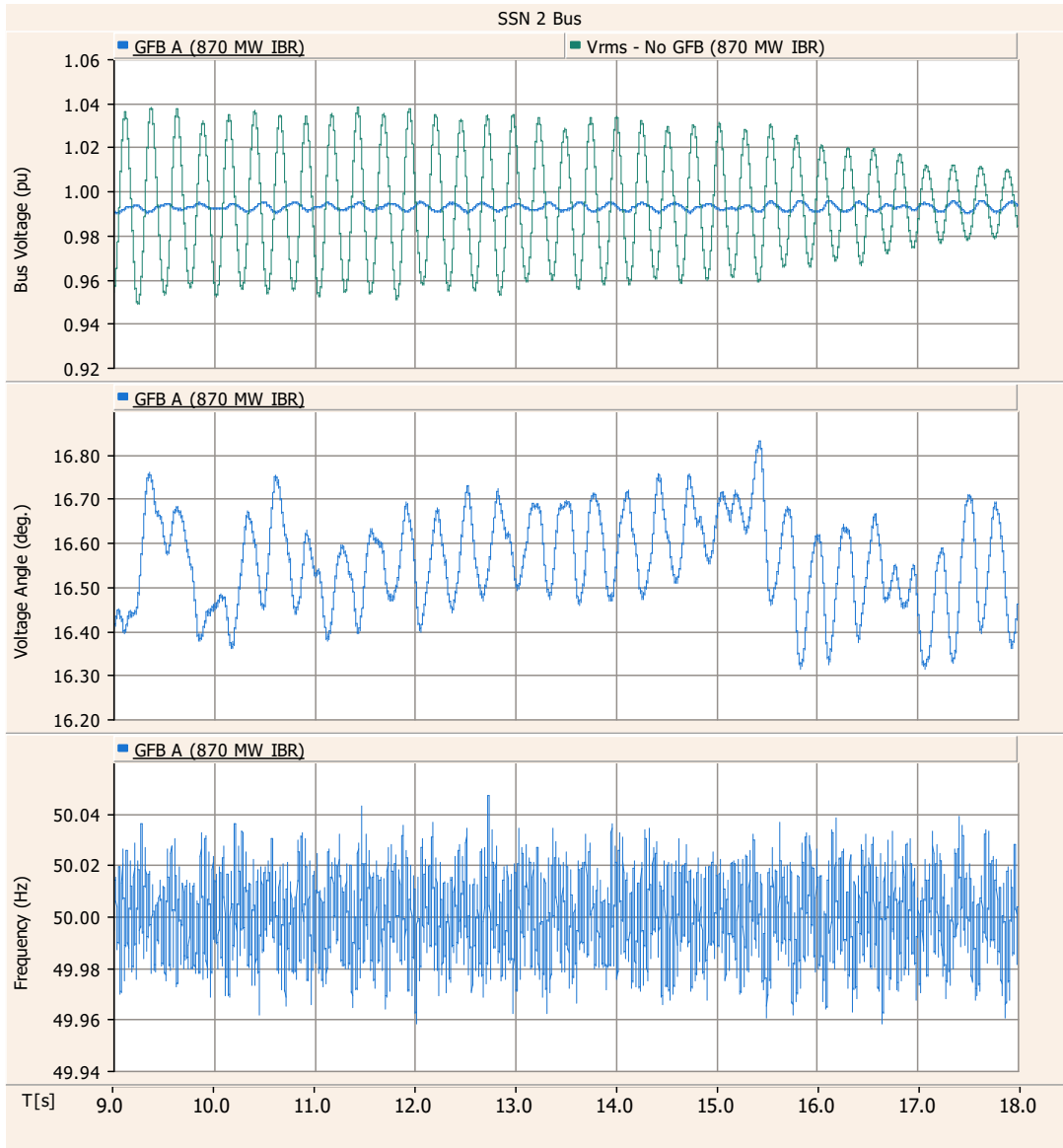


Figure 14: Effect of GFM BESS A on trying to host 870 MW of IBR at SSN 1

### **GFM BESS B in-service (SSN 1)**

With only BESS B operating as a grid forming BESS the network can support up to 880 MW, an increase of ~220 MW from the base case. The 880 MW base case (No GFB (880 MW IBR)) was added to the top graph to demonstrate the effect the GFM BESS has on the network.

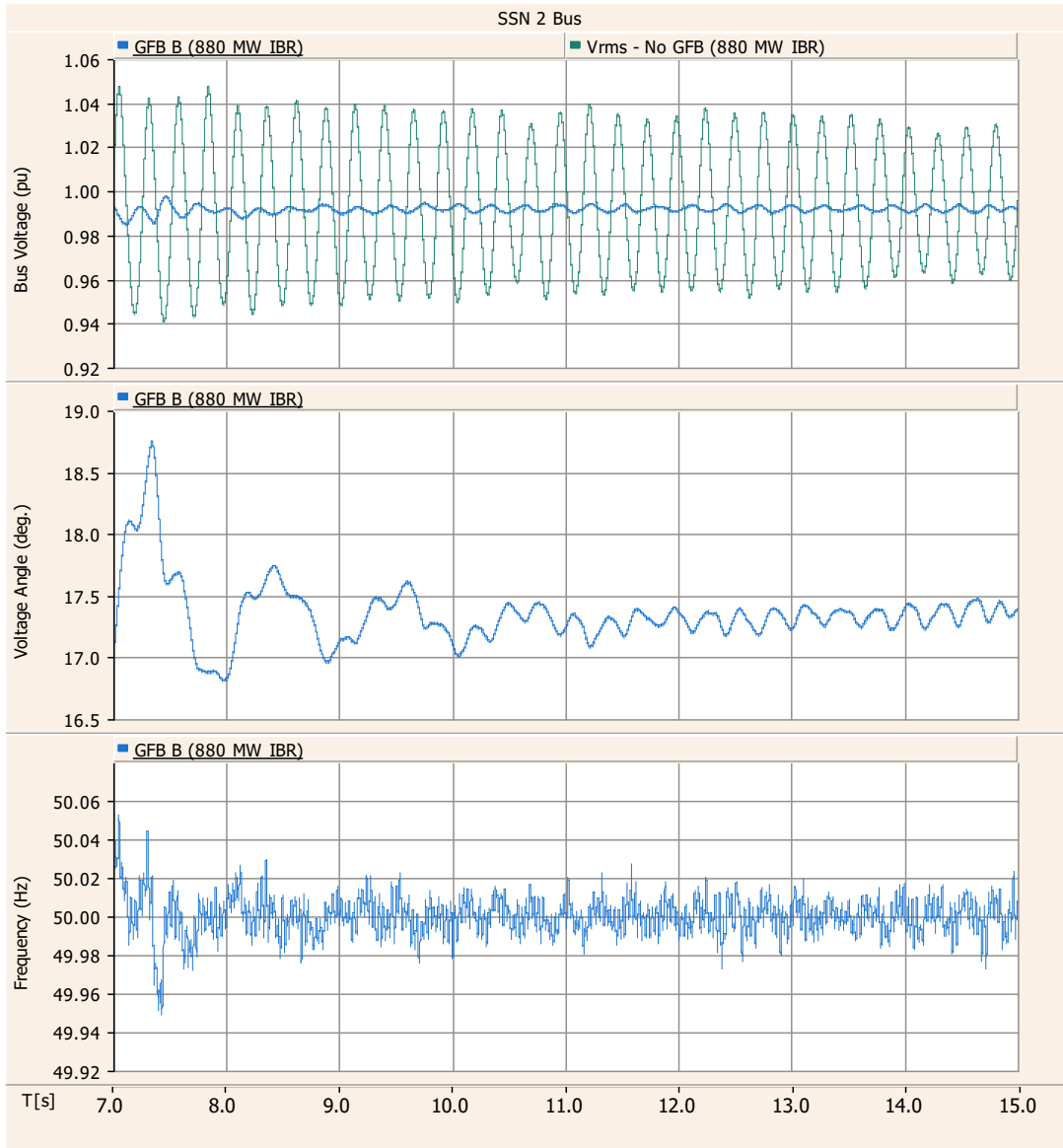


Figure 15: Effect of GFM BESS B on trying to host 880 MW of IBR at SSN 1

**Base Case (SSN 3)**

With only GFL BESS units in-service this node (as-is in the network) can support ~845 MW

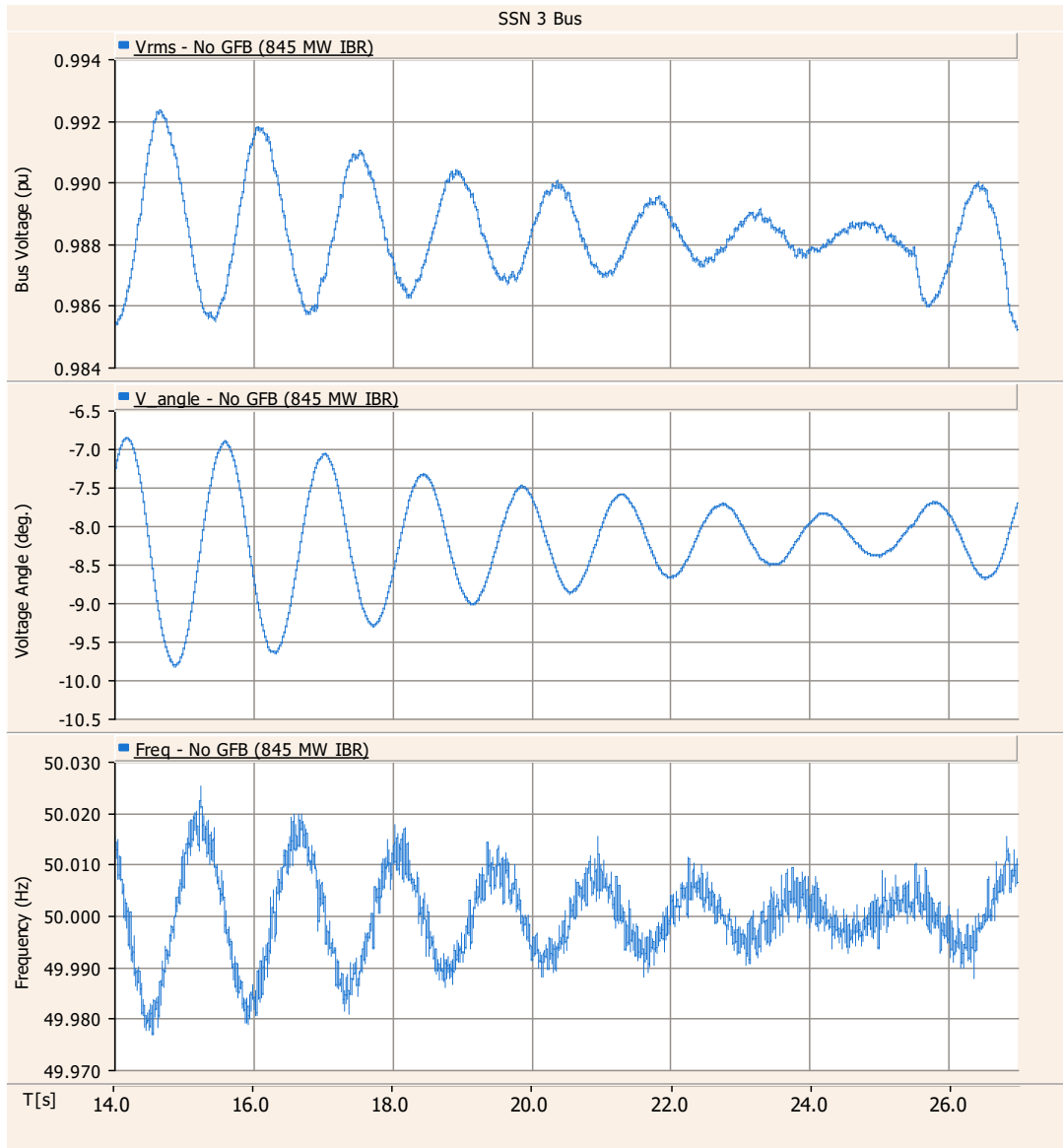


Figure 16: Without any GFM BESS trying to host 845 MW of IBR at SSN 3

**GFM BESS F in-service (SSN 3)**

With only BESS F operating as a grid forming BESS the network can support up to 869 MW, an increase of ~24 MW from the base case. The 869 MW base case (No GFB (869 MW IBR)) was added to the top graph to demonstrate the effect the GFM BESS has on the network.

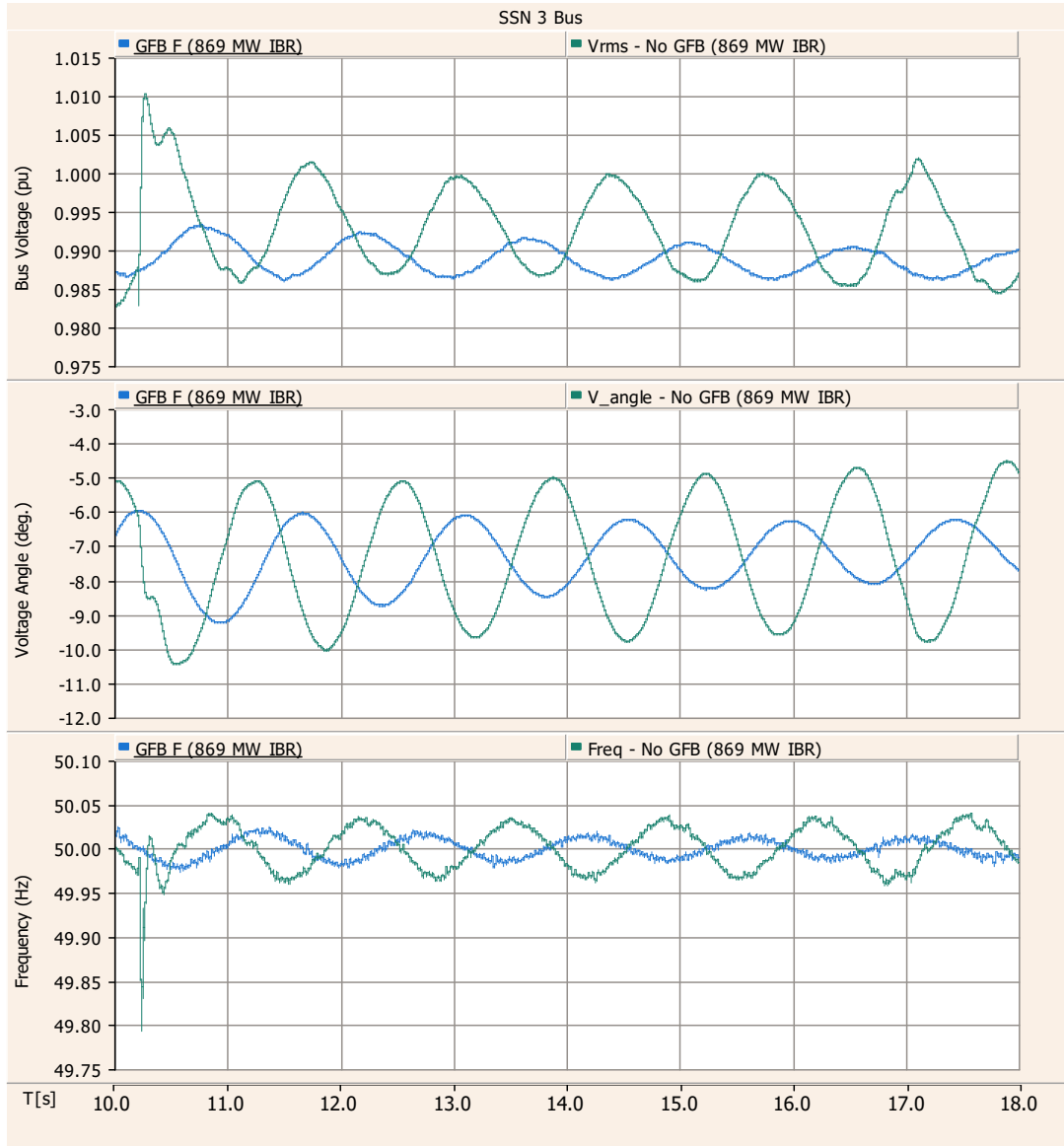


Figure 17: With and Without GFM BESS G trying to host 869 MW of IBR at SSN 3

### GFM BESS G in-service (SSN 3)

With only BESS G operating as a grid forming BESS the network can support up to 1260 MW, an increase of ~415 MW from the base case. The 1260 MW base case (No GFB (1260 MW IBR)) was added to the top graph to demonstrate the effect the GFM BESS has on the network.

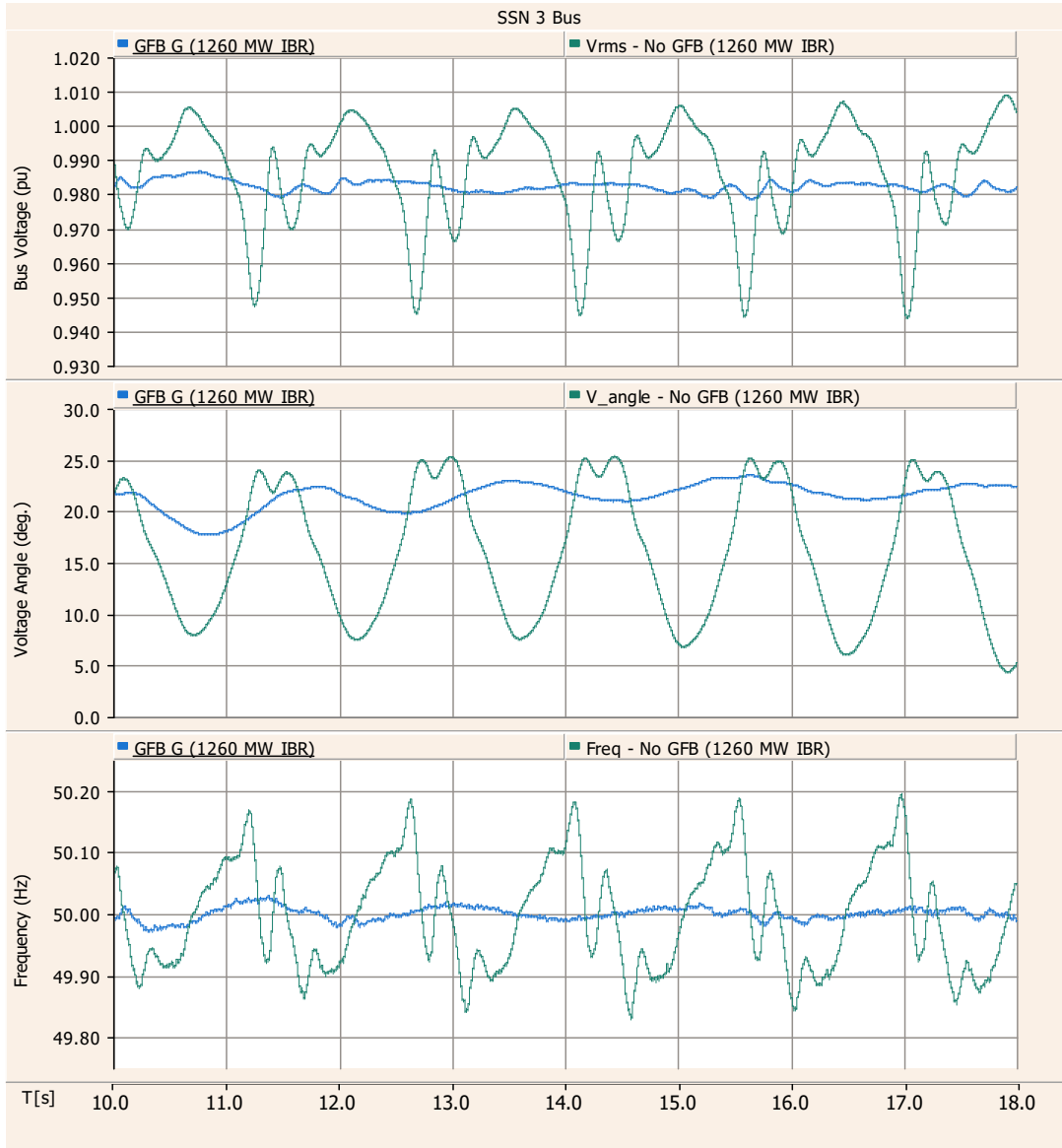


Figure 18: With and Without GFM BESS G trying to host 1260 MW of IBR at SSN 3

## 7. Appendix 7 – AEMO’s four Point Criteria

The acceptable stable voltage waveform (used in these studies) is defined using AEMO’s 4-Point Criteria (See page 20 of [2] [system-strength-requirements-methodology.pdf \(aemo.com.au\)](#)).

- (1) **RMS magnitude:** “The positive-sequence RMS voltage magnitude at a connection point does not violate the limits in the operational guides for the relevant network” [2].

This point is applied to this study through flagging voltages that fall below 0.9 pu (post fault clearance) and ensuring spikes greater than 1.1 pu (post fault clearance) exist within the acceptable system timeframe.

The example (below) is a case that violates this criteria. Here, the bus voltage falls below 0.9 pu and a subsequent voltage collapse follows. In these studies, this was always labelled as a failure. It is noted that this is an extreme example, and a dip below 0.9 pu does not guarantee a voltage collapse.

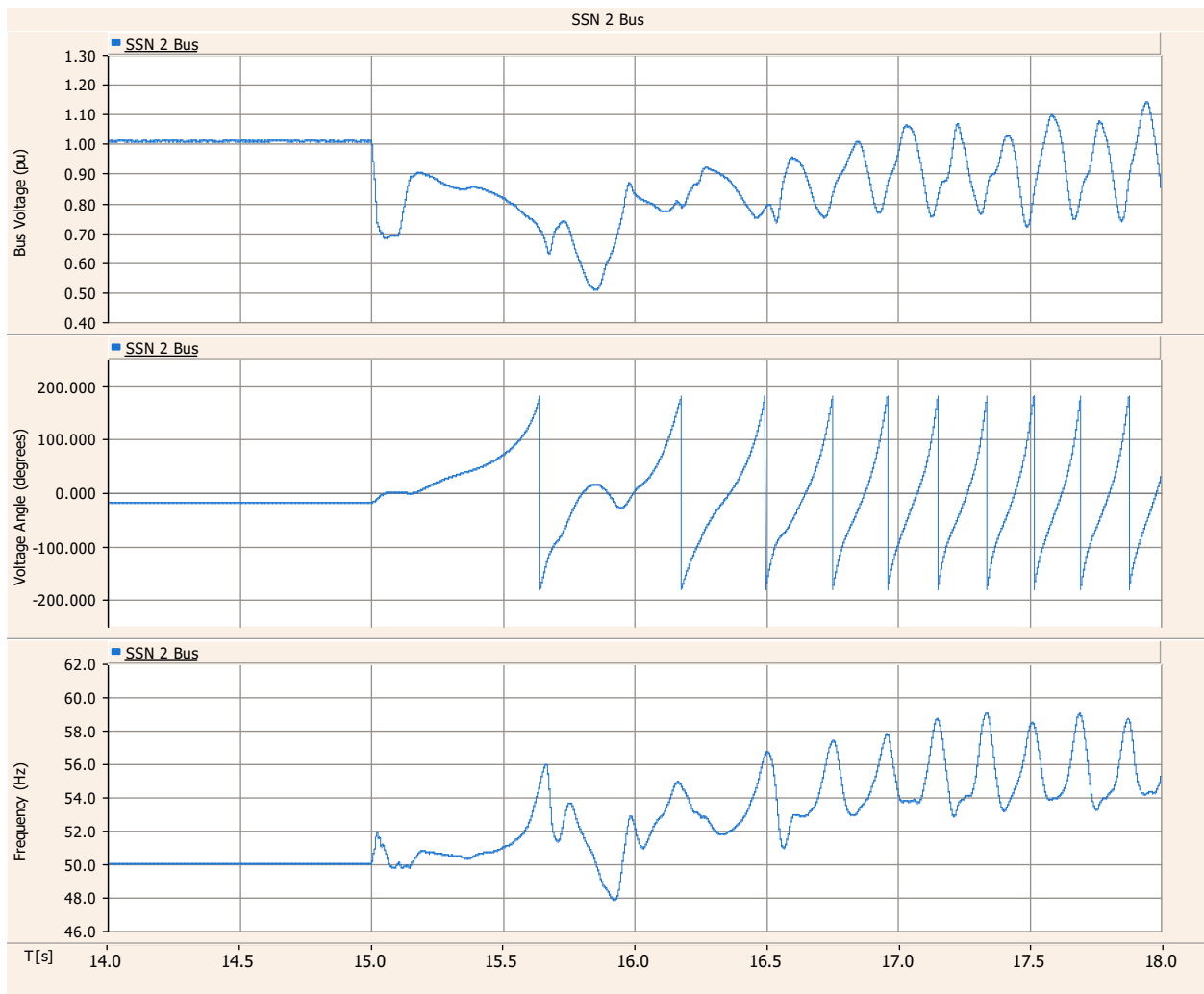


Figure 19: Example of an extreme case that violates the first of the AEMO’s 4-point criteria

- (2) **Phase angle:** “Change in the steady-state RMS voltage phase angle at a connection point should not be excessive following the injection or absorption of active power at a connection point” [2].

This criterion was first used to ensure the base network was modelled to an acceptable standard. To accomplish this, a 100 MW load loss had to exhibit a maximum phase angle change of 20°. To further test this network a 500 MW load loss was also considered.

The plots (below) demonstrate that the base network meets this criterion as even for the 500 MW load loss, phase angle changes (measured at the bus where the load was lost) did not exceed 20°.

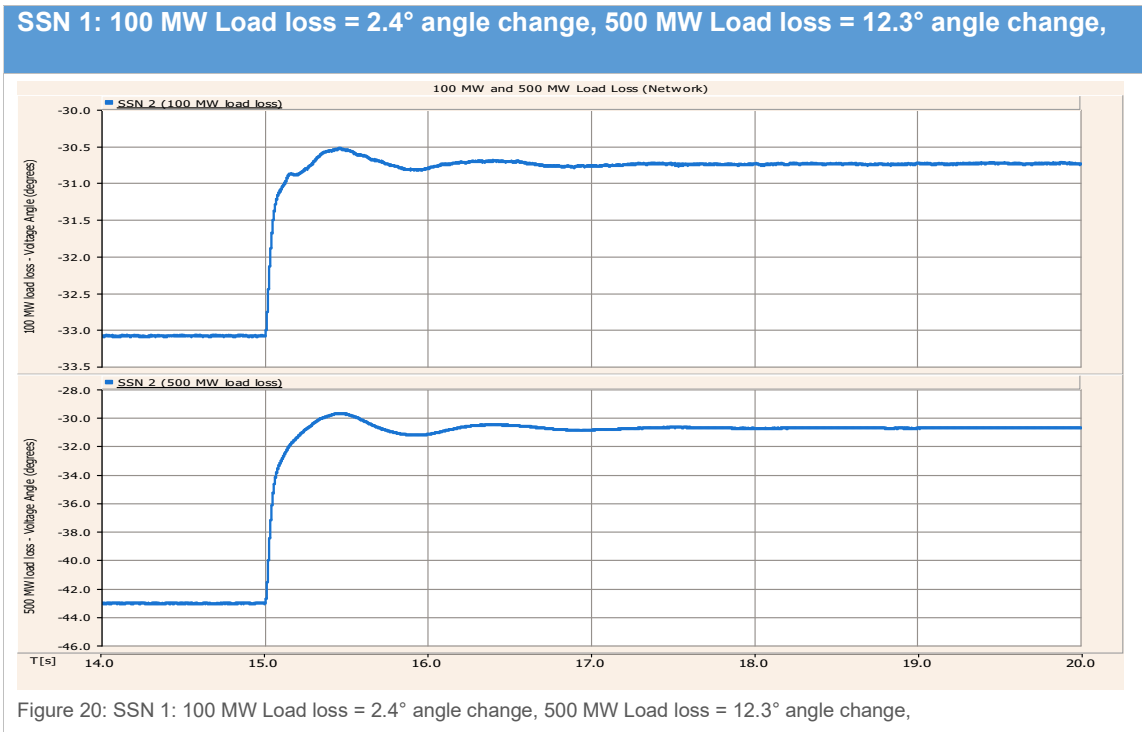


Figure 20: SSN 1: 100 MW Load loss = 2.4° angle change, 500 MW Load loss = 12.3° angle change,

**SSN 3: 100 MW Load loss = 2.4° angle change, 500 MW Load loss = 18.3° angle change**

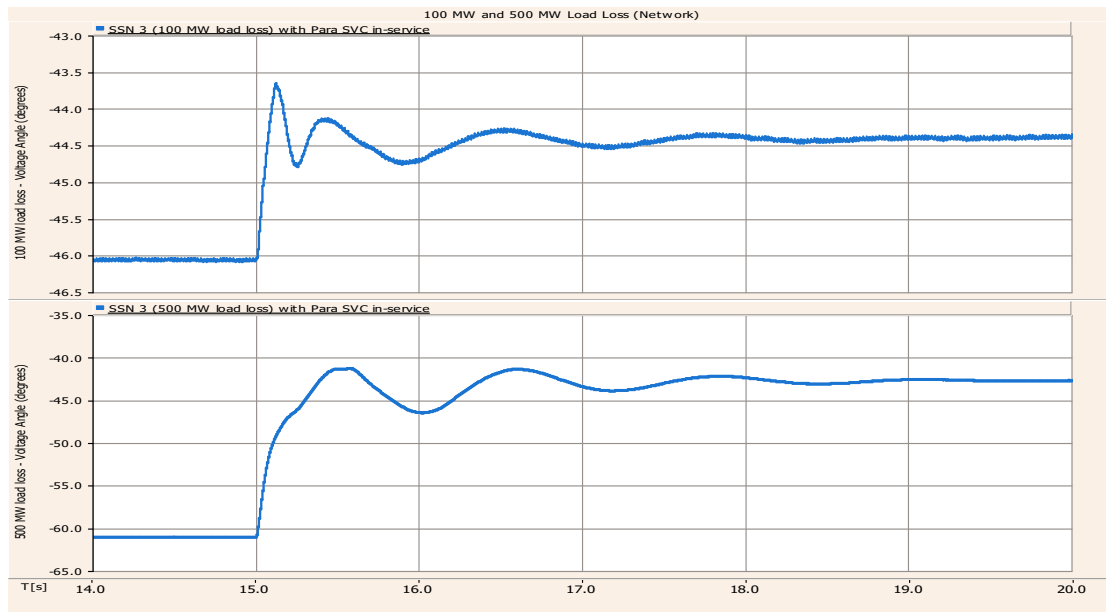


Figure 21: An example case that complies with the second of the AEMO's 4-point criteria<sup>7</sup>

**SSN 2: 100 MW Load loss = 1.19° angle change, 500 MW Load loss = 6.54° angle change,**

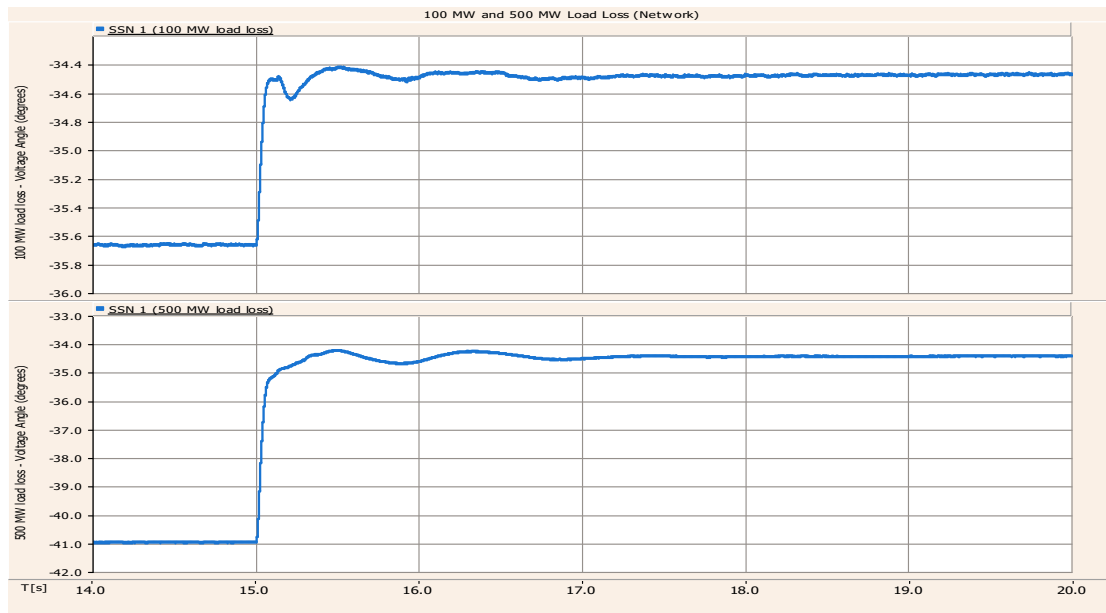


Figure 22: SSN 2: 100 MW Load loss = 1.19° angle change, 500 MW Load loss = 6.54° angle change

Next, a single GFB (GFB B) was put in-service and all line outages for S2 were implemented and the tests were repeated.

<sup>7</sup> See page 20 of [2] [system-strength-requirements-methodology.pdf \(aemo.com.au\)](https://www.aemo.com.au/system-strength-requirements-methodology.pdf)

**SSN 1: 100 MW Load loss = 3.2° angle change, 500 MW Load loss = 16.5° angle change,**

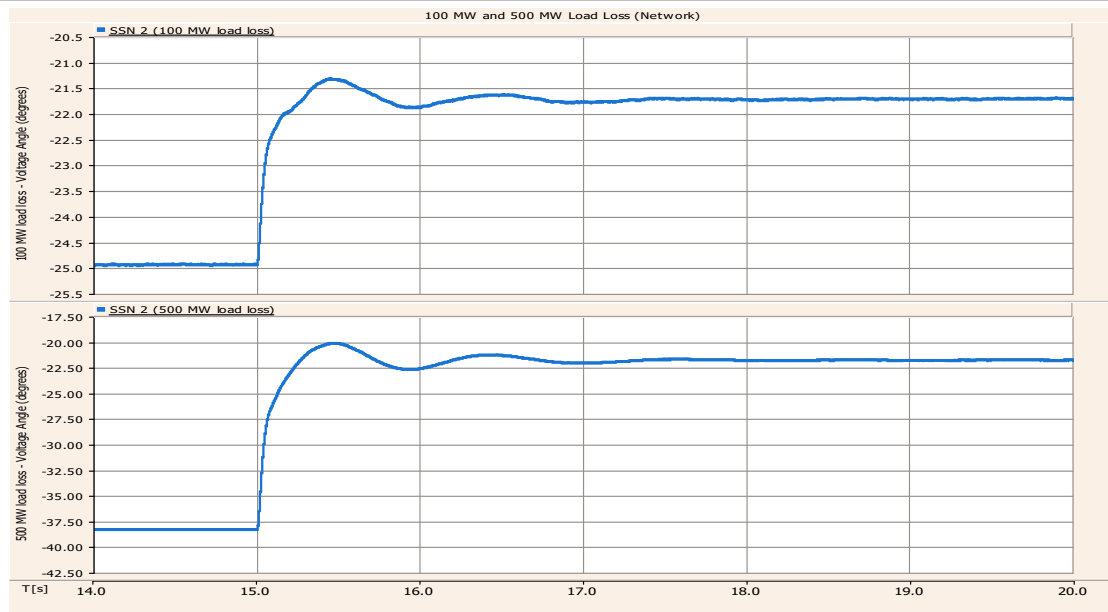


Figure 23: SSN 1: 100 MW Load loss = 3.2° angle change, 500 MW Load loss = 16.5° angle change

**SSN 3: 100 MW Load loss = 1.7° angle change, 500 MW Load loss = 18.3° angle change**

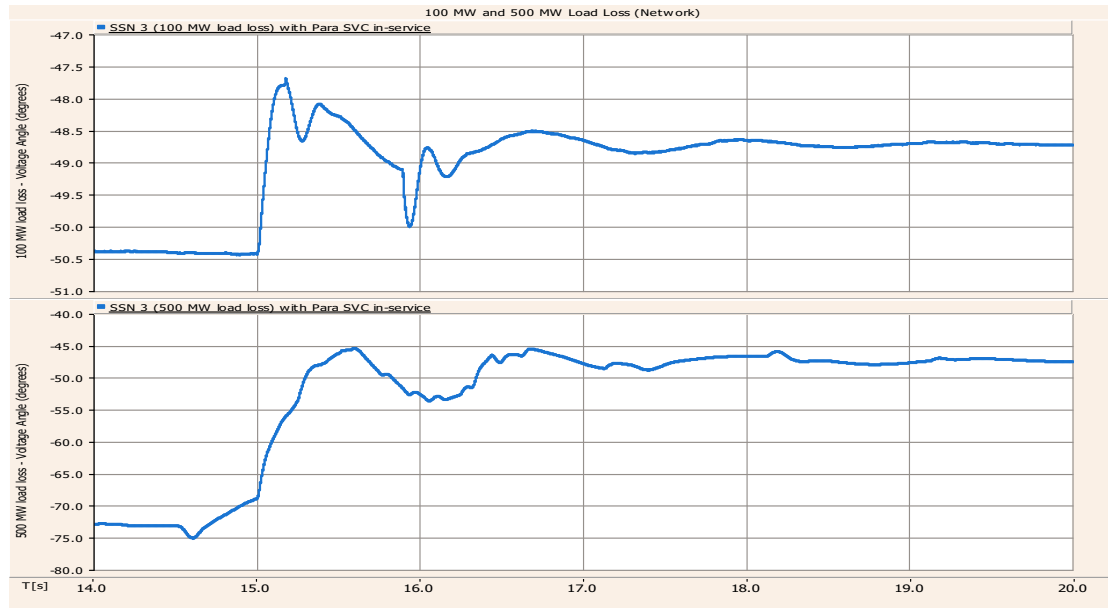


Figure 24: SSN 3: 100 MW Load loss = 1.7° angle change, 500 MW Load loss = 18.3° angle change

**SSN 2: 100 MW Load loss = 1.3° angle change, 500 MW Load loss = 7.1° angle change,**

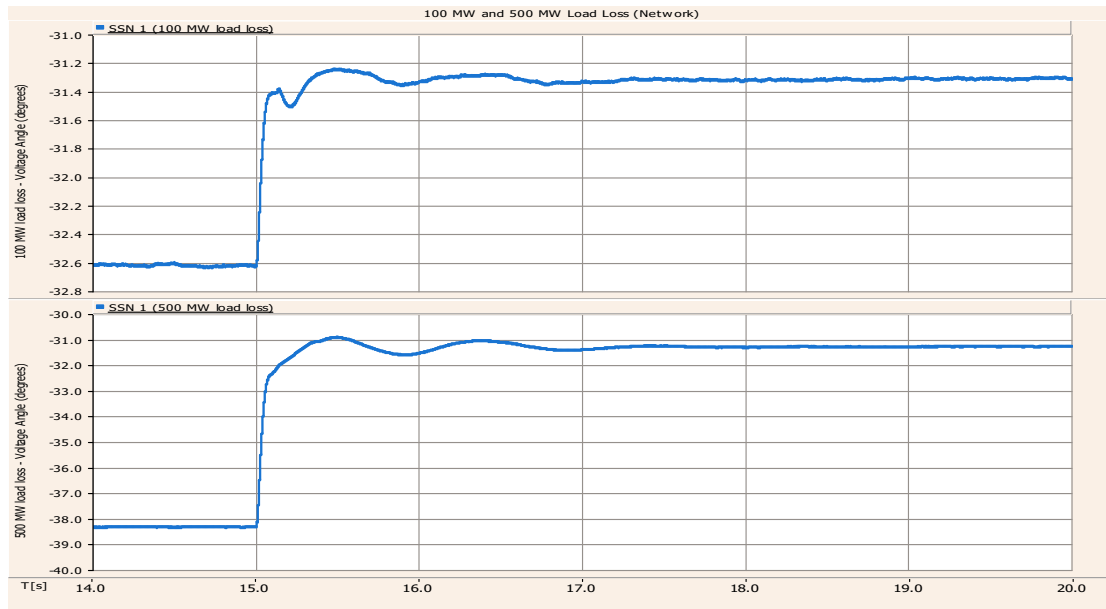


Figure 25: SSN 2: 100 MW Load loss = 1.3° angle change, 500 MW Load loss = 7.1° angle change

The plots (below) demonstrate that the weakened network with GFB A in-service meets this criterion as even for the 500 MW load loss (except for the 500 MW load added at SSN 3. There is instability prior to the loss of the load indicated that this is not a stable case), phase angle changes (measured at the bus where the load was lost) did not exceed 20°.

- (3) Waveform distortion:** “The three-phase instantaneous voltage waveform distortion at a connection point should not exceed acceptable planning levels of voltage waveform distortion for pre- and post-contingent conditions” [2].

This criterion was examined visually and there were no cases of unacceptable waveform distortion.

- (4) Low frequency oscillation:** “Any undamped steady-state RMS voltage oscillations anywhere in the power system should not exceed an acceptable planning threshold as agreed with AEMO” [2]. This criterion was closely monitored throughout the studies and documented in the study tables. If a voltage oscillation exceeded 0.5% (some studies used the conservative value of 0.1%), then the study result was flagged as a failure.

In the case below, the green traces show an example of a failure of this criterion and the blue trace shows an example of a pass of this criterion.

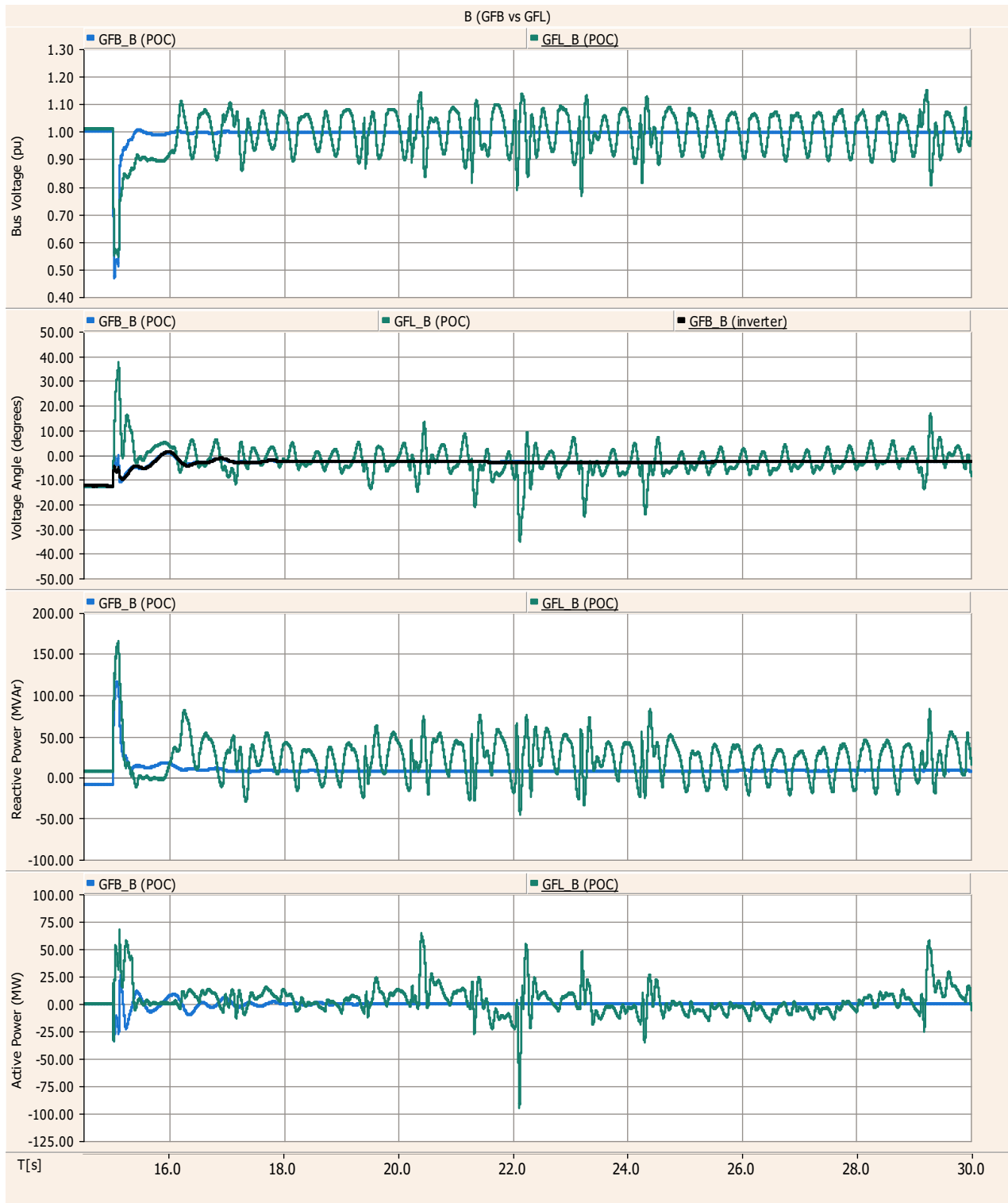


Figure 26: A set of results illustrating the effect of GFM BESS on fourth of the AEMO's 4-point criteria