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Flagship Report

Large-scale battery storage as an inertia substitute

Wallgrove Grid Battery

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The purpose of this document (Report) is to summarise the learnings from the Wallgrove Grid Battery in providing synthetic inertia and discuss the relationship between providing synthetic inertia while operating commercially in the energy markets.

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This Project received funding from ARENA as part of ARENA's Advancing Renewables Program and from the NSW Government, Emerging Energy Program.

Contents

1. Acronyms

AEMC	Australian Energy Market Commission
AEMO	Australia Energy Market Operator
ARENA	Australian Renewables Energy Agency
BESS	Battery energy storage system
BOP	Balance of plant
CCTV	Closed circuit television cameras
COVID-19	Coronavirus disease
D&C	Design and construct
EPC	Engineering Procurement Construction
EP&A Act	Environmental Planning and Assessment Act
ESV	Energy Safe Victoria
FCAS	Frequency control ancillary services
FFR	Fast frequency response
FRT	Fault ride through
GPS	Grid performance standards
LSBS	Large scale battery storage
LVRT	Low voltage ride through
MW.s	Megawatt Seconds
NEM	National Electricity Market
NER	National Electricity Rules
NMI	National metering identifier
OEM	Original equipment manufacturer
POC	Point of connection
PPC	Power plant controller
RoCoF	Rate of change of frequency
RTAC	Real-time automation controller
SCADA	Supervisory Control and Data Acquisition System
SVC	Static VAR Compensator
TNSP	Transmission network service provider
WGB	Wallgrove Grid Battery

2. Executive Summary

This Report presents the key technical findings in pursuit of the knowledge sharing objectives which underpinned ARENA support for the Wallgrove Grid Battery (WGB).

The Report describes the performance of the WGB in responding to grid disturbance with synthetic inertia. In support of that key focus, the report also provides details on the origins of the project and a discussion on the interplay between the provision of inertia and the WGB's commercial operations. Discussion on the regulatory context and the future procurement of inertia services by Transgrid is also provided.

The WGB is a 50MW/75MWh (1.5-hour duration) grid-scale lithium-ion battery. Located at Wallgrove adjoining the Sydney West substation, it became the first large-scale grid battery in NSW. The project commenced commercial operations on 22 December 2021, with its synthetic inertia capabilities enabled on 23 November 2022.

The primary objective, as set out in the ARENA contract, was to support technical innovation by improving the understanding of how the selected Tesla technology could substitute for the inertia that would be leaving the system with the retirement of thermal generation. As the project matured and the performance was analysed, a more nuanced picture emerged. While the WGB was found to provide an inertial response when configured in virtual machine mode (VMM), observation of the performance through grid disturbance and subsequent modelling indicates that the currently implemented technology cannot be tuned to provide a like-for-like substitution for inertia from synchronous generation in all the operating conditions. Tesla maintains that with the addition of significant overload capability, it would be possible to tune the battery energy storage system (BESS) to mimic the behaviour of synchronous generation, though this could not be verified through the trial.

Both Transgrid and Tesla believe with further tuning of the inverter controllers, the active power inertial response can be as fast as a typical synchronous generator, but these tunings will lead to some undesired or non-compliant performance.

The Report outlines these findings, along with various challenges and limitations that were revealed through the project and subsequent analysis. The findings are a valuable step as the industry continues to expand its understanding of emerging technology and the needs of the future power system.

3. Purpose and Distribution

3.1. Purpose of Report

This Report concentrates on the performance of the WGB in responding to grid disturbance with synthetic inertia, with supporting detail on the origins of the project, the interaction between the network service and the commercial operations, and a discussion on regulatory challenges.

3.2. Distribution of Report

This document is intended for the public domain and has no distribution restrictions.

The intended audience of this document includes:

- Network service providers
- Renewable energy industry participants
- Equipment vendors
- Project developers
- General public
- General electricity sector members
- Government bodies
- ARENA.

3.3. Knowledge sharing plan

This document represents one of the deliverables under the Knowledge Sharing Plan that forms part of the funding agreement between Transgrid and ARENA. Documentation associated with the Knowledge Sharing Program for the Project is available on the Wallgrove Grid Battery project websites (details below).

The knowledge sharing deliverables completed to date are shown in Table 1 below.

Table 1 -Knowledge sharing deliverables

Deliverable	Responsibility
Arena 15 min Project Survey	Completed Quarterly
Lesson Learnt Report #1	May 2021
Lessons Learnt Report #2	January 2022
Operations Reports	Every six months for the first two years of operation
Commissioning Report	October 2022
Commercial Model Report	October 2022
Stakeholder Reference Group briefings	SRG Meeting #1 – 3 February 2021 SRG Meeting #2 – 19 October 2021 SRG Meeting #3 – 10 November 2022 SRG Meeting #4 – 14 June 2023
Attendance at Webinar or workshop	ARENA Smart Inverters Webinar participation / Presentation 27 May 2021 Presentation in ARENA Grid Forming / Advance Inverters Webinar 9 August 2022 Presentation to ARENA 'Dispatch' 16 August 2023 Participation in ARENA's Insight Forum March 2024
Project Website	Accessible via: https://www.transgrid.com.au/projects-innovation/wallgrove-grid-battery https://www.lumea.com.au/projects/wallgrove-grid-battery/

Photo 1 – Wallgrove BESS looking towards Sydney West 330/132kV Substation

4. Project Summary

4.1. About Transgrid

Transgrid operates and manages the high-voltage electricity transmission network in NSW and the ACT, connecting generators, distributors and major end users. The Transgrid network is the backbone of the NEM, enabling energy trading between Australia's three largest states along the east coast and supporting the competitive wholesale electricity market.

4.2. About Lumea

Lumea is a renewable energy infrastructure, telecommunications, and energy services business. Lumea operates in contestable markets across the NEM and is the largest connector of renewable generation in Australia to date. Lumea's mission is to help bring 40 GW of renewable energy to market by 2030 using the skills, expertise and heritage as part of the Transgrid Group to help generators, large load customers and governments realise their own clean energy ambitions. Lumea is developing its own innovative projects across a variety of new energy assets and services, as well as establishing a pipeline of grid-scale batteries.

4.3. Key project objectives

ARENA	NSW Government
Supporting technical innovation: Improved understanding of the ability of fast frequency response (FFR) services and Tesla's Virtual Machine Mode to substitute for inertia and help meet Transgrid's requirement to manage Rate of Change of Frequency (RoCoF) in NSW with transferable learnings across the National Electricity Market. Support inclusion of LSBS projects in the Recipient's regulatory submission: The Project will help support Transgrid's vision to include ~240MW of LSBS projects in its revenue submission to the AER for the upcoming regulatory period (2023/24 to 2027/28). New commercialisation pathway: The Project will contribute to the development of a new commercialisation pathway for LSBS by leveraging regulated network expenditure to provide a clear pathway to commercialisation for LSBS. Improving supply chains: Relatively few LSBS projects have been installed. Supporting LSBS will improve supply chains and reduce costs for OEMs and balance of plant providers.	Enhance system reliability and security in NSW by operating in the wholesale energy and frequency control ancillary services markets in the NEM, as well as provide inertia support activities including fast frequency response and virtual inertia. Promote competition through its contracting arrangement with Iberdrola Australia which will operate the project to firm variable renewable energy generation in NSW to supply retail customers. Promote diversification of electricity supply in the NSW region of the NEM by deploying a lithium-ion battery system in the NEM that is dispatchable and capable of firming variable renewable energy generation. Assist in the operation of a low emissions NSW electricity system by firming Iberdrola Australia's variable renewable energy output from their portfolio. Provide value to NSW and the NEM by sharing key learnings to reduce the risk and encourage further investment in utility scale battery energy storage systems in NSW.

4.4. Technical details

Table 2 – Key technical parameters

Deliverable	Responsibility
Nominal Discharge Power capacity	50 MW
Nominal Charge Power capacity	47 MW
Registered Storage capacity	75 MWh
Power capacity degradation	N/A
Number of Megapacks	36
System voltages	132 / 33 / 0.518 / 0.4 kV
Balance of Plant	• 60 MVA 132/33kV Power Transformer • 9 x 33/0.518/0.518kV Coupling Transformers • ABB SafePlus GIS RMU Switchgear • 500kVA 33/0.400 kV Auxiliary Transformer • 75kVA Isolation Transformer for street supply
Point of Connection	Sydney West 330/132kV Substation – Feeder Bay 2X
Metering Point Location	Sydney West 330/132kV Substation – Feeder Bay 2X
Network Connection	132kV
Substation	Sydney West 330/132kV Substation
National Metering Identifier Numbers	Wallgrove Battery 132kV Revenue: • NTTTW0ZQ90 for Import B1 (Generation) • NTTTW0ZQ91 for export E1 (Consumption) Wallgrove Battery 132kV Check • NTTTW0ZQ95

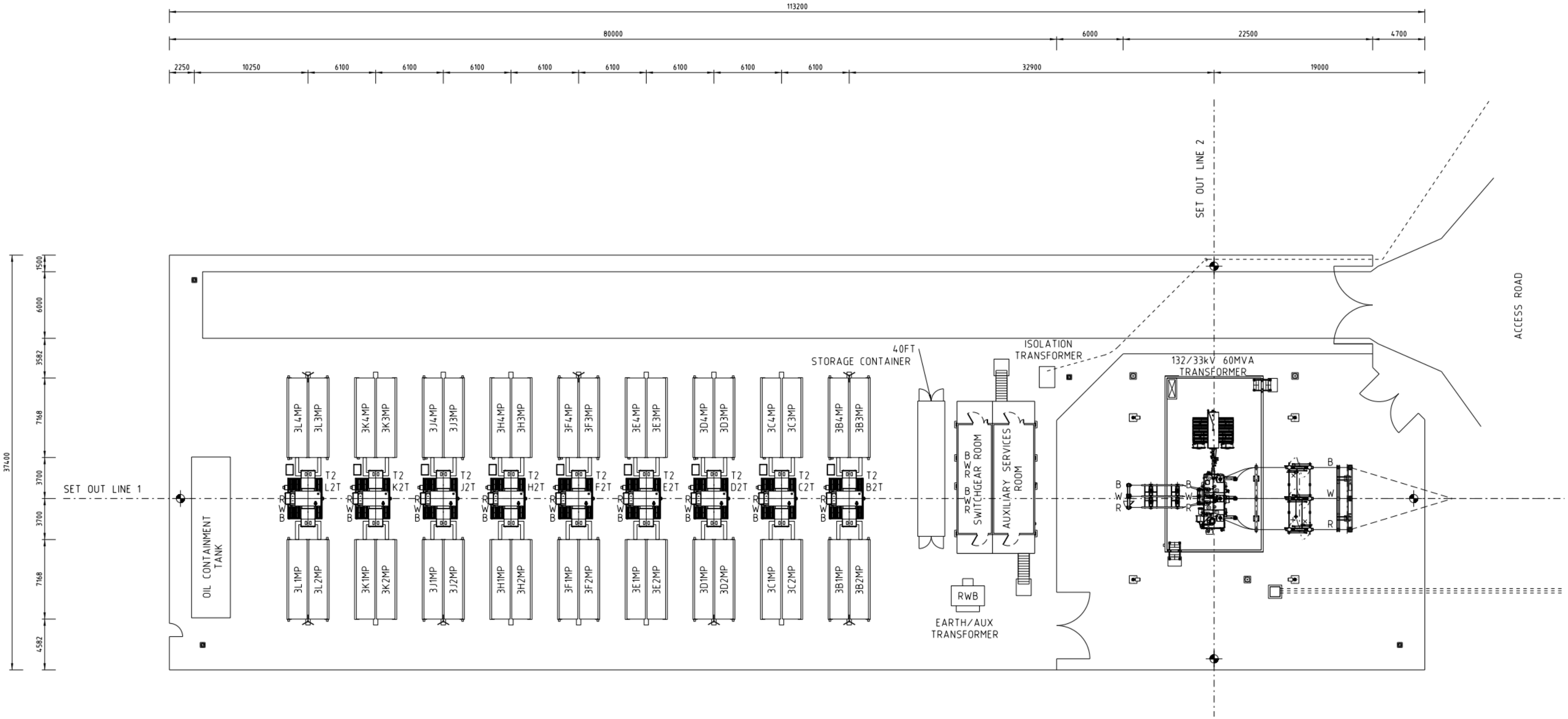

Figure 1 – Wallgrove Grid Battery General Arrangement

5. Analysing Synthetic Inertia through Tesla's Virtual Machine Mode

5.1. Project context

The energy transition creates technical challenges, such as ensuring the system has enough inertia. A stable and reliable network requires inertia to support the power system to resist changes in frequency. Traditionally, inertia is provided by synchronous generators, such as coal plants, but following the retirements of Liddell, Vales Point, Eraring and Bayswater Power Stations, the inertia level in NSW is unlikely to meet the double contingency secure planning level. One possible way to address this inertia shortfall is through the provision of synthetic inertia through BESS.

BESS are increasingly recognised as a potential solution to network challenges, with the additional benefit of providing storage capacity so the grid can access renewable generation when the sun isn't shining, and the wind isn't blowing.
The Australian Energy Market Operator (AEMO) anticipates that by 2050, 14GW of storage will be provided by utility-scale batteries .

As existing sources of inertia, predominantly coal-fired generators, are progressively withdrawn from the market, Transgrid is investigating alternative technology solutions to establish the technical and commercial viability of lower-cost solutions to address the inertia gap, including its first hybrid grid-scale battery – the Wallgrove Grid Battery.

5.2. Overview of the Wallgrove Grid Battery Project

The WGB is a 50MW/75MWh (1.5-hour duration) grid-scale lithium-ion battery. It became the first large-scale grid battery in NSW. Located at Wallgrove, the WGB is a pilot demonstration of the viability of synthetic inertia from a battery to support frequency stability on the network.
Iberdrola Australia controls the dispatch of the WGB and participates commercially in the frequency control ancillary services (FCAS) and wholesale energy markets.

The WGB was undertaken as an innovation pilot, to build battery expertise, and to support the development of synthetic inertia technologies in different locations on the grid, including strong areas of the grid. Transgrid embarked on the WGB project to explore synthetic inertia using specialist firmware to mimic the "swing equation" that governs the rotor dynamics of a synchronous machine. This product is manufactured by Tesla and, when configured to deliver synthetic inertia, is described as operating in virtual machine mode (VMM).

The project commenced commercial operations in December 2021, and has operated with its synthetic inertia capability enabled since November 2022. The project has generated valuable technical information about how often it is needed for fast frequency response, how it performs as a source of inertia in the event of grid disturbance, and how much electricity it stores and dispatches under different conditions.

5.3. Advanced inverters and Virtual Machine Mode

Advanced inverters of a grid-forming nature, including the system deployed in the WGB now enabled with VMM, seek to mimic the response of a traditional rotating machine to provide an inertial response. The virtual machine is a blended mode that brings the dispatchability of a current source operating in parallel with the stability benefits of a voltage source. The flexible and fast controls in an advanced inverter seek to replicate the response of a traditional rotating machine. As the inverter's inertial response is created by the inverter controls, the response is tuneable through configurable parameters such as inertial constant that can be modified based on the grid's needs (unlike traditional generators that have a fixed inertial constant based on their physical characteristics).

5.4. Project and testing plan objectives

The objectives of the ARENA funding, highlighted in section 4.3, are achieved through:

- Improved understanding of the ability of FFR services and Tesla's Virtual Machine Mode to substitute for inertia and help meet Transgrid's requirement to manage RoCoF in NSW with transferable learnings across the National Electricity Market.

- A reduction in barriers to renewable energy uptake by identifying any limitations to the use of large-scale battery storage for resolving future inertia shortfalls
- Improved commercial readiness through the identification of a clear commercialisation pathway for large-scale battery storage providing inertia services in NSW

The aims of the VMM testing plan were for:

- Objective 1: To test the hypothesis that a BESS operating with synthetic inertia capabilities can provide a useful inertia service to the power system.
- Objective 2: To demonstrate the above whilst the BESS is in normal commercial operation.

5.4.1. Methodology description

To achieve the abovementioned objectives, the primary approach was to analyse the performance of the battery using data from real-time events.

5.4.1.1. Event-based analysis

A few seconds before and after the disturbance have been captured, presented and analysed. The testing plan articulated the following analysis approach:

- Connect monitoring equipment in the vicinity of the WGB to monitor an inertia-type response
- Obtain data from the whole power system following a trigger event, to enable modelling of the exact conditions that occurred at the time of the event
- Determine the output that would be expected from an "inertia source" from the model, (i.e. BESS operating in VMM)
- Compare the actual output of the BESS with this model, to establish the amount of useful inertia that has been delivered.

To achieve Objective 2 of the testing plan, the inertial response must be demonstrated during normal commercial operation. The methodology to achieve the objective was therefore simple – retrospectively assess that commercial operation continued through the period that grid disruption events occurred and explore the commercial data to understand the circumstances in which network service might be constrained by commercial operations. These findings are provided in section 9.

5.4.1.2. Methodology refinement

As is discussed fully in section 8 on the regulatory context, the tuning of VMM was complicated by the 5.3.9 process, which is the process under the National Electricity Rules (NER) that the WGB was required to follow to register with grid forming characteristics.. The final approved parameters of the WGB were: H = 1, and D = 0.9. When the initial results were assessed, it was assumed that conforming to the 5.3.9 process had resulted in a trade-off in performance where more aggressive tuning would have yielded a stronger inertial response.

To confirm this assumption and to better understand the potential of the technology without AEMO's Grid Performance Standards (GPS) constraints, a secondary approach was initiated – to perform modelling-based analysis to interpret the performance of VMM in broader applications.

To better appreciate how synthetic inertia and frequency response from VMM could substitute for synchronous machines, Transgrid sought to explore how the WGB could have been tuned more optimally if the tuning parameters were not constrained by the 5.3.9 requirements. In the process, additional aspects that could affect the inertia performance were raised, such as the location of the battery in the network, the nature of the real-time events, and the WGB's relatively small size compared to synchronous generators.

5.4.1.3. Modelling-based analysis

In the modelling environment, the following analysis is discussed:

1. Comparison of grid forming model equipped with VMM response in Megapack 1 and standard grid following mode control prior to the 5.3.9 process (to enable VMM).
2. Comparison between a scaled-up TESLA BESS with VMM response (with compliant tuning) and equivalent synchronous generator
   a. Frequency event
3. Comparison between scaled-up Tesla BESS with VMM response (with non-compliant tuning) and equivalent synchronous generator
   a. Frequency event
   b. Fault event

The following real events have been analysed to understand the performance of VMM as tuned at the WGB in responding to system disturbance, contrasted with a large synchronous generator in NSW.

6.1. Event 1 – Loss at Kogan Creek

On 12 June 2023 at 12:33 hrs, the Kogan Creek synchronous generator unit tripped at 759 MW resulting in frequency going down to approximately 49.77 Hz measured by the Wallgrove power quality meter at the 132kV bus. The highest ROCOF for this event has been estimated to be approximately –0.17 Hz/s.

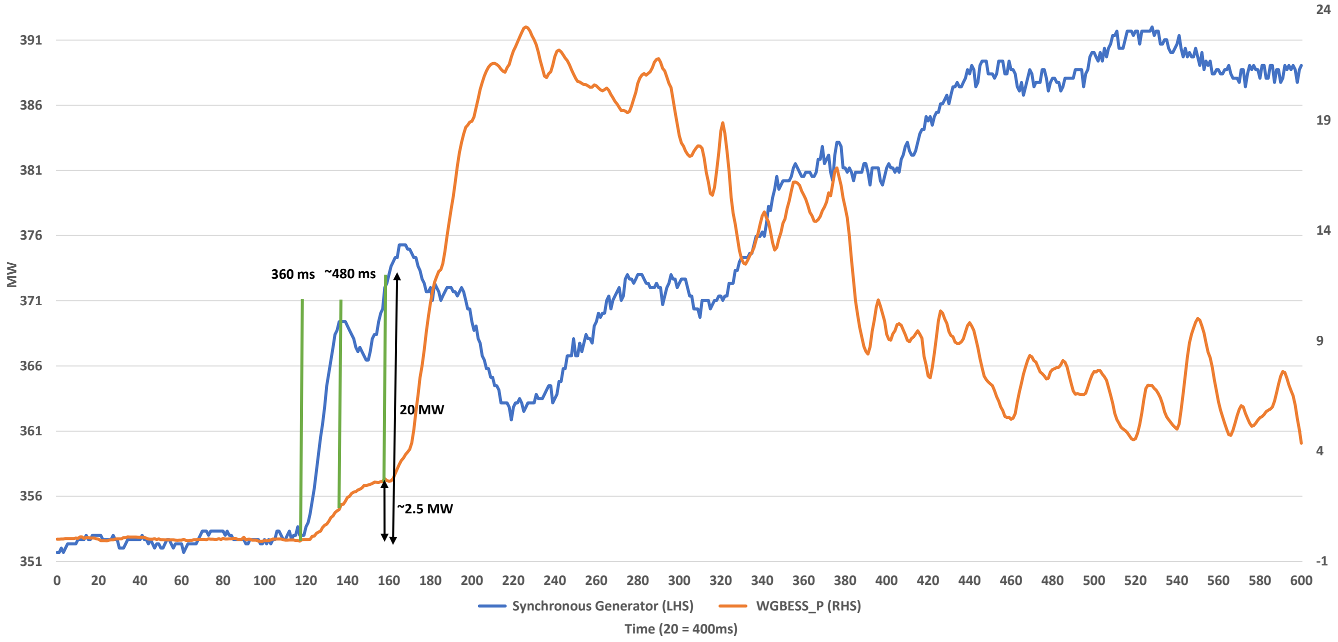

Figure 2 – Kogan Creek Trip – Active Power Overlay – NSW synchronous generator and WGB

As can be seen in Figure 2, the synchronous generator reaches its first active power inertial peak within 360 milliseconds of the response and the WGB reaches its first active power injection peak 480 milliseconds later.

Transgrid played back the measured data into the WGB's PSCAD model to validate the model against the real controller, and to also see if changing inertia constant (H), damping constant (D) in Figure 3, or follower filter time constant (P), in Figure 4, would make the battery's response faster. A strong correlation between the site results and the simulated results in the PSCAD model is evident. However, while it increases the magnitude of the response, Figures 3 and 4 indicate that tuning of D, H, and P does not materially increase the speed of the response.

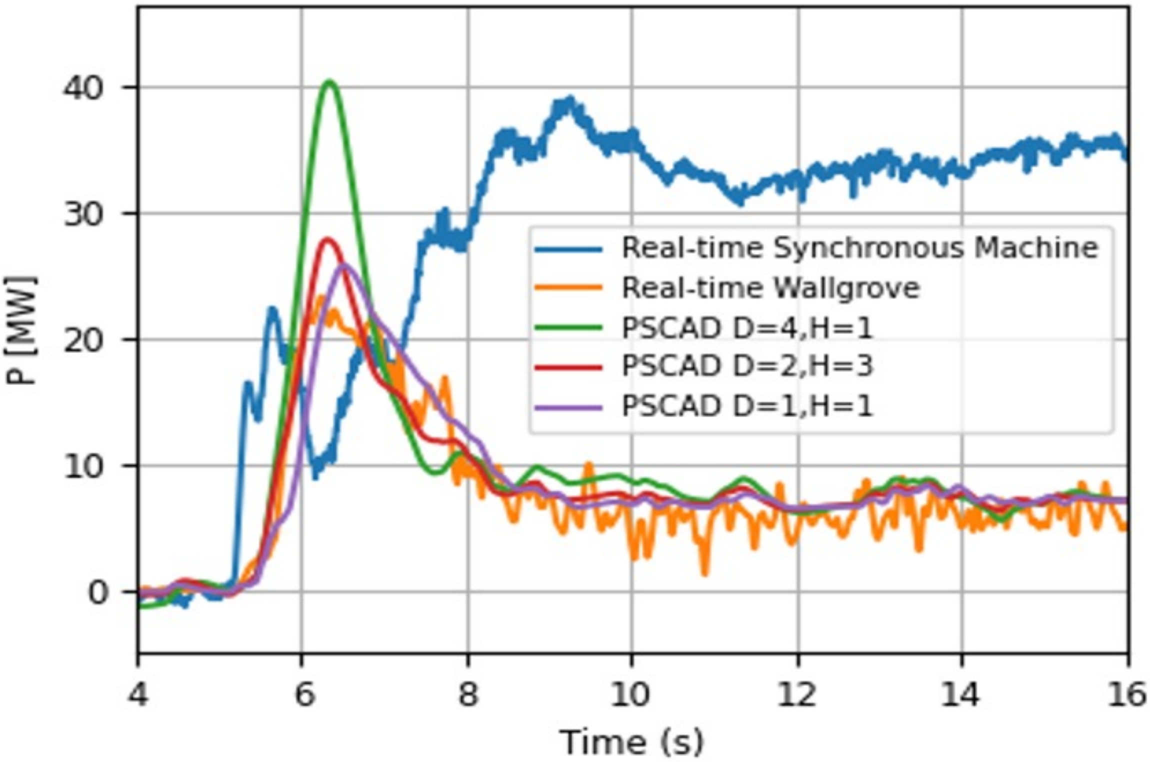

Figure 3 – Kogan Creek Trip – Active Power Response comparison with H, D

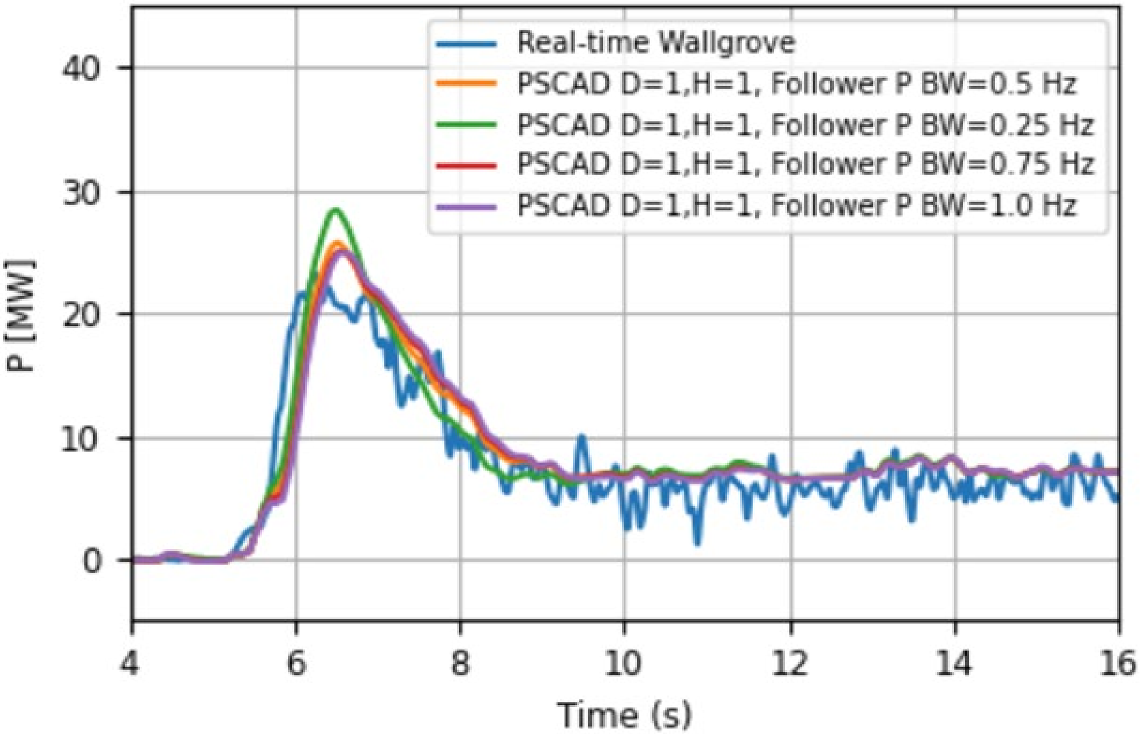

Figure 4 – Kogan Creek Trip – Active Power Response comparison with P

Figure 5 presents the overlay of active power over the measured frequency to determine when the contribution from PFR and FFR was triggered. From this overlay it is evident that PFR and FFR have both been triggered at the early stages of the response – prior to active power reaching its first peak. While the triggered point might have been earlier than the controller actually changes, the output of the inverters as the mode of the response seems to remain the same at least until the first small peak has been reached.

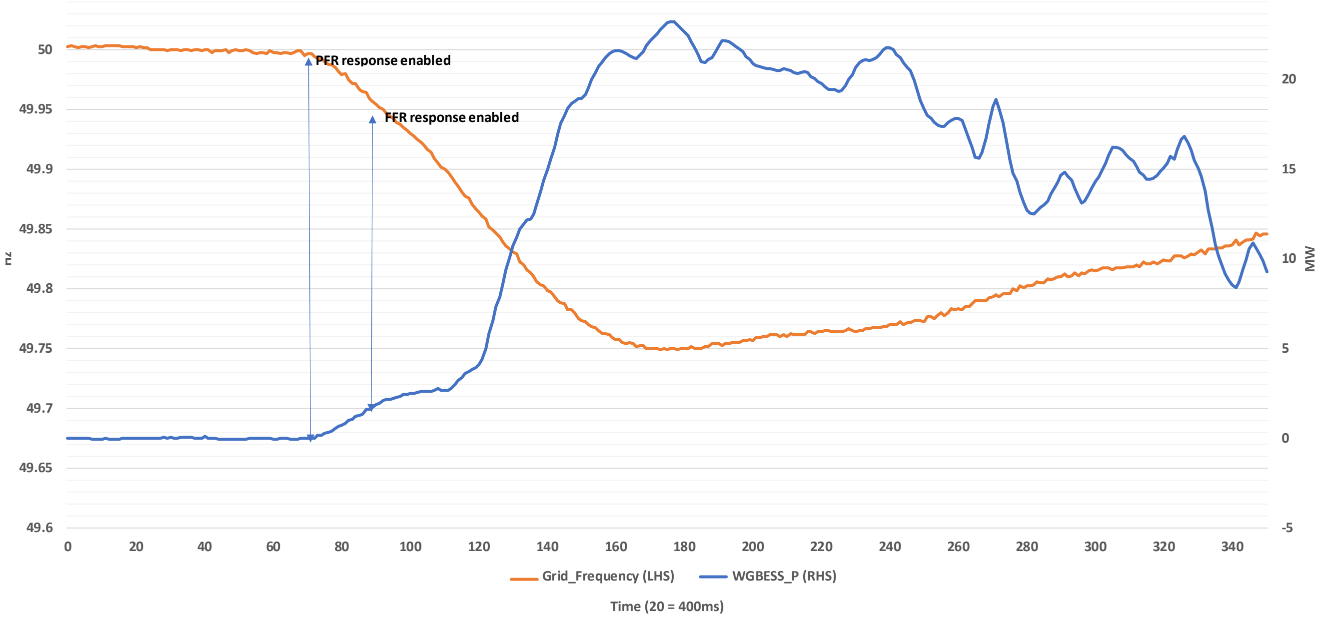

Figure 5 – Kogan Creek Trip – Active Power and Grid Frequency

This triggering of Primary frequency response (PFR) and FFR makes it challenging to separate the contribution from each controller through real-time events, as the responses are coincidental and it is not possible to definitively identify the response attributable to each controller. To pursue the central objective of the project and determine whether a combination of inertial response and FFR can substitute for the inertial response from synchronous machines, the energy injection method must also be considered.

Table 3, below, provides the amount of inertial energy that is released to the grid in the format of electrical energy. To provide a comparison of when volumes of energy are released in different stages of the response, the table provides the amount of energy in four different windows. As a result, instead of looking at the magnitude of the energy, we can look at what percentage of total energy is released in which window of the data from the beginning of the disturbance. To consider substituting the energy provided by coal generation with another source, the rate of change, meaning the speed of the response, plays a key role in addition to the amount of energy provided. This method is proposed to conceptually compare generators of different sizes.

Table 3 – Kogan Creek – Energy released by the source of power in frequency disturbance

Energy Provided in Loss of Kogan Creek by	200 ms	500 ms	1000 ms	2000 ms
Wallgrove Grid Battery	0.37 MW.s	0.6 MW.s	2.078 MW.s	18.50 MW.s
	0.0056 MW.s/MVA	0.0092 MW.s/MVA	0.031 MW.s/MVA	0.284 MW.s/MVA
Proportion of 2-second response	2%	3.2%	11.2%	100%
NSW Synchronous Machine	3.84 MW.s	5.15 MW.s	13.58 MW.s	27.93 MW.s
	0.0005 MW.s/MVA	0.0066 MW.s/MVA	0.0175 MW.s/MVA	0.035 MW.s/MVA
Proportion of 2-second response	13.7%	18.4%	48.6%	100%

Table 3 only considers the speed and the amount of energy, not other aspects such as reliability or quality of performance. The top rows for each generator illustrate the magnitude of the difference in the output in MW.s. However, as the size of the two generators differs, the second rows present the per-unit value on the generator's apparent power base. While broadly comparable, Wallgrove achieves slightly higher per unit MW.s/MVA values. An additional row details the percentage of the total energy released in different windows within the initial two seconds. Based on this comparison in four different windows of data, the synchronous generator provides relatively more of its total injection earlier within the response windows.

Tesla maintains that it is unnecessary to mimic a synchronous machine, and a future grid with high renewables plus grid forming inverters will be more than sufficient to meet network and system security requirements. Transgrid maintains that the distinction in performance complicates the substitution of inertia from synchronous generators with large-scale battery systems and that further specific research would be required to understand the criticality of the rate of change of response.

6.2. Event 2 – Loss at Eraring

On 17 August 2023 at 15:56 hrs, Eraring unit 1 tripped at 668 MW resulting in frequency going down to approximately 49.86 Hz measured by the Transgrid power quality meter at the 330kV bus of the Eraring Power Station. The highest ROCOF for this event was reported in AEMO's quarterly report as –0.3 Hz/s. Unlike Event 1, this event is associated with a Low Voltage Ride Through (LVRT), so the analysis focuses on the related aspects of the performance.

Figures 6–9 present the voltage, active power and reactive power overlays of the WGB and a NSW synchronous unit which was further away from the fault location (Eraring Power Station) and experienced a shallower voltage response due to the increased electrical distance.

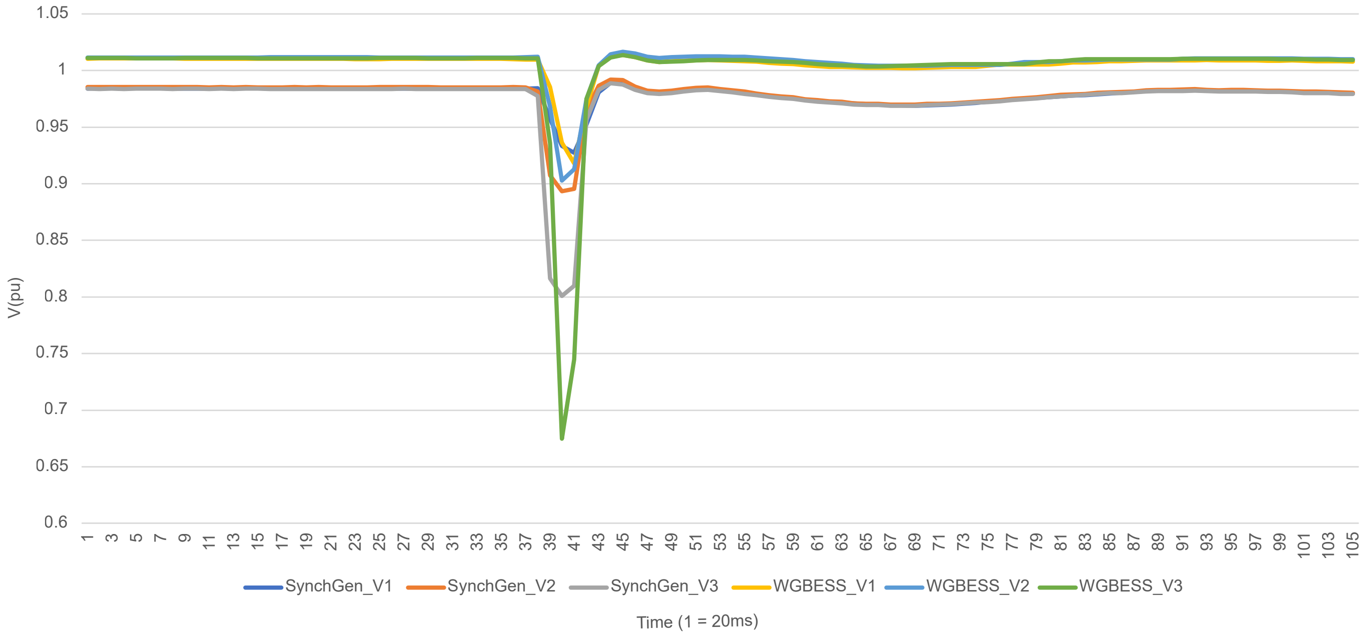

Figure 6 – Eraring Trip – Phase Voltage Overlay – NSW synchronous generator and WGB

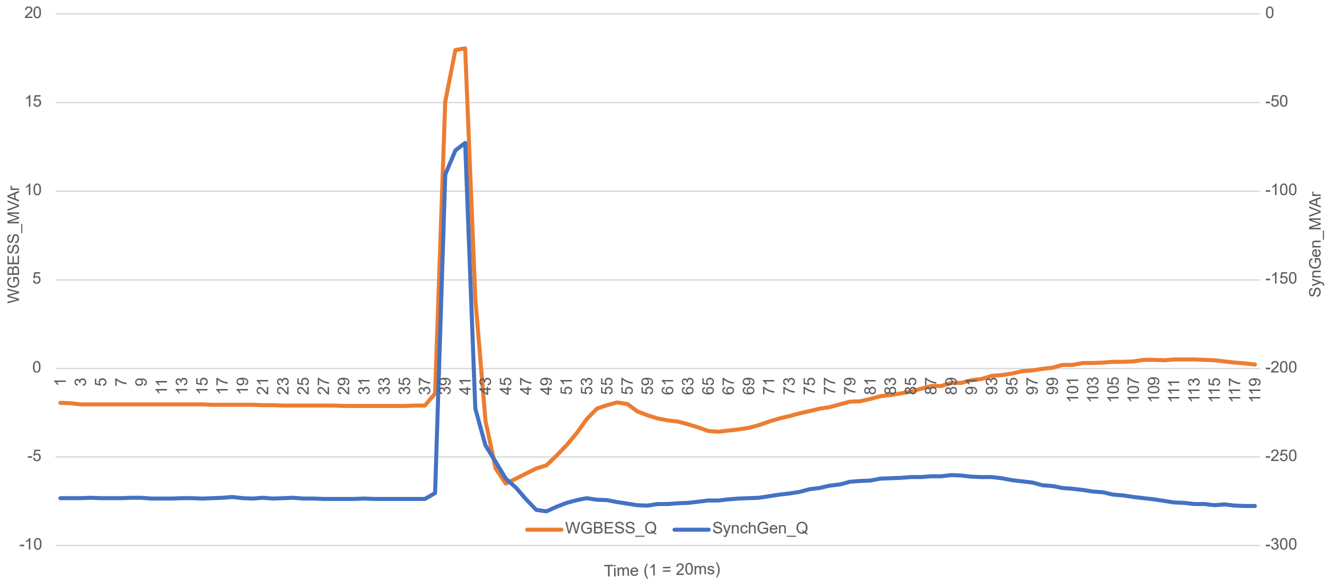

Figure 7 – Eraring Trip – Reactive Power Overlay – NSW synchronous generator and WGB

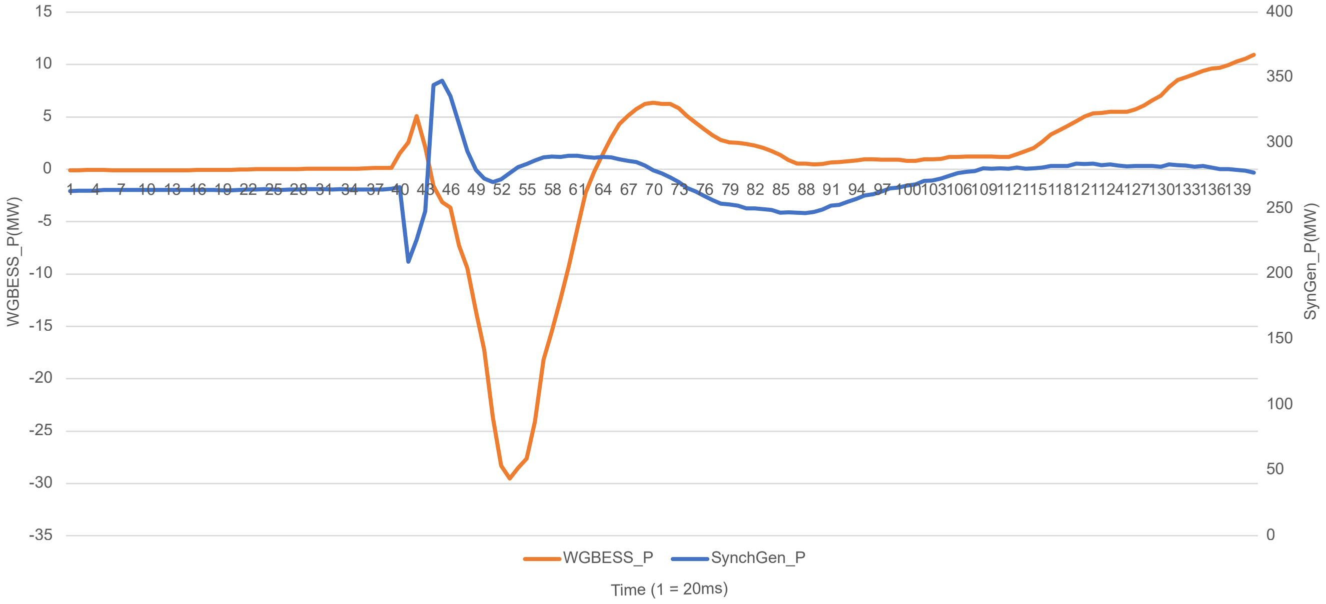

Figure 8 – Eraring Trip – Active Power Overlay – NSW synchronous generator and WGB

During this event, both generators' phase voltage drops below 0.9 pu. This means that the WGB would have triggered its LVRT. This can be observed by the sharp reactive power response from the reactive current injection. However, unlike the synchronous generator, WGB had major (60% of its rating) negative power swing as the frequency is ramping down towards its nadir, which would amplify rather than counter the drop in frequency. Figure 9 illustrates this observation of active power and grid frequency.

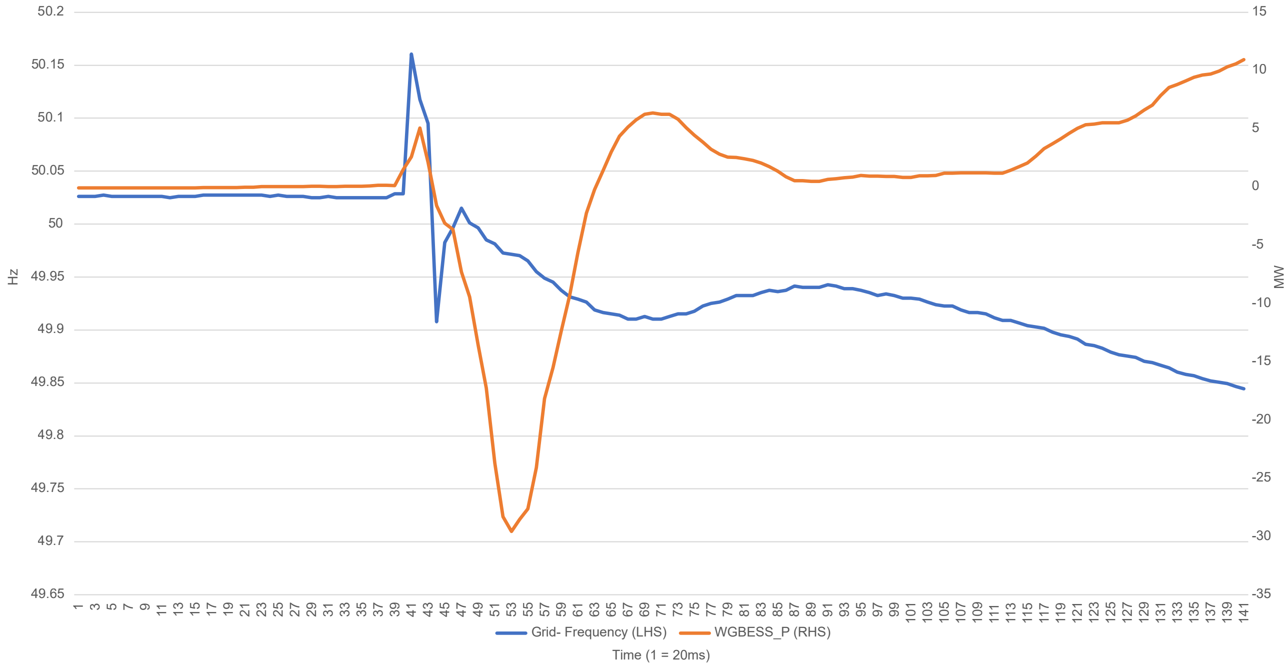

Figure 9 – Eraring Trip – Active Power and Grid Frequency

It must be acknowledged that the frequency measurement may have been slightly inaccurate due to the unbalanced voltages during the first few cycles of the event. However, beyond the few cycles at the beginning of the fault, the frequency measurement should be adequately accurate.

6.3. Event 3 – Loss at Loy Yang

On 17 December 2023 at 05:22 hrs, Loy Yang unit 4 tripped while generating at 556 MW resulting in frequency going down to 49.82 Hz reported by AEMO and measured as 49.824 Hz by the Power Quality meter at 132kV busbar at Wallgrove. The highest ROCOF for this event has been estimated to be approximately –0.16 Hz/s at the steepest part of the disturbance. There is a 0.03 Hz discrepancy between the estimated ROCOF by AEMO and the estimated ROCOF using the power quality monitoring of WGB, but it does not impact the findings.

The time between the occurrence of the event and the frequency nadir can be divided into three phases. The phases are illustrated by windows of data: A, B and C. As anticipated, window A has the fastest ROCOF, then the ROCOF reduces through B, before increasing until about 2.2 seconds from the event when the nadir is reached at the end of C. If the small active power disturbances are discarded, the active power response is directly proportional to ROCOF.

As was found in the analysis of Event 1, the active power response increases with an increase in the deviation of frequency and it reduces with the decrease in the deviation of frequency. This pattern is seen over the whole captured window of data. In other words, active power is almost 'anti-phase' with frequency across the transient and the steady state. While this makes the estimation of inertial response more challenging, it also indicates that the frequency response is more dominant than the inertial response.

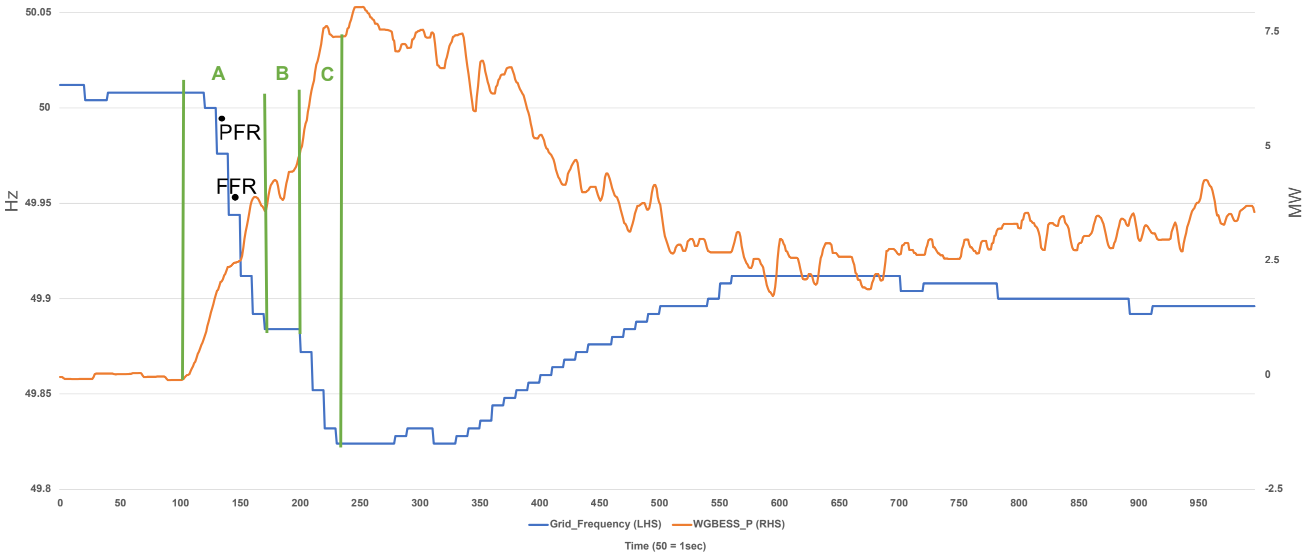

Figure 10 – Loy Yang Trip – Active Power and Grid Frequency

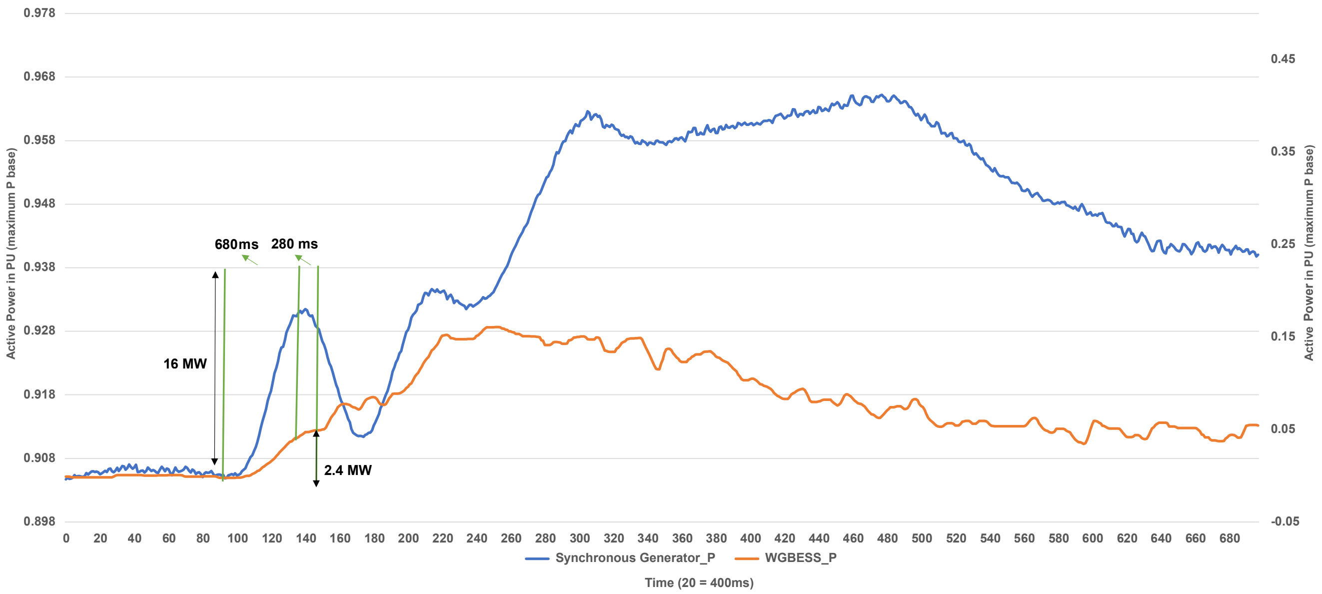

Figure 11 – Loy Yang Trip – Active Power Overlay – NSW synchronous generator and WGB

As with Event 1, Table 4 provides the amount of energy in MW.s that the battery provided in four different windows of time from the beginning of the event to communicate the effectiveness of the energy injected by the battery at different points in time, e.g. This detail expands on Figure 11, which graphically contrasts how active power was provided by the WGB relative to a synchronous generator.

Table 4 – Loy Yang – Energy released by the source of power in frequency disturbance

Energy Provided in Loss of Loy Yang by	200 ms	500 ms	1000 ms	2000 ms
Wallgrove Grid Battery	0.036 MW.s	0.3622 MW.s	1.545 MW.s	5.58 MW.s
	0.00055 MW.s/MVA	0.0055 MW.s/MVA	0.023 MW.s/MVA	0.086 MW.s/MVA
Proportion of 2-second response	0.6%	6.5%	27.7%	100%
NSW Synchronous Machine	0.462 MW.s	3.54 MW.s	10.887 MW.s	18.55 MW.s
	0.00059 MW.s/MVA	0.0045 MW.s/MVA	0.014 MW.s/MVA	0.023 MW.s/MVA
Proportion of 2-second response	2.4%	19.1%	58.7%	100%

Table 4 demonstrates that the proportion of the energy provided by the synchronous machine earlier in the response is relatively greater than the battery. On the other side, we see that the normalised ratio of the MW.s over the total rating of each generator (e.g. (MW.s)/MVA) are comparable or higher with the WGB. While it is not a scope of work for this project, the industry would benefit from further exploration on the criticality of the rate of change of response within 1-2 seconds of the frequency disturbance at a much larger scale.

6.4. Event 4 – Loss at Bayswater

On 31 December 2023 at 20:40 hrs, Bayswater unit 1 synchronous generator tripped while generating at 505 MW resulting in frequency going down to 49.81 Hz and the recovery back to normal operating frequency band after 5 seconds.

Four windows – A, B, C and D – are provided in Figure 12 to track the response of the WGB against the frequency change. Like the previous events, the active power response from WGB commences (Window A) prior to observation of any measurable frequency change as captured at the power quality meter of the WGB. As previously discussed, this response is beneficial to the grid compared to a standard grid following inverter response with PFR or FFR. While the relationship between active power and frequency is similar to the Loy Yang event, differences in the 'anti-phase' behaviour are evident in all windows, particularly A and D.
In Figure 12, the set thresholds for triggering PFR and FFR are also illustrated by the two black dots to indicate the point on the active power curve that the responses from these controllers applied.

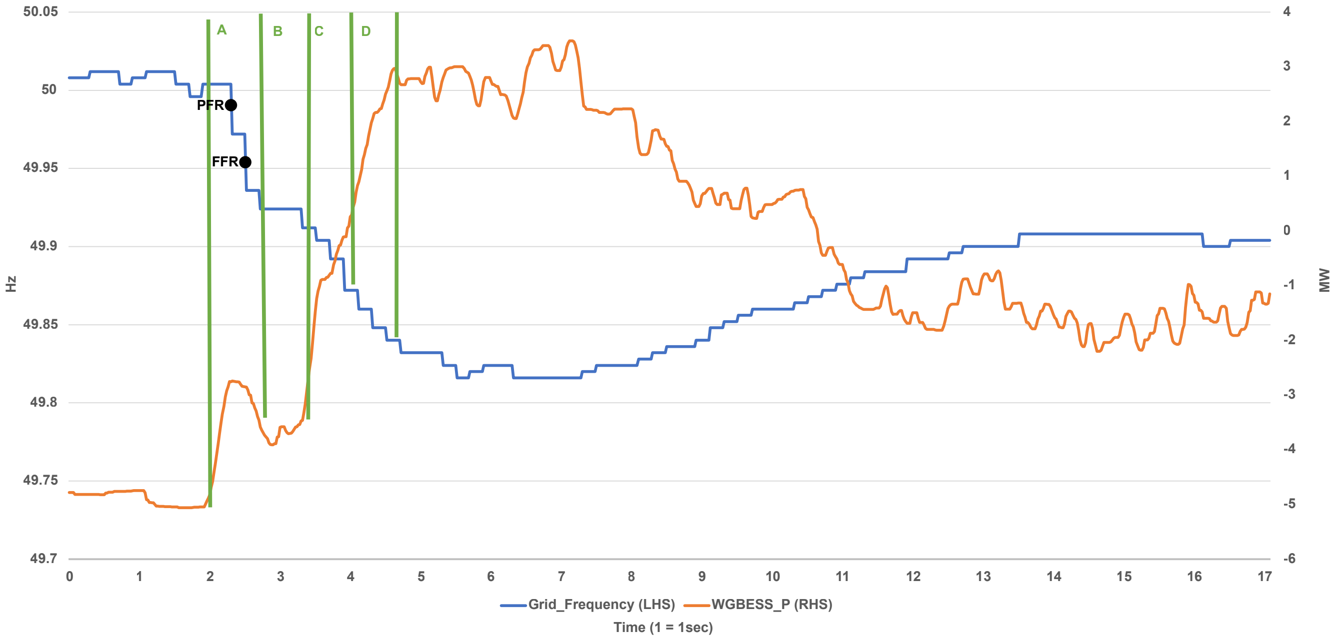

Figure 12 – Bayswater Trip – Active Power and Grid Frequency

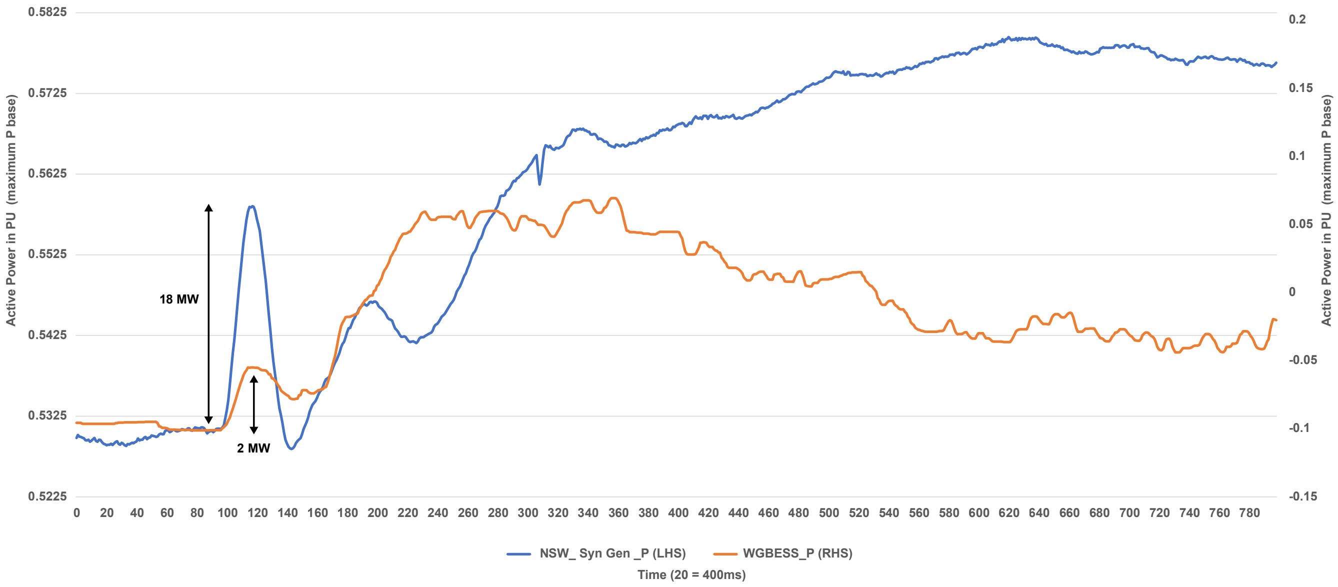

Figure 13 – Bayswater Trip – Active Power Overlay – NSW synchronous generator and WGB

The active power injections of a NSW synchronous generator and the WGB follow different profiles as demonstrated in Figure 13. The below table provides the amount of energy (MW.s) that the battery has provided in different windows of time from the beginning of the event to observe the effectiveness of the energy injected by the battery at different points in time.

Table 5 – Bayswater – Energy released by the source of power in frequency disturbance

Energy Provided in Loss of Bayswater Unit	200 ms	500 ms	1000 ms	2000 ms
Wallgrove Grid Battery	0.098 MW.s	0.67 MW.s	1.53 MW.s	4.32 MW.s
Proportion of 2-second response	2.3%	15.5%	35.4%	100%
NSW Synchronous Machine	0.62 MW.s	5.36 MW.s	7.8 MW.s	12.7 MW.s
Proportion of 2-second response	4.9%	42.2%	61.4%	100%

6.5. Operational scenario conclusions

(i) The immediate response from the battery, even before the frequency deviation commences (at the beginning of the windows marked 'A'), can be considered as evidence that the controller is following the ROCOF not the magnitude of frequency deviation as intended by the design.

(ii) Virtual machine mode operation shows faster response than standard grid following technology which aids grid operation in the event of frequency disturbance. However, the VMM installed at Wallgrove is slower in providing effective active power response in an event, relative to observations shared from synchronous generators over the first 2 seconds.

(iii) In multiple points of the frequency trend, the direction of active power is not as per ROCOF polarity. This can mean that the BESS controller may be attempting to satisfy both inertial response and absolute frequency deviation. Alternatively, this can be a sign that additional factors within the controller make the ROCOF and active power change fail to build a linear and predictable relationship, unlike a synchronous generator. As a result, if synthetic inertia from batteries is to replace the inertial response from the synchronous generator, care must be taken to understand all the non-linearities and conditions which the controllers may have embedded in.

These conclusions raised the following questions, which helped to shape the approach to subsequent modelling:

1. Would increasing constant inertia increase the speed of the response to make it closer to the synchronous machine?
2. Would changing the location of the BESS make a big difference?
3. Will the impedance of the Point of connection (POC) Transformer make any difference in the frequency response?
4. Would any other parameter tuning increase the amount of energy provided by the battery on the same scale as the synchronous generator?
5. How would a larger battery (same size as one of the large NSW's synchronous generators) with the same technology, behave?
6. What adverse impacts might be seen if more aggressive tuning is applied?

7.1. Modelling investigation

To further understand the possibilities and potential limitations of the technology, Transgrid built a platform to test and compare the VMM control of a battery with a like-for-like synchronous generator.
Tesla collaboratively developed a large-scale BESS model using both the Megapack 1 and Megapack 2 generations of VMM technology. Transgrid integrated these large VMM-base batteries (one at the time, tuned by Tesla), to the same location as an equivalently sized synchronous generator to simulate a retirement of the corresponding synchronous generator.

7.2. Grid following with and without VMM

The studies were performed in the PSCAD software platform against a frequency event simulated in the SMIB model of Wallgrove, once with and once without VMM being enabled. As can be seen in Figure 14, below, the WGB responds immediately to the event and it reaches its inertial peak faster than grid following. In addition, the active power exceeds the steady state limits in the maximum active power scenario (P=50 MW). It should be noted that these studies were performed in a modelling environment with a low synchronous machine dispatch scenario, which has led to a fast ROCOF.

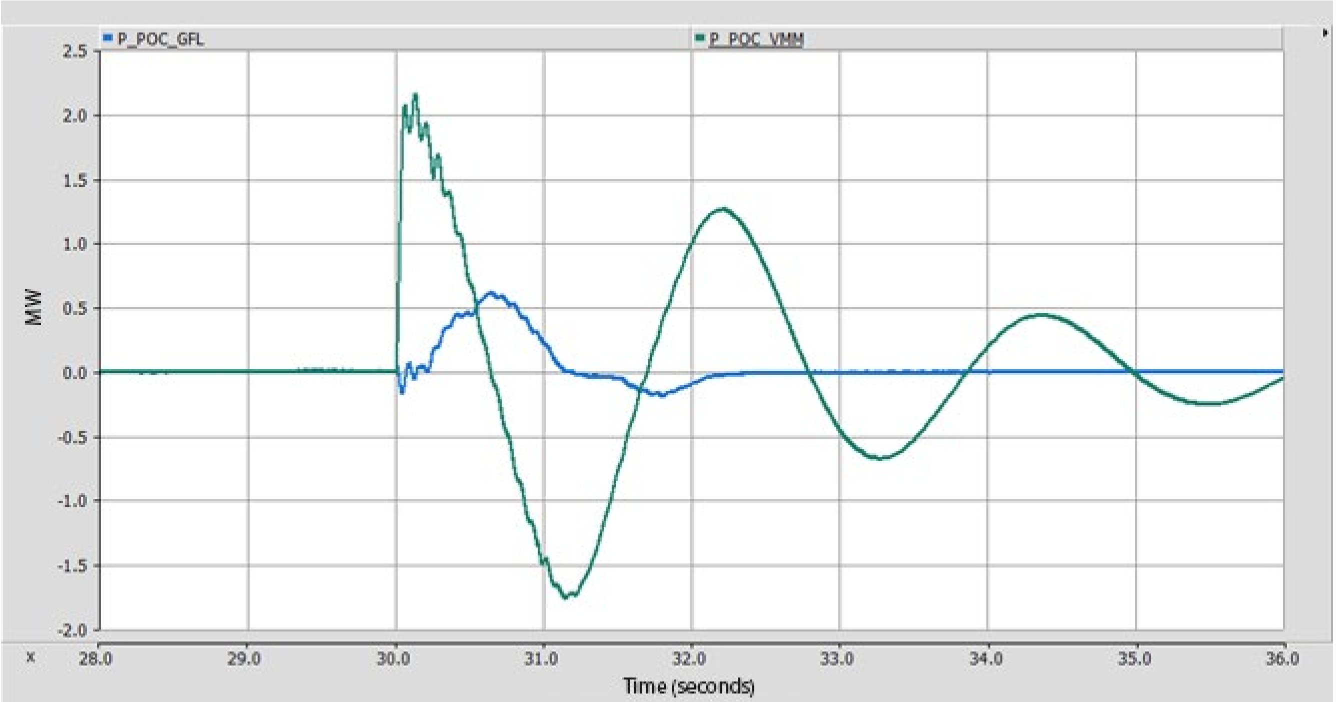

Figure 14 – Effectiveness of VMM at WGB for frequency event

7.3. Impact of location

Figures 15 and 16 illustrate that the response to a frequency disturbance is not dependent on the location, as the charts present consistent results from identically sized BESS at Sydney West, Eraring substation and Liddell substation.

It should be noted that the scaled-up BESS (660 MW-MP1) was used to run these studies tuned by Tesla while the BESS was dispatched at 0 MW for the study of each location, i.e. the BESS was entirely available to provide an inertial response.

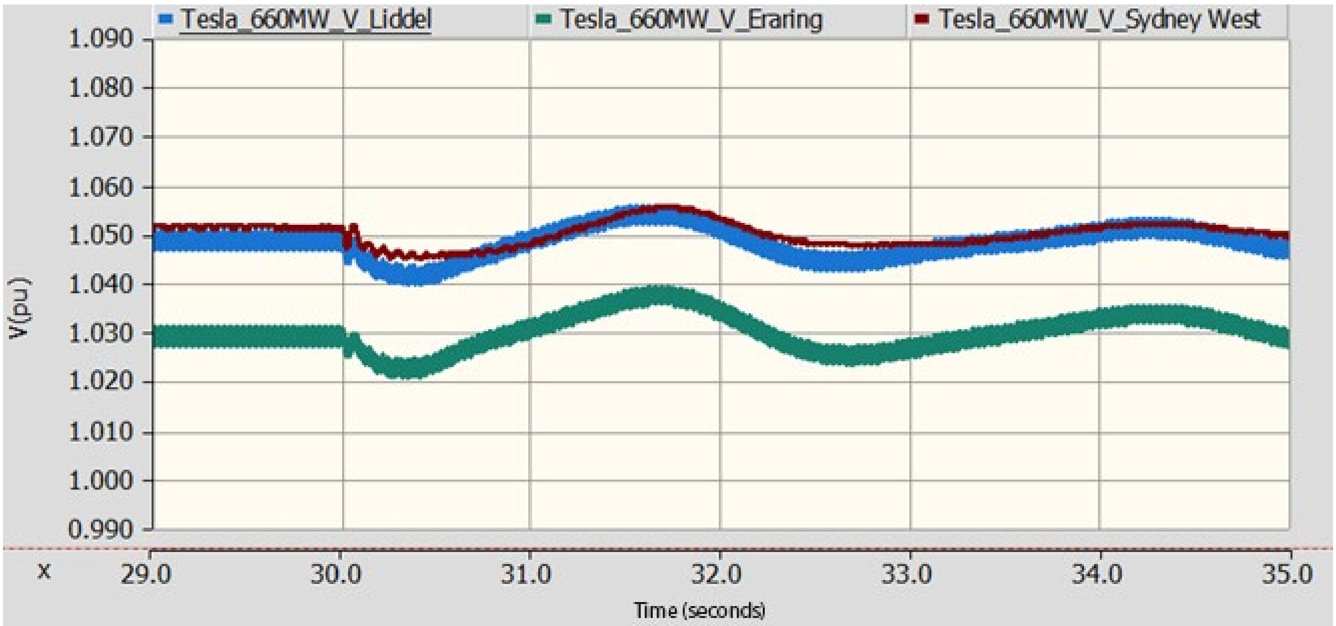

Figure 15 – Voltage profiles – 660 MW Tesla BESS at Sydney West, Eraring and Liddell

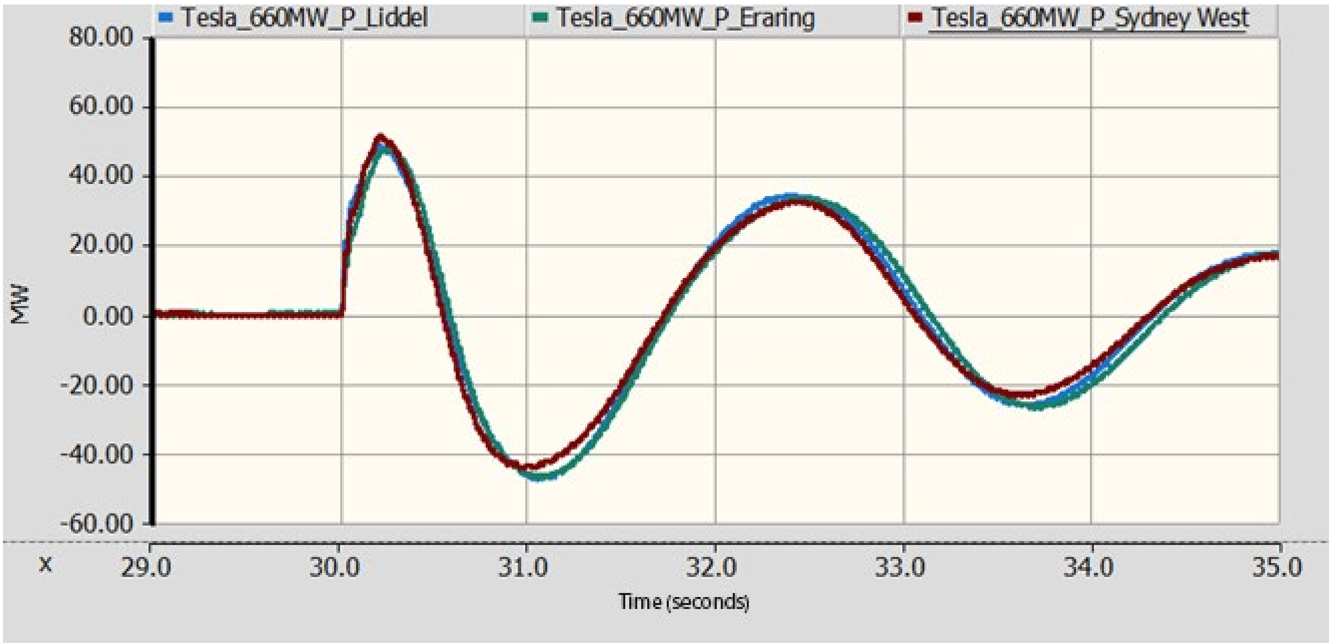

Figure 16 – Active Power Overlay – 660 MW Tesla BESS at Sydney West, Eraring and Liddell

Figure 17 shows the overlay of Active Power from the 50MW WGB integrated into the network model at three different locations to present the impact of location for a frequency disturbance that has not triggered Fault Ride Through (FRT) operating mode.

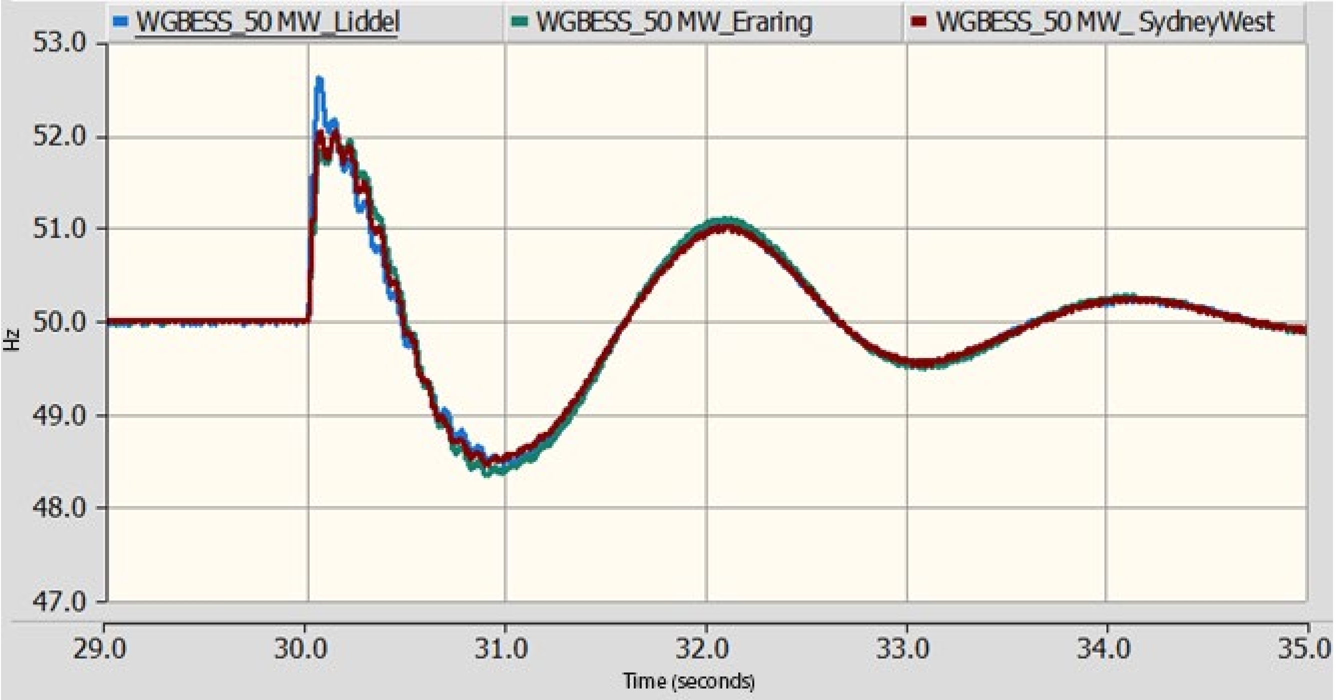

Figure 17 – Active Power Overlay – WGB at Sydney West, Eraring and Liddell

7.4. Scaled-up TESLA BESS with VMM response (with compliant tuning) and equivalent synchronous generator

In this section, comparisons are presented between a scaled-up Tesla BESS with VMM enabled and an equivalently sized synchronous generator.

The tuning of this VMM has been selected to meet at least a high-level compliance with the same Generator Performance Standard as the Wallgrove Battery.

7.4.1. Frequency event

Figure 18 presents the overlay of active power from the scaled-up battery and a synchronous generator in the event of the trip of one of NSW's large synchronous generators.

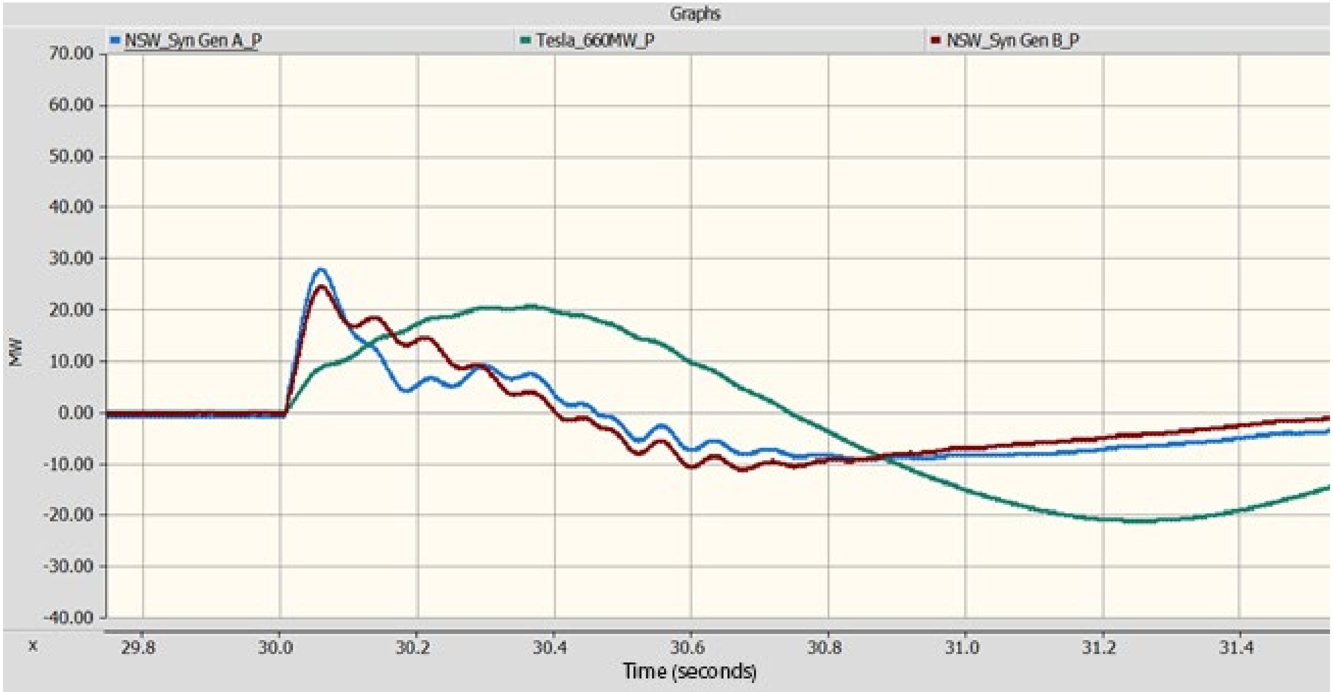

Figure 18 – Active Power Overlay – 660 MW Tesla BESS vs two NSW synchronous generators

Figure 19 presents the same overlay, but with a second generator also tripping.

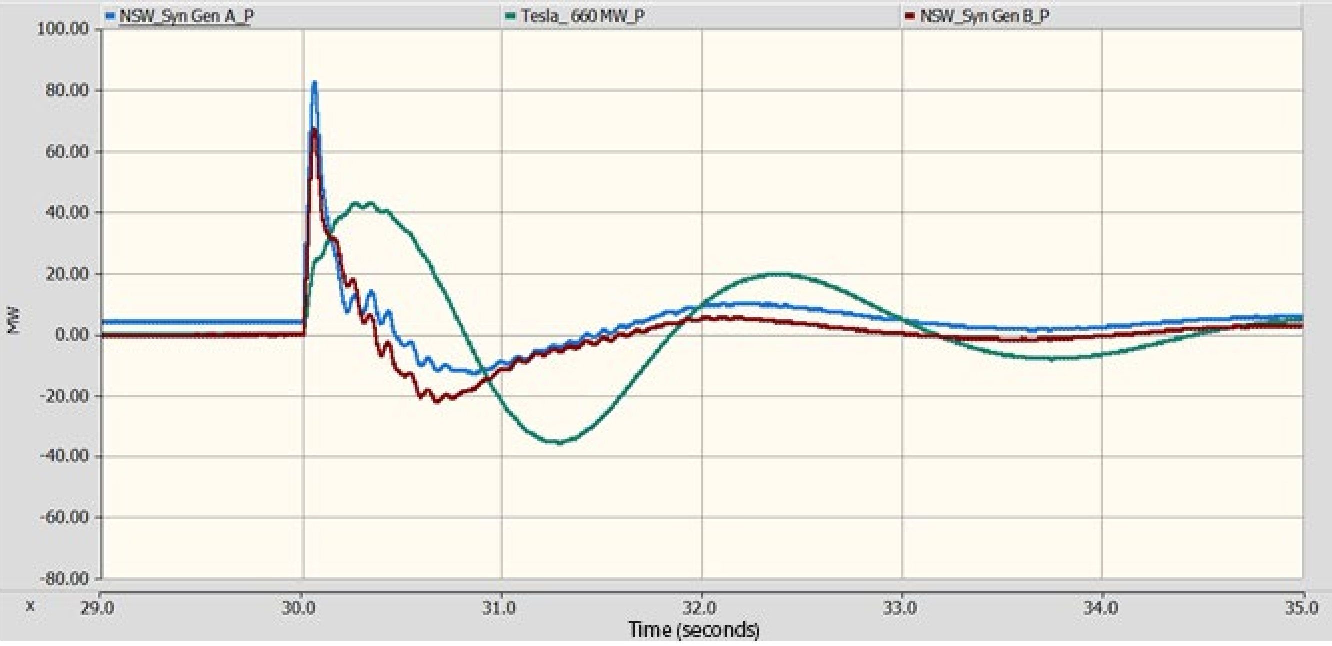

Figure 19 – Active Power Overlay – 660 MW Tesla BESS vs two NSW synchronous generators in double trip

The figures demonstrate that the scaled-up BESS (green line) has a sharp active power response within the first 100-200 ms of the event; however, the response is not as fast and has a lower magnitude than the synchronous generators, as well as less damping.

It should also be noted that the scaled-up BESS performs differently to the 50MW WGB. Figure 20, below, shows the overlay of Active Power between the WGB (5.3.9 model) against a frequency disturbance under the minimum synchronous generator dispatch; which led to a ROCOF of about 0.5 Hz/s, versus active power from a NSW synchronous generator. For this overlay, the output of the synchronous generator (in blue) has been scaled down and vertically shifted to make the overlay more comparable.

It must also be noted that the selected synchronous generator was further to the tripped generator but it has a similar voltage profile as the trip did not associate with a fault.

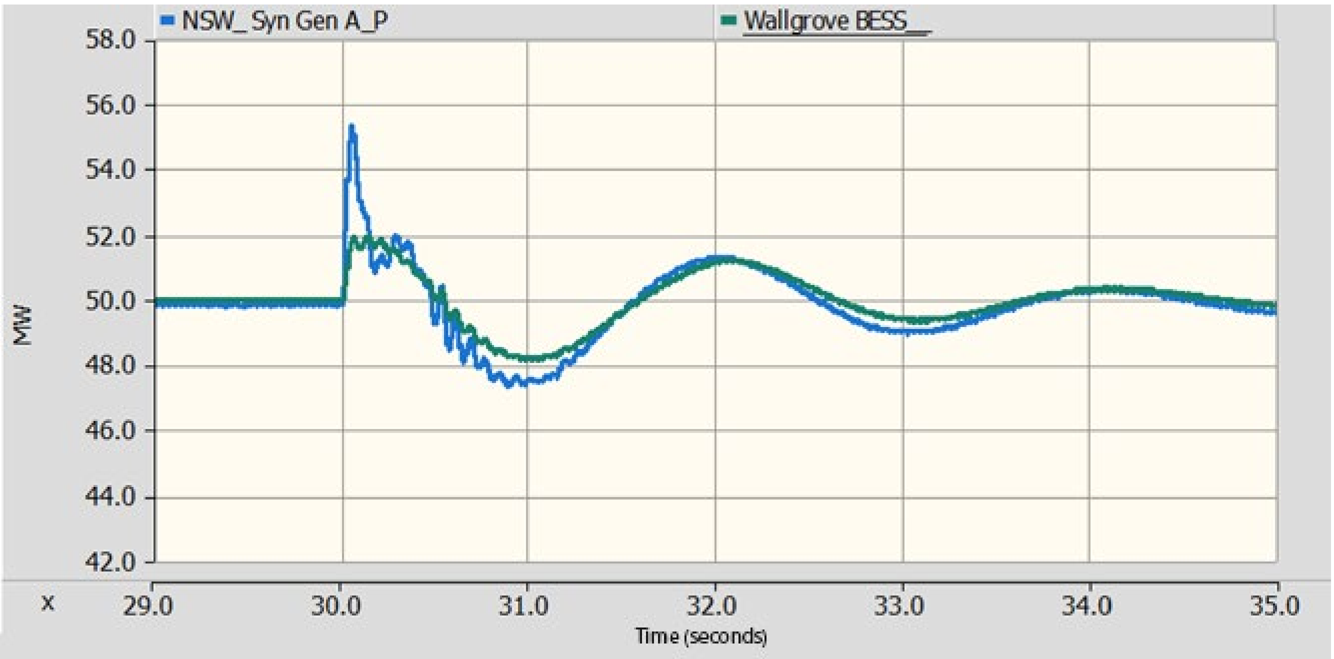

Figure 20 – Active Power Overlay – WGB and NSW synchronous generator

7.5. Scaled-up TESLA BESS with VMM response (more aggressive tuning) and equivalent synchronous generator

To increase the speed of the response and match the level of inertial response from the synchronous generators, Transgrid worked with Tesla's engineering team to further tune the scaled-up battery. The same events were then repeated on the same set of contingencies. Additionally, to check the compliance of the scaled-up battery, more studies such as fault scenarios were applied with the results also presented below.

7.5.1. Frequency event

The three locations selected for the 660 MW Tesla BESS from Megapack 1 technology are Sydney West (original Wallgrove location), Eraring and Liddell.

As can be seen in Figures 21-24, with the new set of tuning, the scaled-up WGB provided the same amount of active power within the same time window of data (Zoomed-In and Zoomed-Out) that the synchronous generators did.

However, the damping of the response post-disturbance is adversely affected, as can be seen with the active power injections which swing more positively and negatively than the equivalent synchronous machines.

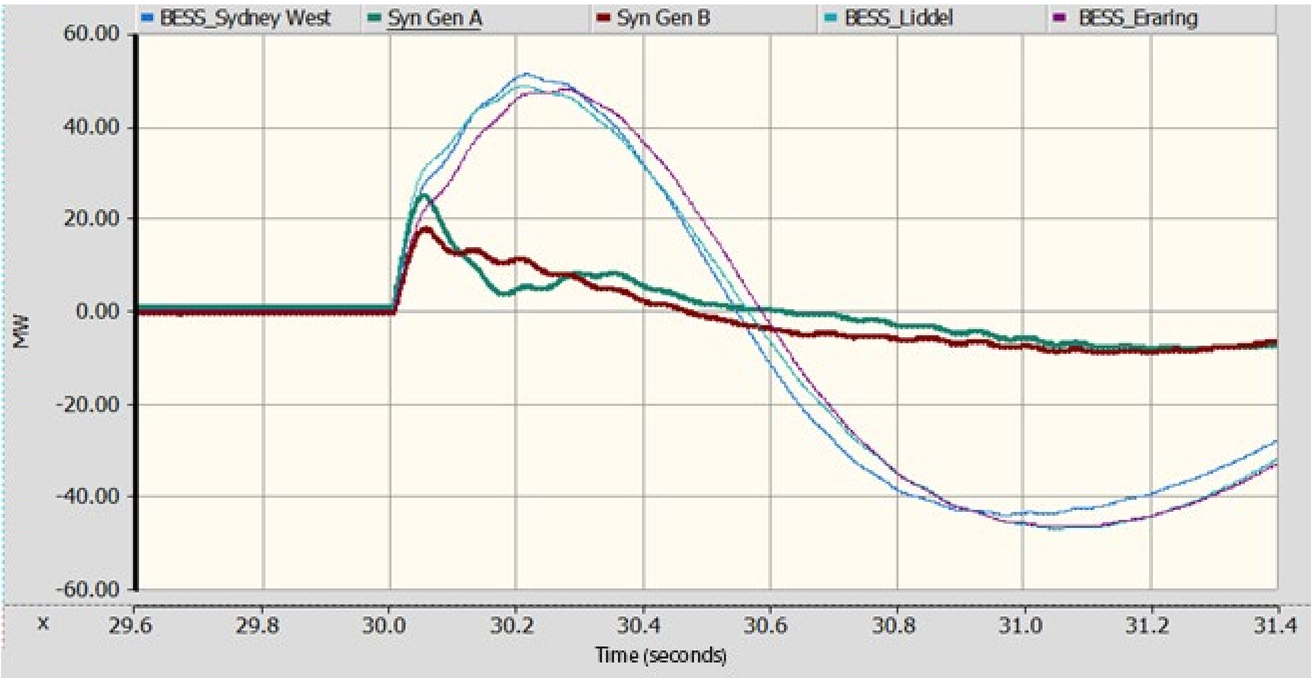

Figure 21 – Active Power Overlay – 660 MW Tesla BESS vs two NSW synchronous generators at three locations

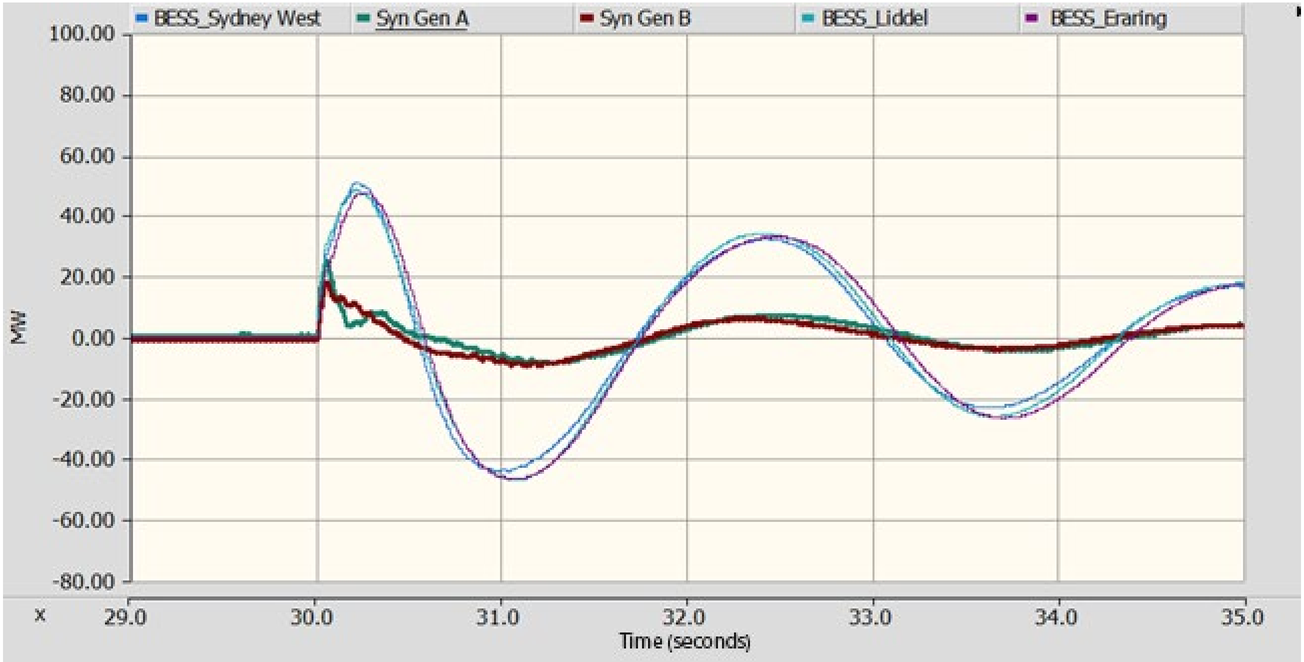

Figure 22 – Active Power Overlay – 660 MW Tesla BESS vs two NSW synchronous generators at three locations (zoomed out)

7.5.2. Fault Ride Through

For all the generators, it is critical to be able to ride through faults as required under the Automatic Access Standards. This is even more critical for the generators that need to provide other services such as inertia or system strength to other generators. As a result, some standard fault ride-through scenarios are imposed on the scaled-up Tesla battery to check the FRT capability.

7.5.2.1. 220 ms Fault leading to frequency disturbance

This fault was applied close to NSW Generator B, which led to its tripping and created a frequency disturbance too. This contingency has been selected to check the performance of Tesla BESS equipped with VMM against concurrent voltage and frequency disturbance relative to other synchronous generators in the network.

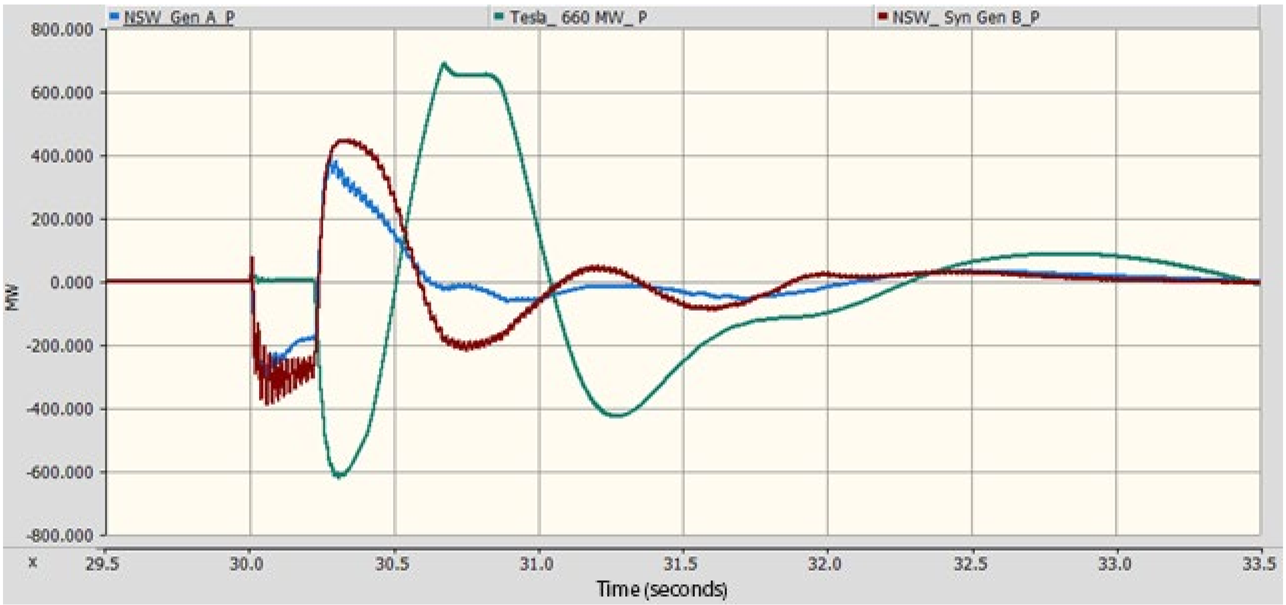

Figure 23 – Active Power through fault – 660 MW Tesla BESS vs two NSW synchronous generators

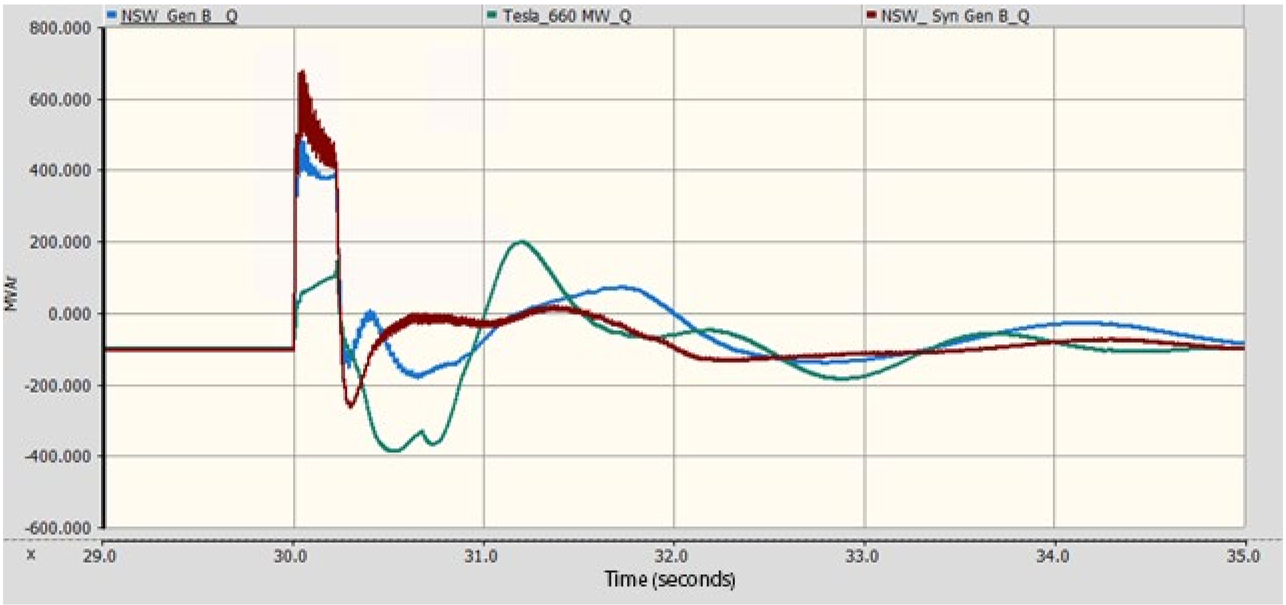

Figure 24 – Voltage through fault – 660 MW Tesla BESS vs two NSW synchronous generators

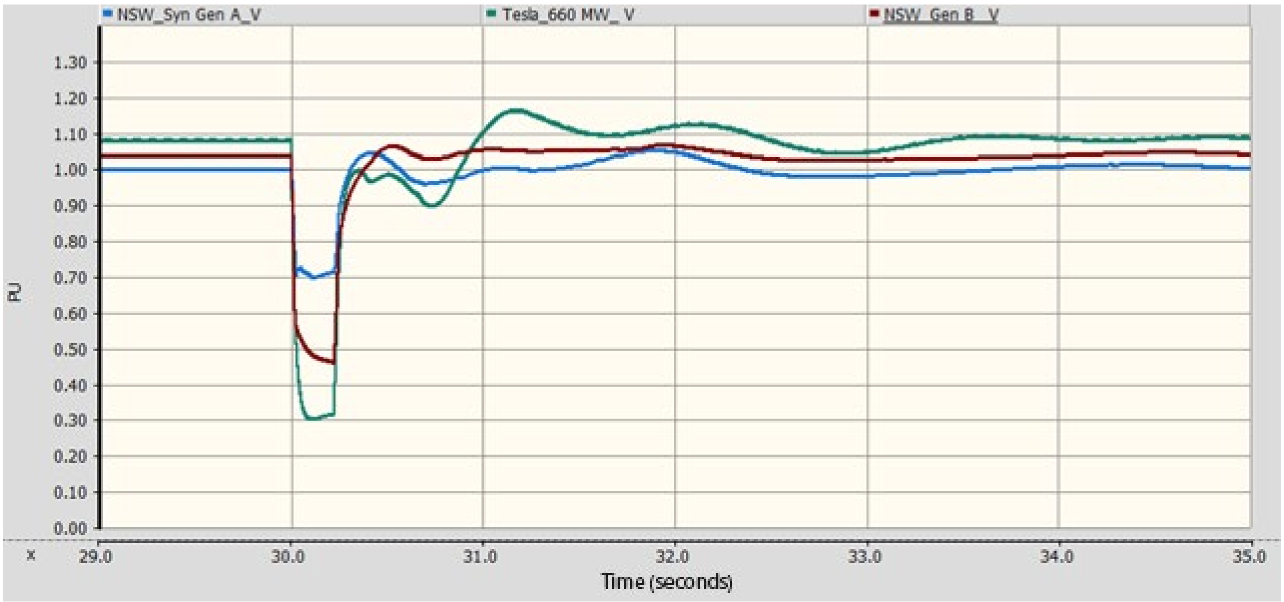

Figure 25 – Voltage – 660 MW Tesla BESS vs two NSW synchronous generators

Unlike the other two synchronous generators, one of which was in the same location as Tesla 660 MW BESS (Gen B) and the other was further away (Gen A), the Tesla BESS has managed to hold the active power in the same level as pre-fault.

As with the real-event observation at Wallgrove presented in section 6.2, post-fault active power goes through a large swing down to -600 MW. Similar observations are evident in reactive power, which has led to voltage going back to 0.9 pu.

7.5.2.2. 340 ms fault leading to frequency disturbance

When the fault duration has increased from 220ms to 340 ms, as shown in Figure 25, even though the disturbance is very significant, the network still recovers within normal operating range as all the generators recover back to a healthy status. However, when one of the synchronous generators at the same location was replaced with Tesla VMM BESS, the battery could not recover post-fault to a stable operating point and tripped. This trip has also led to the network becoming unstable due to its negative power swing during under-frequency.

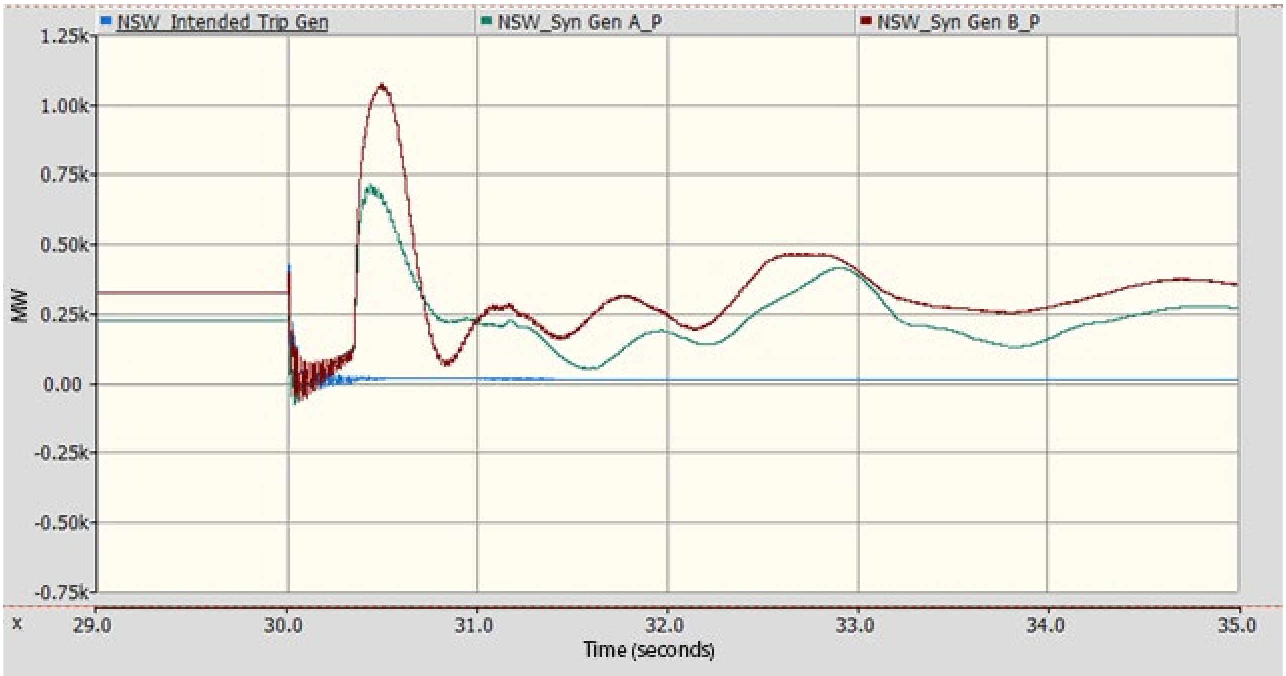

Figure 26 – Fault ride-through test on 660 MW Tesla BESS

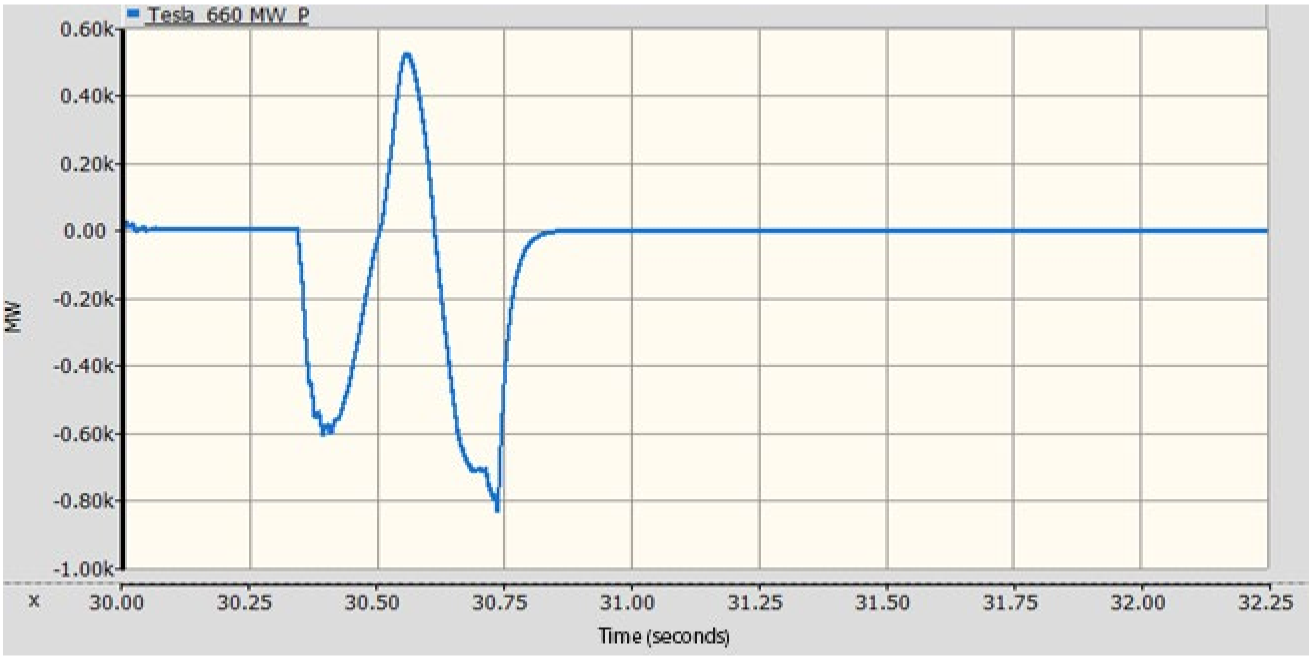

Figure 27 – 660 MW Tesla BESS MW during 340 ms fault associated with the loss of a generator

7.6. Scaled-up TESLA BESS with 0.018 pu and 0.009 pu Transformer Impedance

Figure 28, below, shows the comparison of active power from the scaled-up 660MW Tesla BESS with the same tuning and model but connected to the grid with different transformer impedances – one of approximately 0.018 pu and the other approximately 0.009. The impact of halving the transformer impedance on the inertial response can be seen in Figure 28.

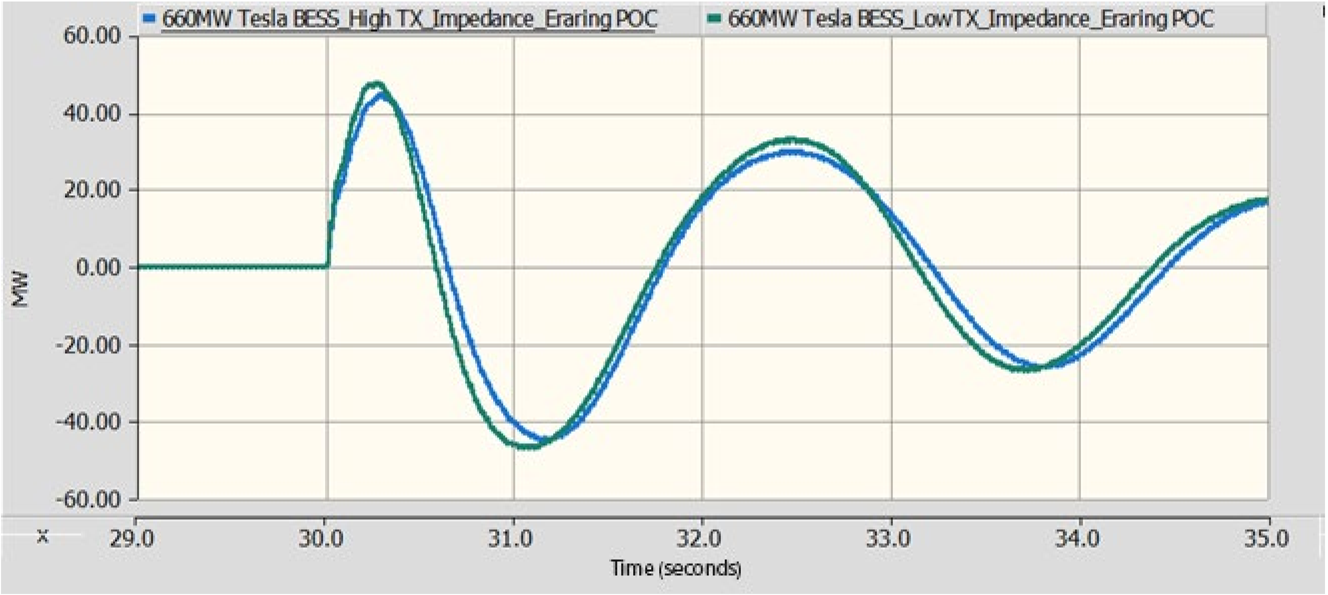

Figure 28 – Active Power Response – 660 MW Tesla BESS MW during fault with low and high transformer impedance

7.7. Conclusion of theoretical and modelling investigation

1. The VMM modelled through both Megapack 1 and Megapack 2 platforms appears to be faster and more effective than typical grid-following technology which only responds to the variation in frequency. This can be seen both at Wallgrove and the hypothetical large-scale BESS, as they respond to the variation in the supply and demand of the active power rather than the variation in the magnitude of the frequency. This feature is particularly useful and creates the capacity to contribute to the network inertia.
    a. It must be noted that the scaled-up battery implemented in Megapack 2 has improved from Megapack 1 which is installed on Wallgrove BESS.
2. The implemented technology can have a very fast frequency response which is also helpful with general frequency control. This response is found to be faster than what a typical synchronous generator can provide using its governor.
3. For the VMM technology to provide the same amount of MW.s from the source of power to the grid within a certain window, (i.e. to mimic the reference synchronous machine) it will require aggressive tuning which introduces adverse impacts. Transgrid's observation has been that aggressive tuning (within the existing technology made available to Transgrid for testing), introduces non-compliant trade-offs and adverse impacts, namely in Fault Ride Through (FRT) capability, stability, and damping. However, BESS technology is flexible to meet the objectives of speed of response as well as FRT using a combination of tuning, controls, and overall MVA capability. For this reason, it is important to clearly define required performance requirements so that these factors can be optimised through a combination of the overall design, control and tuning of a project. Tesla is aware of the adverse effects, and it is not their intention to mimic synchronous generators but to offer a different solution to frequency management that is a combination of inertia and fast frequency response.
4. Unlike a synchronous generator, based on the information available to Transgrid, the relationship between the event's ROCOF and corresponding active power response did not appear to be linear in the same way as would be expected for a synchronous machine. Tesla finds that this non-linearity is acceptable for power system operation, as demonstrated by VMM operating seamlessly in various contexts globally, including in high renewable microgrid operations. From Transgrid's perspective, these non-linearities make planning for inertia more challenging.

In conclusion, subject to careful tuning, Tesla's VMM technology contributes to both frequency control and system inertia support in pure frequency events. This response can reduce the system frequency nadir following a system frequency disturbance event. It can be argued that these advantages are sufficient, and it is unnecessary to mimic the behaviour of synchronous generators, but the finding from the research in pursuit of the Project objective is that the implemented technology does not replicate the behaviours and capabilities of a synchronous machine. In particular, riding through some of the conditions required under the NER appears to be challenging for this technology in its currently implemented format and tuning. Tesla maintains that it is unnecessary to mimic synchronous machine, and a future grid with high renewables plus grid-forming inverters will be more than sufficient to meet network and system security requirements.

The industry would benefit from further research across a diverse range of technologies to better understand the trade-offs and operational limitations that must be considered for each specific project when substituting inertia from synchronous machines with synthetic inertia. As the synthetic inertial response is provided by the control system of a battery, the inertial response can be affected by the control structure and filter tunings. This means that conclusions on virtual inertia response cannot be drawn exclusively from one specific model within one technology.

8.1. Connection application approvals

Preparation of the connection application for the battery commenced in May 2020 with research and discussions with AEMO.

As part of the GPS and registration phase, AEMO requested that the technical due diligence be performed by two teams within Transgrid, with an information barrier between them. One team represented Transgrid as a Proponent and the other team represented Transgrid in its role as a Transmission Network Service Provider. Transgrid established this structure and engaged a grid consultant to assist with the preparation of the proponent's connection application.

The preparation of the Generator Performance Standards formally commenced in October 2020, at contract commencement. They were approved by AEMO and Transgrid (as the TNSP) on 11 May 2021. The approval of the GPS was a significant milestone within the project, which was completed within the scheduled timeframe.

A connection agreement was completed and notified to AEMO subject to Clause 5.3.7(g) of the NEM Rules, on 17 May 2021. The market participant, Iberdrola Australia, commenced commercial operations of the Wallgrove Grid Battery on 22 December 2021. At that time the battery did not have VMM enabled, as the process of approving registration with VMM would have delayed the commencement of commercial operations and the project delivery milestones were prioritised with the understanding that VMM would be enabled through the course of 2022.

8.2. VMM, GPS and commissioning tests

To enable VMM, Lumea proposed to alter the generating system under the 5.3.9 process, of the NER. At the time of commencing this process only one other battery (Hornsdale Power Reserve) had gone through a similar alteration process with AEMO. The lack of current incentive structures and the perceived, or actual, complications in connection alterations have prevented more operational batteries from undertaking a similar alteration. As such there were limited market insights on how smooth the connection alteration would be, and whether challenges would arise concerning either specific clauses in the NER or the AEMO connection process.

During the alteration process, several issues highlighted barriers that exist in connecting grid batteries with grid-forming characteristics. The most significant challenge faced was that under the 5.3.9 process, the performance standards of the existing plant effectively become the minimum standards that the plant must adhere to when alterations are made [clause 5.3.4A(b)(1A) , NER Version 206]. An unintended consequence of the current access standards in Schedule 5.2 of the NER for asynchronous generation is that a project with grid-forming inverter technology is assessed against access standards that appear more suited to asynchronous generating systems that are of a grid-following nature, which can trade-off some of the benefits offered by advanced inverters with grid-forming capability. Grid-forming inverters are more analogous to synchronous machines (which are assessed differently to asynchronous generators under s5.2.5.5 due to these inherent and recognised differences). While the overall performance of the WGB improved, under certain clauses, notably s5.2.5.5, it was not able to meet the existing performance standard agreed for the grid-following configuration.

Lumea established through dialogue with AEMO and ElectraNet that this issue was not faced to the same extent by ElectraNet when they followed a similar process on the Hornsdale battery. Two reasons were established:

- ElectraNet were able to adjust some parameters to enable the battery to meet the minimum access standards for one of the clauses of the GPS, specifically s5.2.5.5. This same approach was not a viable option for the WGB as the performance standards of the existing plant at WGB, and therefore the minimum standards applied to the alteration, were different to those at Hornsdale.

- Hornsdale is located in a weaker part of the network electrically, while Wallgrove is in a stronger part of the network. The original performance standard agreed for WGB in grid-following configuration in this strong part of the network made it more challenging to replicate the same behaviour using a grid-forming configuration, due to the inherent differences between grid-following and grid-forming control systems.

The most impacted performance standard was s5.2.5.5, which has a provision to enable AEMO and the TNSP to have some discretion on the parameters of operation. Lumea and Transgrid sought external advice which provided guidance that enabled alteration of the wording of the clause along with further studies to ensure that the minimum standard could be met. The wording was ultimately presented to AEMO and received their agreement which was the critical hurdle before hold point testing could commence. The battery was ultimately successfully registered and began operating with VMM enabled on 23 November 2022.

The project team identified that an existing rule change process was underway through the Australian Energy Market Commission (AEMC) which would most likely address the issue being encountered. The specific AEMC page for the rule change 'Efficient reactive current access standards for inverter-based resources' can be found at:

https://www.aemc.gov.au/rule-changes/efficient-reactive-current-access-standards-inverter-based-resources

The Transgrid planning team provided input which can be found at:

https://www.aemc.gov.au/sites/default/files/2023-02/230202%20Transgrid.pdf.

8.3. Final settings

The final registered parameters are:

Inertia Constant (H) = 1 MWs/MVA

Damping factor (D) = 0.9

The primary objective in determining the final settings was to demonstrate that the previously agreed GPS (negotiated for a grid-following configuration) could be met as required by the NER. While this resulted in a trade-off in performance in some areas where a more optimal tuning of the virtual machine could have been offered for the provision of inertia services, alternate tunings and configurations introduced other issues, as discussed previously in sections 6 and 7.

8.4. Procurement of inertia services

Under existing NER obligations, AEMO is responsible for declaring inertia shortfalls where they appear in a 5-year outlook, on the basis that there is a credible risk of islanding occurring. AEMO does not believe there is a credible risk of NSW islanding alone, and there are no forecasted shortfalls in inertia in the next 5 years for a QLD-NSW island. As such, under existing NER obligations, it is difficult for Transgrid to proactively procure for future inertia requirements, even though Transgrid's analysis indicates that when all coal retires in NSW, there is very little inertia that can be relied upon (See Transgrid's System Security Roadmap, section 2.5). These obligations are likely to change (in 2027), based on indications from the AEMC for the 'Improving security frameworks for the energy transition' rule change, which will follow system strength obligations, where TNSPs are required to proactively ensure that there are sufficient levels of system strength in the state based on a 10-year forecast of requirements. This will lead to Transgrid seeking solutions to declining levels of inertia in the state.

Moving forward, under updated inertia rules as per the 'Improving Security Frameworks for the energy transition' rule change, Transgrid will start co-optimising investment in inertia and system strength assets and services. Transgrid believes the market will be shallower for inertia than it is for system strength, as system strength has a more local effect (where provision diminishes with electrical distance) while inertia is more global. As such, meeting system strength needs may go a long way to meeting inertia requirements.

9.1. BESS storage reservation for network services

9.1.1. Contractual obligations

A portion of the WGB's energy storage capacity is reserved to ensure there is always sufficient energy available to deliver inertia and fast frequency response in case of a significant frequency disturbance. Iberdrola Australia is required to maintain an agreed margin from the minimum and maximum states of charge, to ensure that the BESS is always able to deliver frequency response in either direction in the event of a significant frequency disturbance. These margins are agreed in terms of MWh (not in terms of percentage of capacity) and will always comprise less than 5% of the battery's usable energy storage capacity.

9.1.2. Operational impact for Iberdrola Australia

In line with the contract, Iberdrola Australia is therefore only required to reserve energy storage capacity and is free to bid the WGB's power capacity across the energy and FCAS markets up to the full discharge/charge capacities of 50MW / 47MW respectively.

On a short-term basis (5-minute dispatch intervals), Iberdrola Australia takes a view on the potential for WGB's dispatch to encroach upon these contractual state of charge thresholds, limiting dispatch in a market (typically Regulation FCAS or Energy) where there is a possibility of excessively charging or discharging. As the state of charge is actively managed throughout the day, it is very rare for the BESS to be restricted in terms of participating in the Energy and FCAS markets to below its full capability, especially in the provision of Contingency FCAS.

The constraints on reserving energy storage capacity do need to be considered over the medium-term operations of the battery where an extended charge or discharge will bring the battery to the limits of its energy storage capacity (either ~0% or ~100% energy storage capacity).

Iberdrola Australia's bidding strategy is consistent with naturally reserving energy storage headroom for either dispatching or charging the battery for unforeseen market volatility. Analysis of operational data over the past two years demonstrates that Iberdrola Australia prefers to maintain at least 15 percent of energy storage capacity reserved to capitalise on unforeseen market events.

Given the alignment of reserving energy storage capacity for network services and Iberdrola Australia's bidding strategy, there have been limited operational impacts on market services from complying with the network service requirements.

9.2. Inertia provision and market revenues

Objective 2: To demonstrate that a BESS operating with synthetic inertia capabilities can provide a useful inertia service to the power system whilst the BESS is in normal commercial operation.

As the commercial operation of the battery was not encumbered by requirements to reserve power capacity for the network service, analysis of the operational data provides insight into the availability of the WGB to provide the necessary responses.

Figure 29 shows a summary of the WGB's dispatch behaviour in the NEM from the commencement of operations in late 2021, to the introduction of the very fast frequency response market in October 2023. The battery is idle and therefore available to provide inertia and FFR in both directions at its nameplate capacity approximately 22% of the time. The steepness of the chart at either end shows that the battery charges or discharges near or at its full capacity in limited situations. This means that for the vast majority of the time, most of the nameplate capacity is available in both directions to provide either a raise or lower FFR and/or inertial response.

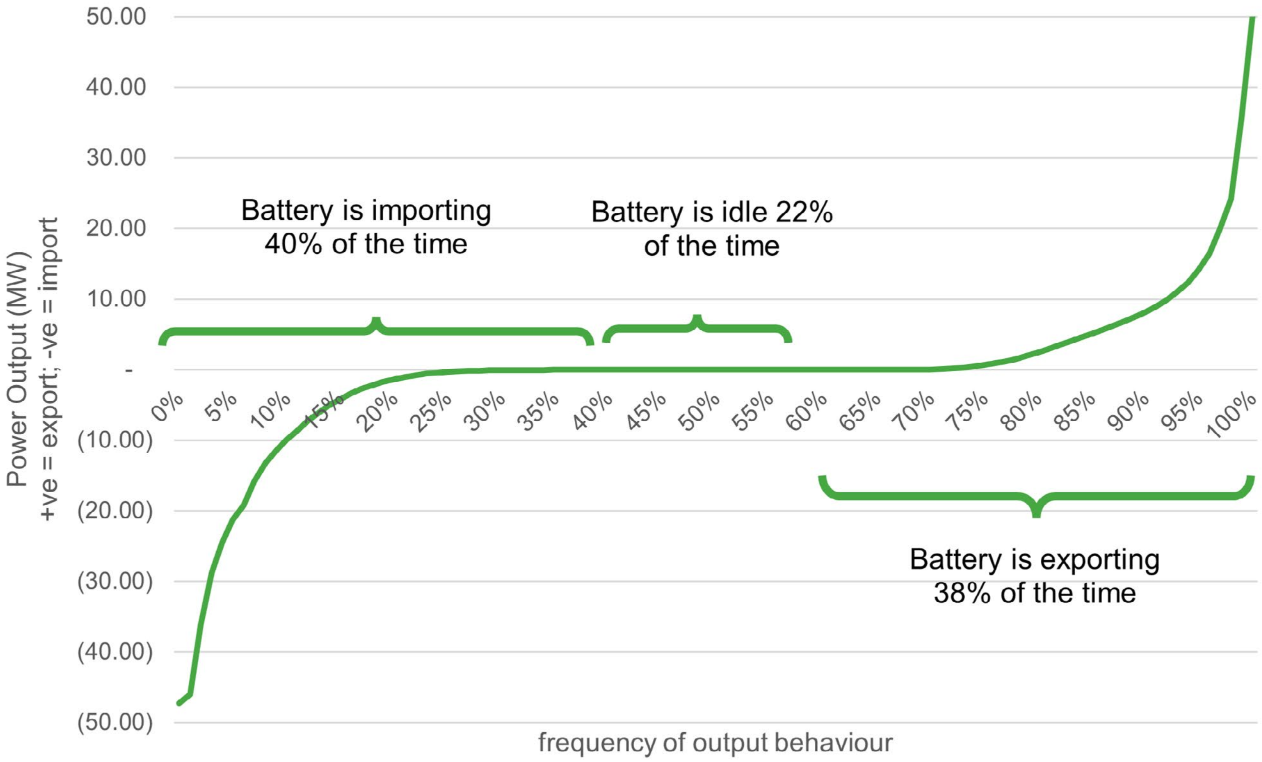

Figure 29 – WGB output behaviour – 23 December 2021 to 8 October 2023

9.2.1. Availability for inertia and FFR

As noted previously, when the battery is idle, 100% of its nameplate capacity is available for raise and lower services. When it is actively charging or discharging, there is a corresponding increase in available capacity for the opposing service, i.e. when charging, the WGB has more than its nameplate capacity available for raise services as the frequency response reverses the load and then discharges. The scale of the available capacity is therefore between 0 and 200% of the nameplate, with a slight accommodation for the asymmetric charging and discharging registrations.

9.2.1.1. Raise

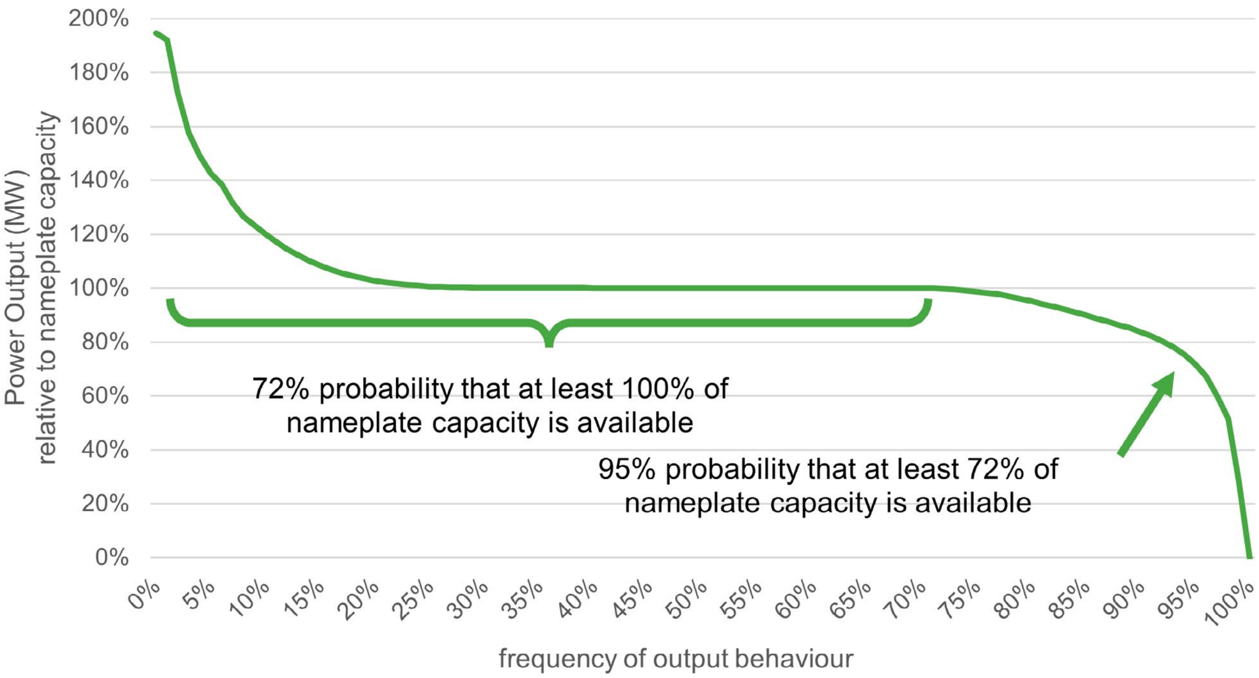

Figure 30 – Percentage of nameplate capacity available for inertia and FFR (raise) 23 December 2021 to 8 October 2023

Key findings:

- At least the WGB's full nameplate capacity is available to provide raise services approximately 72% of the time.
- For 95% of the time, at least 72% of the WGB's nameplate capacity is available to provide raise services.
- For a quarter of the time, greater than 100% of the nameplate capacity is available to provide raise inertia services.

9.2.1.2. Lower

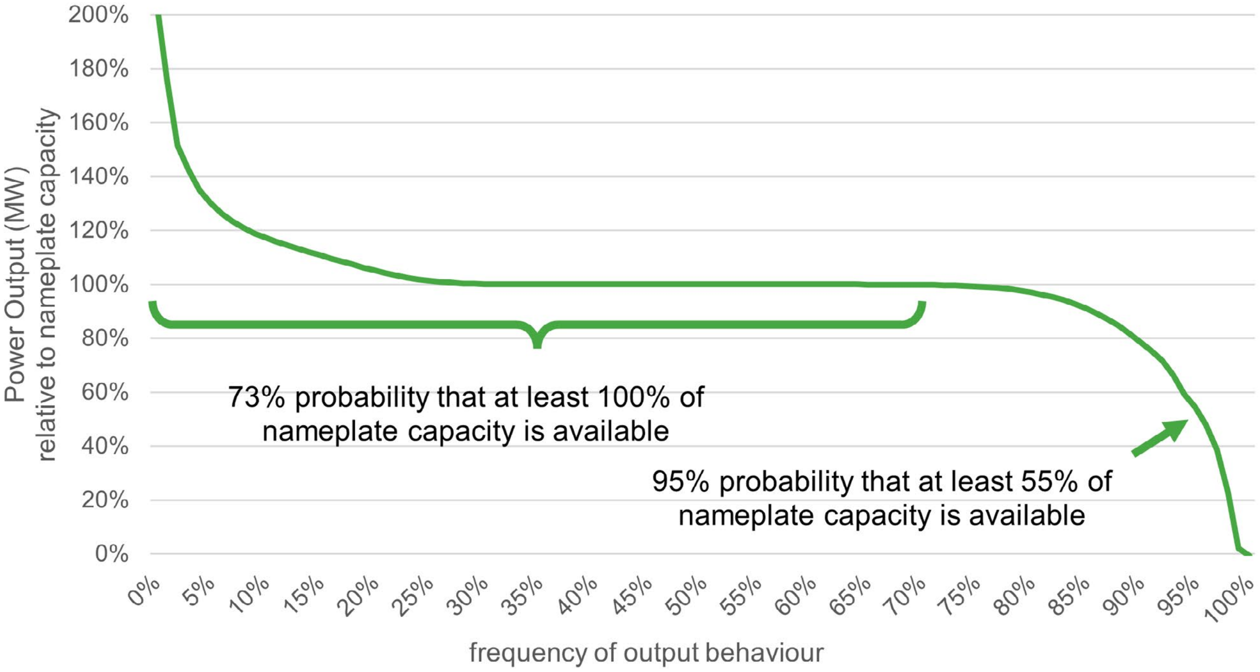

Figure 31 – Percentage of nameplate capacity available for inertia and FFR (lower) 23 December 2021 to 8 October 2023

Key findings:

- The WGB's full nameplate capacity is available to provide lower services approximately 73% of the time.
- For 95% of the time, at least 55% of the WGB's nameplate capacity is available to provide lower services.
- For a quarter of the time, greater than 100% of the nameplate capacity is available to provide lower inertia services

9.2.1.3. Conclusions on complementarity

This analysis shows that without imposing any restrictions on Iberdrola Australia's use of the WGB, the battery can provide FFR and inertia to at least nameplate capacity around three-quarters of the time, i.e. to a large extent the commercial operations do not inhibit the provision of the network service.

Under the current NER, a battery that has been contracted to provide inertia only needs to guarantee the provision of inertia when "enabled" by AEMO, and this would only occur when there is a credible contingency event that could result in a region of the NEM being islanded. While it demonstrates that in times of network need anything less than 100% available is not an option, discrete procurement of inertia, particularly considering evidence of the complementarity between market and network services such as the above, speaks to an opportunity for further market development.

FFR became a market service in October 2023, giving AEMO the ability to co-optimise the provision of FFR along with energy and FCAS via the NEM dispatch engine. In simple terms, this means Iberdrola Australia (via the bidding process) and AEMO (via the dispatch process) can choose the combination of energy, FCAS, and FFR services that is most complementary and optimal for the network and market conditions at that time.

A future inertia market could operate in the same way when the volume of batteries with grid-forming inverter capability continues to grow along with the appreciation of how much inertia they can provide.

9.3. Energy market charges

The case studies provided in section 6 detail the volume of energy used in the provision of inertia in the event of grid disturbance. The 610MW trip of Mt Piper unit 2 initiated an inertial response of 1.46MW within 1.16 seconds. This is equivalent to an energy throughput of ~0.0005MWh discharged.

Assessment of four-second data suggests that there are approximately two large frequency disturbances caused by trips of key generators, loads and/or transmission lines, such as the Mt Piper event, each month. 24 Mt Piper events is a total energy response of 0.012MWh per year, however, as these inertial responses would include both charging and discharging of WGB based on whether a raise or lower inertial response was required, the throughput would likely be even less. The associated wholesale energy market impact should not be purely considered a cost, as the events may occur in periods of extreme or negative pricing, though it is clear from this analysis that through any variations, the impact is likely to be negligible.

In terms of impacts to the battery, a total throughput of 0.012MWh per year is negligible compared to WGB's average annual throughput of ~25,000MWh per year, which is critical given the value that this throughput has to the battery in other services (such as energy arbitrage).

9.4. Appropriateness of minimum and maximum state of charge constraints

As noted above, constraints are applied to WGB to maintain an agreed amount of energy storage capacity to be able to provide network services. The amount of energy reserved is significantly more than required to deliver inertia (delivered within the first ~0.5 seconds) and FFR (delivered within the first one second) following a network event.

This additional capacity ensures the BESS will be able to continue providing frequency response after the inertia and FFR has been delivered, i.e. it will also be able to provide contingency FCAS for at least 60 seconds (and probably for several minutes). It also allows some safety margin in case of multiple disturbances, inaccurate state of charge measurement, or extended periods during which it is undesirable or impossible to import energy from the grid to maintain the required minimum state of charge.

Given the alignment of reserving energy storage capacity for network services, Iberdrola Australia's bidding strategy, and the energy storage levels required to provide the desired network service responses, the minimum and maximum state of charge constraints for WGB are seen to be appropriate and non-restrictive.

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