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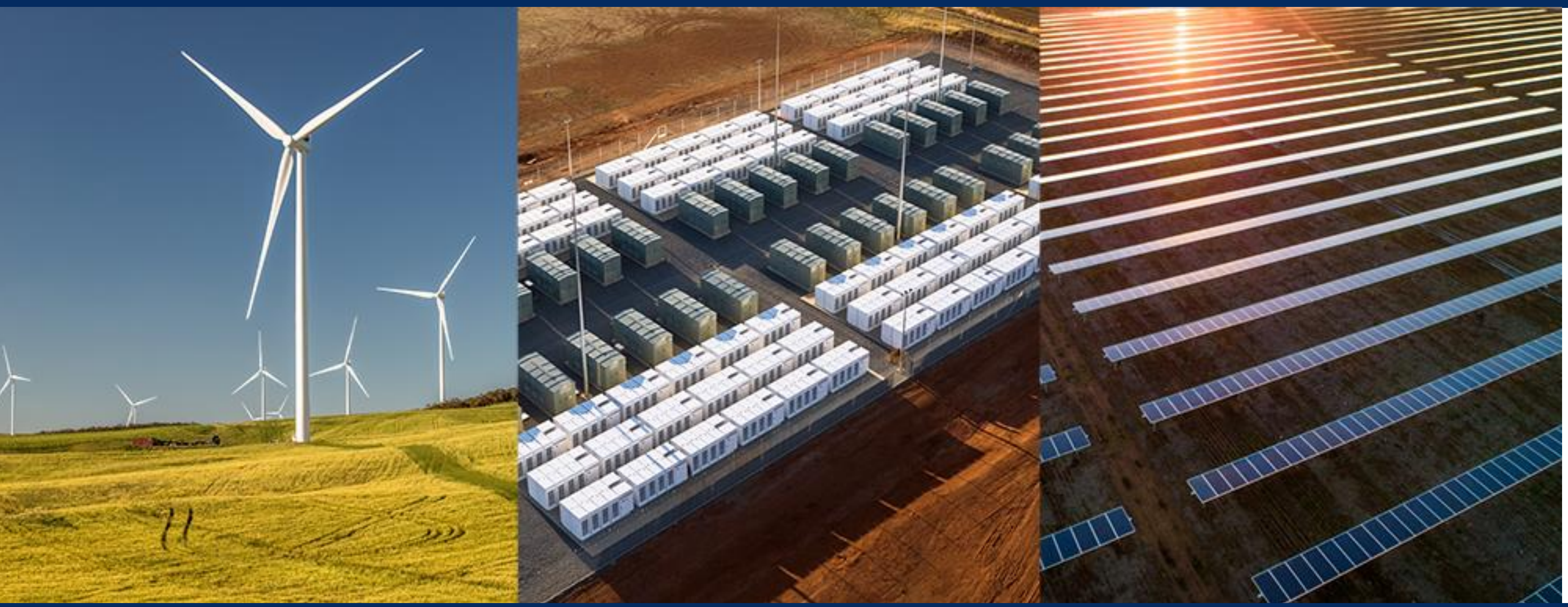
HORNSDALE POWER RESERVE EXPANSION



HPR OPERATIONS REPORT – H2 2022

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Disclaimer

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Government of South Australia
Department for Energy and Mining

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TESLA

2. Executive Summary

Following the September 2016 state-wide blackout which left South Australia without power, Neoen and Tesla were selected by the South Australian Government to supply Australia's first grid scale battery named the Hornsdale Power Reserve (HPR).

Carrying on the success of HPR, Neoen, in partnership with Tesla, received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program, and the South Australian Government's Department of Energy and Mining (DEM) to expand the existing 100MW/129MWh HPR by a further 50MW/64.5MWh. The South Australian Government provided support to the project by committing $15 Million AUD over 5 years through its *Grid Scale Storage Fund* and ARENA committed $8 Million AUD in grant funding through its *Advancing Renewables Program*.

This Australian-first battery expansion project committed to trial a new virtual inertia operating mode which mimics the behaviour of a synchronous generator when responding to rapid changes to frequency, stabilising the grid when electricity supply and demand unexpectedly fluctuate.

This report details the first 6-months of operations since the implementation of Virtual Machine Mode (VMM) at HPR.

3. Background

HPR is located approximately 16km north of Jamestown in South Australia. With initial nameplate capacity of 100MW/129MWh it was the world's largest utility scale battery at the time of completion. The fast-ramping capability of the Tesla Powerpack systems used at HPR enables the facility to dispatch large amounts of power quickly and reliably. This supports the South Australian electricity grid and delivers major cost savings by providing frequency control and short-term network security services.

A technical and market study carried out in 2018 by independent consultant Aurecon[1] noted that "*The introduction of HPR has significantly increased competition in the Regulation FCAS market. This has effectively reduced the pricing impact of the SA 35 MW FCAS constraint, which is estimated to have added nearly AUD 40 million in regulation FCAS costs in both 2016 and 2017*."

The HPR expansion project (HPRX) commenced construction in November 2019 and completed commissioning in September 2020 with the installation of an additional 50MW, bringing the total installed capacity to 150MW.

In consultation with ARENA and the South Australian Government DEM, Neoen and Tesla developed a test plan which outlined the innovations that would be demonstrated through the expansion of HPR. Notably, this included the implementation of VMM, with a view to providing utility-scale virtual inertia services to the SA grid. This test plan involved a staged approach to rolling out VMM which commenced with small-scale bench testing of the Tesla Powerpack

[1] https://www.aurecongroup.com/-/media/files/downloads-library/thought-leadership/aurecon-hornsdale-power-reserve-impact-study-2018.pdf

system operating in VMM through to the full implementation of VMM at the entire 150MW expanded HPR facility.

The grid's tendency to remain stable and maintain a constant frequency can be attributed in several ways to the basic characteristics of synchronous machines. Each machine's rotational kinetic energy, or *inertia*, operates as a reservoir of energy that is transferred to or from the grid instantly as load changes occur.

Unlike many other forms of energy storage and generation, batteries (coupled with advanced inverters) are particularly valuable because they provide flexibility due to the types of services and grid support they are able to provide. They can respond faster to grid disturbances and/or operator commands than most other energy storage or generation technologies, thereby helping maintain grid stability by ramping up or down in fractions of a second.

This can deliver numerous specific benefits to the grid operators today, including improving system inertia, facilitating standalone operation, and adding voltage smoothing to weak grids. The application of VMM to HPR aims to achieve the delivery of inertia to the South Australian power tuned for optimal performance. To achieve this, settings have been carefully selected that maximise the amount of inertia being delivered, while retaining the fast overall response that HPR is required to provide.

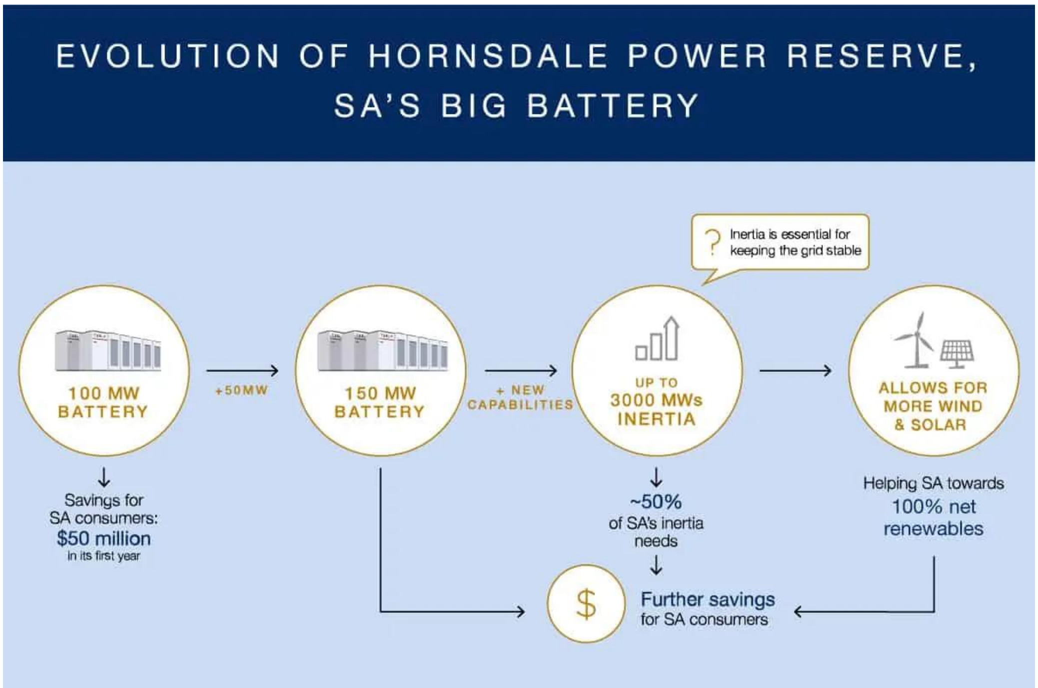

Figure 1 - Evolution of Hornsdale Power Reserve

The Australian Energy Market Operator (AEMO) identified an inertia shortfall in its December 2018 National Transmission Network Development Plan[2] and noted that the South Australian grid requires 6,000 megawatt-seconds (MWs) to maintain a secure operating level of inertia. It was anticipated that Hornsdale Power Reserve, when expanded could provide up to 3,000MWs of inertia. For scale and reference, South Australia's generating unit with the highest inertia is a 160MW Pelican Point Gas Turbine which provides 1,625 MW.s when running at its nameplate

[2] https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/NTNDP/2018/2018-NTNDP.pdf

capacity[3]. It should be noted that synchronous machines typically have overload ratings many times greater than inverters, which will see an inverter reach their maximum limit (saturate) earlier. As such, when comparing different technologies, it is important to consider the entire nature of an inertial response, along with the advantages and disadvantages each technology brings, rather than the quantity alone.

3.1. VMM Objectives

The application of VMM at HPR aims to achieve the delivery of system specific inertia to the South Australian power system, tuned for optimal performance. This aims to subsequently achieve:

- Successful integration of VMM across the full expanded 150MW capacity at HPR
- Demonstrate that BESS projects can provide inertia services in Australia, by using Tesla's VMM capability, thereby replacing the inertia traditionally provided by synchronous generation
- Arrest frequency rate of change during system events and stabilize grid
- Reduce curtailment of asynchronous generation in South Australia
- Pathway to higher penetration of renewable energy in SA / National Energy Market (NEM)
- Market development of new services
- Knowledge sharing of the project journey.

3.2. Virtual Inertia

In an electric system, inertia refers to kinetic energy contained in the rotating components of power generators. This stored energy is valuable when a large power plant fails, as it can act as a temporary response to make up for the power lost, helping maintain frequency stability. Inertia is a measure of the ability of the system to resist changes in frequency due to sudden changes in supply and demand. It is naturally provided by synchronous generators such as coal, hydro and gas-fired power stations[4].

Inverter-based resources, on the other hand, are connected to the grid without rotating mass, thus reducing the amount of inertia available. To compensate the reduced inertia available, Tesla inverters under VMM implement an inertial response synthetically via microprocessor-based control.

3.3. VMM Functionality

VMM is a mode of operation which can be implemented on Tesla Powerpack inverters that mimics the behaviour and inertial response of a synchronous machine to grid disturbances.

The virtual machine component runs in parallel with the conventional current source component as show in Figure 2.

[3] https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/System-Security-Market-Frameworks-Review/2018/Inertia_Requirements_Methodology_PUBLISHED.pdf

[4] https://www.aemc.gov.au/sites/default/files/2018-07/Final%20report.pdf

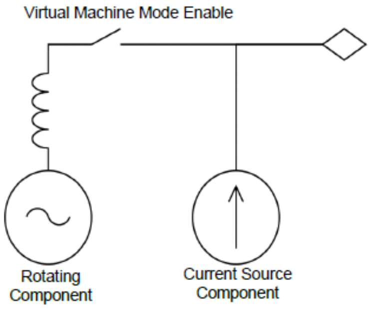

Figure 2: Virtual Machine Mode representation

Like more traditional inverters, under stable system conditions the inverter's behaviour is driven by the current source component. The inverter charges and discharges in accordance with the real and reactive power commands received from the operator.

If there is a grid disturbance, the rotating component responds by:

- Producing an active power response proportional to the rate of change of frequency
- Producing a reactive current in response to changes in voltage.

Characteristics such as inertia, and stator damping are created synthetically in Tesla's inverter; these parameters are programmable, unlike a synchronous condenser machine, which has a fixed characteristic inherent to the physical machine.

4. Implementation of VMM to the full 150MW HPR facility

4.1. VMM Test Plan Overview

The process for completing a full-scale roll-out of VMM at HPR required the submission of a proposal to alter a connected generating system under the National Electrical Rules (NER) Clause 5.3.9. This submission requires a comprehensive suite of modelling, technical and operational information to be supplied to the TNSP and AEMO in order for them to successfully complete their due diligence works.

At the conclusion of this process, approval was granted under NER Clause 5.3.10 to commence commissioning testing in a staged manner (referred to more commonly as "hold-point testing"). For HPR, this was conducted over two (2) hold-points, followed by a 3-month monitoring period whereby performance was analysed during real grid events.

The test plan aims to demonstrate compliance with the agreed generator performance standards, while also demonstrating that the functionality of the facility (and VMM) is in alignment with expectations. This is achieved with the use of data recorded at the facility during testing, and overlayed with models for the same test event.

Table 1 - Test plan

	HP1	HP2
Date of test	14/06/2022	27/06/2022
% of total capacity with VMM enabled	33%	100%
MW capacity enabled	50MW	150MW
Inverters with VMM Enabled	102	294
Frequency support status (droop response)	Disabled	Disabled (Except during FCAS test)

It is worth noting that HPRX had already completed extensive hold-point testing as part of its expansion to 150MW in 2019. During VMM hold point testing, the plan focused on a suite of standard commissioning tests, combined with tests targeting affected generator performance standards, as they relate to the implementation of VMM.

4.2. Test Results

Testing was conducted on 14/6/2022 and again on 27/6/2022. All testing was witnessed by AEMO and ENET, with supporting reports and raw data also provided.

One of the challenges of evaluating VMM is that it is highly dependent on actual disturbances to trigger a response. This external disturbance was achieved through energising a nearby 275kV Transformer at an agreed time. Figure 3 provides an example of an external voltage disturbance test, and the subsequent response recorded at the facility. For clarity, the dotted lines represent a nominal 10% tolerance between the model and actual data and is used as an assessment guide).

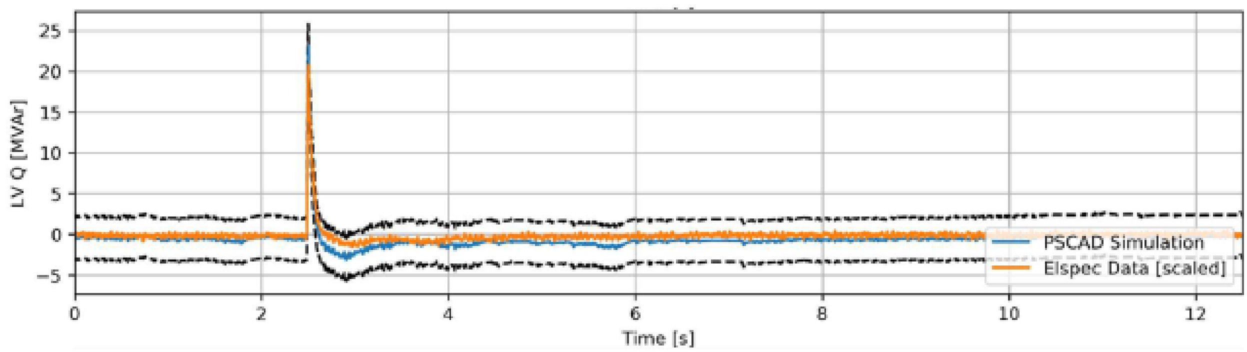

Figure 3 - Example of recorded (Elspec) data and model (PSCAD) overlay

At the conclusion of the first hold-point, the plant was re-configured to a pre-VMM state and returned to operation, whilst the data was analysed. Once approval was granted, the process was completed again for the second hold-point.

Both hold-points were successfully completed, and approval was granted by AEMO to permanently enable VMM across the entire facility on 20/07/2022.

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4.3. Key Insights and Learnings

The energisation of a nearby 275kV transformer was successful in creating a suitable disturbance for the purposes of testing, however an anomaly was observed in the data recorded at the 275kV meter but was not being observed at the HPR inverter meter.

Further analysis and investigation determined that this anomaly was due to “sympathetic inrush”. Sympathetic inrush occurs when an unenergized transformer is switched into service while parallel transformers are already in operation. This particular anomaly is largely related to the configuration of HPR, and the physical relationship with the adjacent transformer used to create the disturbance, however it is still relevant as a learning for future commissioning tests utilizing this type of disturbance.

5. Performance and services

5.1. Operational Status

VMM was enabled on 22/7/2022 and has remained continuously in service since that time.

No adverse impacts have been observed in relation to the performance or degradation of the facility. Annual performance testing conducted in December 2022 demonstrated that the facility continues to perform above expectations in terms of storage degradation.

New registered FCAS capacities were accepted into AEMO’s Electricity Market Management System (EMMS), becoming effective 20/09/2022.

5.2. Results of Key BESS Services Delivered

The second half of 2022 provided numerous opportunities for HPR to demonstrate its suite of enhanced inverter capabilities to the grid.

5.2.1. VMM

After the enablement of VMM on 22/7/2022, a 3-month monitoring period commenced to evaluate VMM performance during real grid events. A selection of the most significant events were evaluated with model overlays.

On 11/08/2022, a network event saw the grid frequency drop to 49.764Hz, significantly below the lower nominal operating frequency band of 49.85Hz.

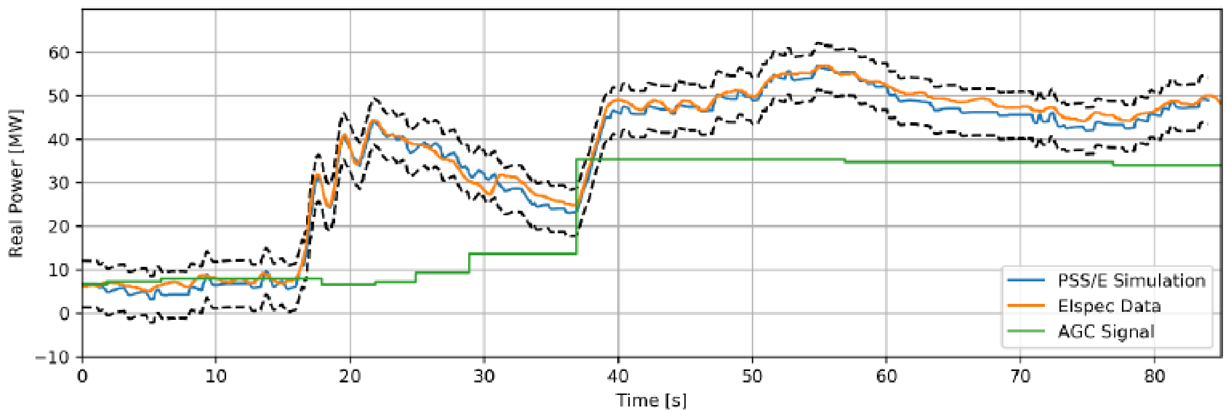

Figure 4 - Actual and modelled response during a grid event

Extensive testing has previously demonstrated that HPR is providing ~2,070MW.s of inertia - equivalent to an H constant of 11.02MW.s/MVA. Data from the event shows that the maximum RoCoF for the event was -0.16Hz/s. Applying these values to the swing equation, an expected VMM response is ~13.2MW calculated.

$$\Delta P_{pu} = \frac{df}{dt} \times \frac{2H}{f_{nom}}$$

$$\Delta P_{pu} = 0.16 \times \frac{2 \times 11.02}{50} = 0.0705pu = 13.2MW$$

Figure 5 separates elements of the model to demonstrate the contribution from the frequency-watt (droop) response and the VMM response during the event. At the time of maximum RoCoF (Grid Frequency plot), it can be seen that the VMM response moves from -1.2MW, to +12MW, giving ~13.2MW response. This combined with the overall good alignment between the model and actual performance gives excellent confidence in the quantity of inertia delivered.

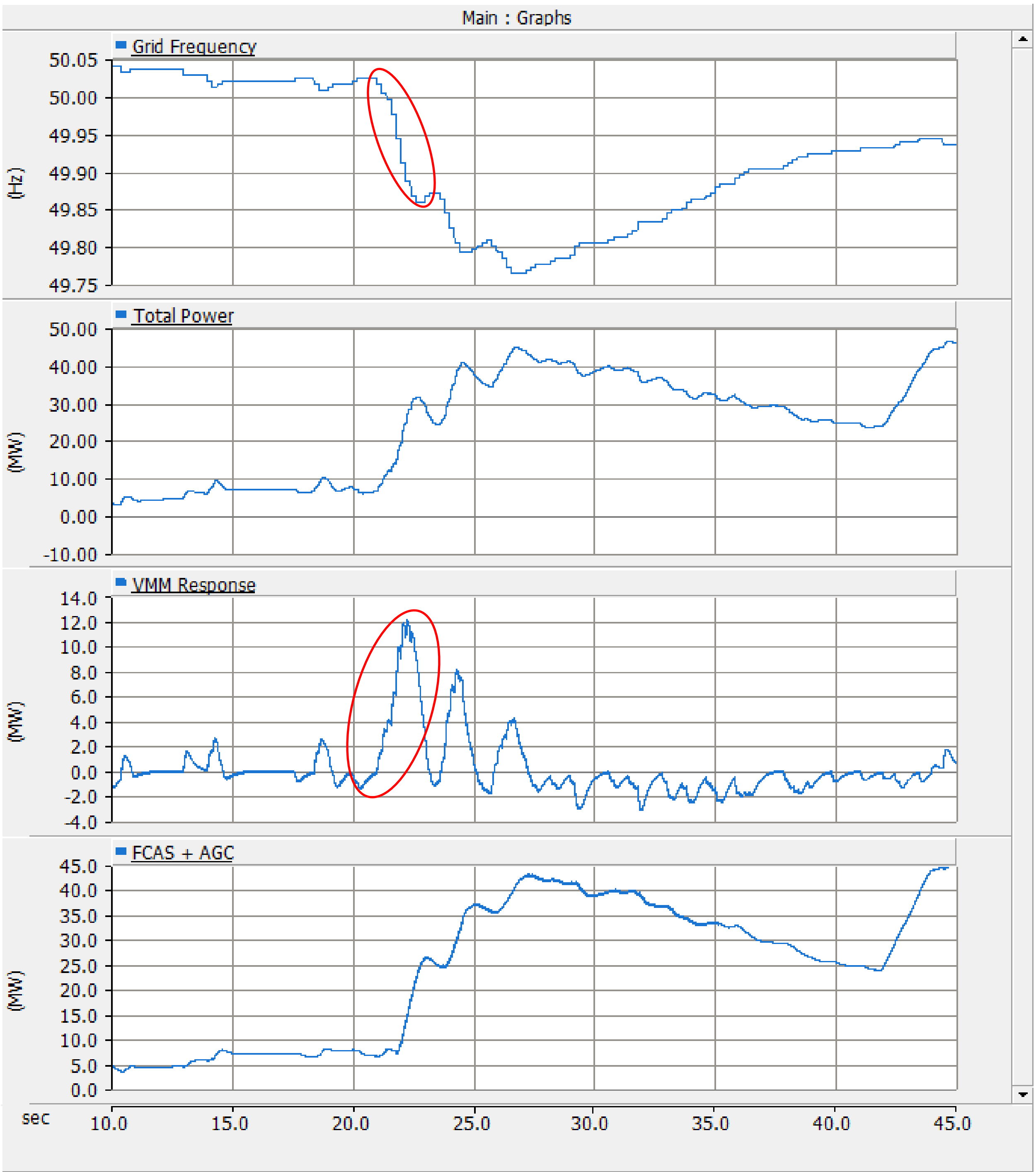

Figure 5 - Model elements separated from the overall response

5.2.2. FCAS and Fast Frequency Response

On the evening of 12/11/2022, a severe storm event impacted South Australia, damaging the VIC-SA interconnector (fallen tower) and tripped Tailem Bend 275kV transmission lines, separating SA from the NEM, effectively creating an "island grid".

At the time of separation, SA was exporting into Victoria, and as such created a local over-supply when the interconnector tripped. As the frequency increased, HPR absorbed ~90MW of this over-supply and significantly helped arrest the frequency. Figure 6 shows an excellent match between expected and actual performance of HPR at this critical time.

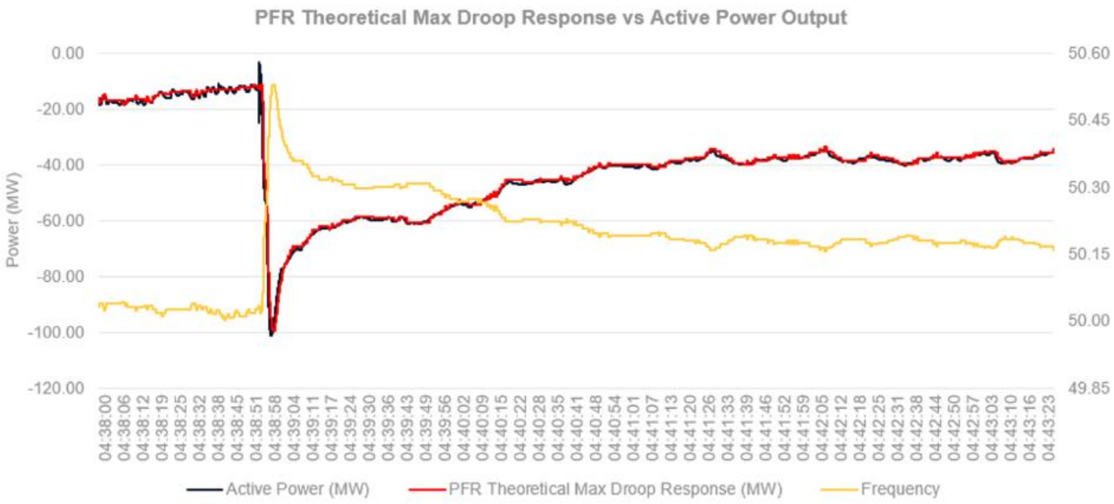

Figure 6 - Expected and actual active power response to frequency

Shortly after the separation, ENET contacted Neoen control room and requested the activation of Fast Frequency Response (FFR) services. This involved limiting HPR Energy and Regulation FCAS bids to +20MW generation, -30MW load, effectively reserving the remaining capacity to respond to frequency deviations in the grid.

FFR services were officially enabled for 4-hours, during which HPR provided critical support to SA to help arrest frequency swings. The frequency and subsequent response from HPR can be seen in Figure 7.

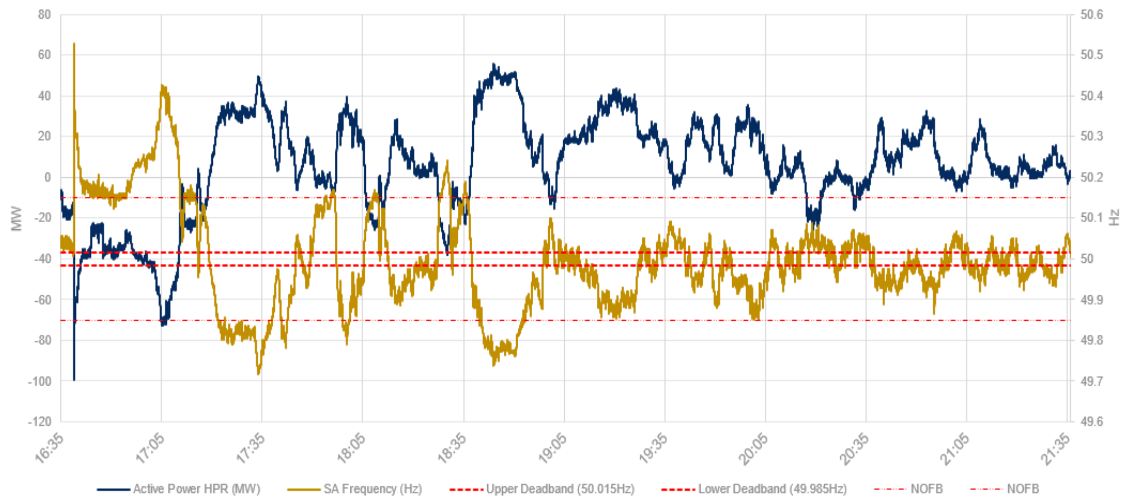

Figure 7 - Frequency and active power during FFR enablement period

SA remained separated from the NEM until the evening of 19/11/2022, and in this time, HPR responded to >600 frequency excursions outside the NOFB. To reserve HPR for these critical frequency services, AEMO invoked constraints, limiting HPR to 2MW energy (generation and load) and 5MW regulation FCAS.

The support provided by HPR during this challenging period, combined with gas generation and the four synchronous condensers that are strategically placed within the SA network, was critical to maintain system reliability with high renewable penetration (instantaneous renewable penetration in SA peaked at an extraordinary 91.5% on 19 November)[5].

6. Market Impacts and Regulatory Changes

6.1. Market Impacts

- Currently there is no market in the NEM for the provision of inertia services, as the responsibility lies with the transmission network service providers to procure these services to meet inertia shortfalls.
- HPR was able to deploy its increased FCAS capacity into the market during the SA Islanding event and provide further competition to the market. However, as SA was separated from the NEM, this created extreme volatility and made analysis of this impact exceedingly difficult.

6.2. Regulatory Changes

AEMO conducted a consultation to amend the MASS under the NER to accommodate two new markets for very fast frequency control ancillary services (Very Fast FCAS), with the final determination published 7 October 2022[6].

AEMO commenced this consultation by publishing an Issues Paper that proposed a Very Fast FCAS specification with the following attributes:

- 1 second (s) response time
- 6s total timeframe
- Raise/Lower reference frequency at ±0.5 Hertz (Hz) for the NEM mainland and ±2 Hz for Tasmania, in line with comparable Contingency FCAS
- An assumed frequency ramp rate of 1 Hz/s

The amended MASS will take effect on 9 October 2023, which is the date for commencement of the Very Fast FCAS markets.

7. Emerging Challenges and Opportunities

- The upcoming change to the MASS (refer section 6) opens new opportunities for markets that are well suited to inverter-based technologies. Equally, the new market has different requirements for compliance, data resolution and assessment that need to be fully understood and validated for HPR.

[5] https://aemo.com.au/newsroom/media-release/lower-energy-prices-and-high-renewable-generation-saw-record-setting-quarter-closing-out-2022
[6] https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/amendment-of-the-mass/final-determination/final-determination.pdf?la=en

8. Conclusions and Lessons Learnt

8.1. Technical

1. HPR has been able to successfully demonstrate an inertial response to real system events in the NEM. The response was very close to that predicted by the model.
2. The response of HPR is an aggregation of both the VMM and traditional frequency droop, and there is no switched transition from one response to the other.

8.2. Regulatory

1. Having successfully navigated the regulatory process for implementing VMM, HPR has effectively paved the wave for other BESS to follow. The 5.3.9 at HPR was a learning exercise for all project stakeholders and a first for a BESS of this capacity.

8.3. Economic

1. No market currently exists for inertia services.
2. Revenue from existing markets impacted by specific events in the NEM.

8.4. Social

3. No social impacts of any significance observed.

9. Glossary of Terms

AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollars
BESS	Battery Energy Storage System
DEM	Department of Energy and Mining
FCAS	Frequency Control and Ancillary Service
FIA	System Strength Full Impact Assessment
GridSim	Tesla Grid Simulator facility located in California, USA
HIL	Hardware In Loop
HPR	Hornsdale Power Reserve
HPRX	Hornsdale Power Reserve Expansion project
Hz	Hertz
Iq	Quiescent Current
kVAr	Kilo Volt-Ampere (reactive)
LSBS	Large Scale Battery Systems
LV	Low Voltage
MVA	Mega Volt-Ampere
MVAr	Mega Volt-Ampere (reactive)
MW	Mega Watt
NEM	National Energy Market
NER	Nation Energy Regulations
OFGS	Over Frequency Generator Shedding
P	Active Power
PQM	Power Quality Meter
PSCAD	Power System Computer Aided Design (modelling software)
PSS/E	Power System Simulation for Engineering
Pu	Per unit
Q	Reactive Power
RMS	Root Mean Square
RoCoF	Rate of Change of Frequency
RUG	Releasable User Guide
S	Seconds
SA	South Australia
SAIT RAS	South Australia Interconnector Trip Remedial Action Scheme
SEL	Schweitzer Engineering Labs
US	United States
USA	United States of America
VMM	Virtual Machine Mode