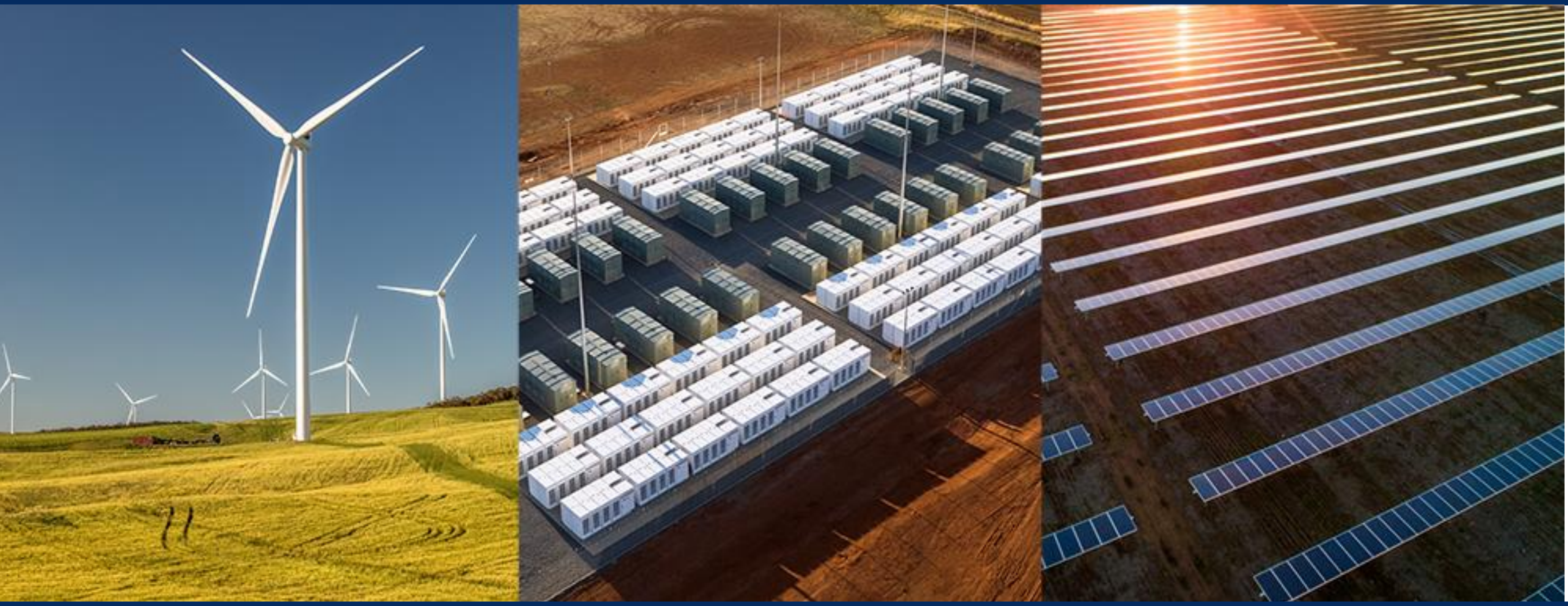
NEOEN

HORNSDALE POWER RESERVE EXPANSION



VIRTUAL MACHINE MODE ACTUAL VS MODELLED STUDY

Revision	0
Released	06/02/2023
Document Owner	Neoen

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This report is intended solely to share information about the innovations and lessons learnt about Tesla's Virtual Machine Mode (VMM) on Large Scale Battery Systems (LSBS). This report may not be copied, reproduced, or distributed in any way without the prior written consent of Neoen or Tesla.

This Project received funding from ARENA as part of ARENA's Advancing Renewables Program.

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Government of South Australia
Department for Energy and Mining

NEOEN

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, this project 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 journey that led to the implementation of Virtual Machine Mode (VMM) at HPR and focuses on the testing, modelling and pilot trials undertaken to demonstrate the functionality of the VMM and the subsequent validation of the model for full-scale implementation.

3. Background

HPR is located approximately 16km north of Jamestown in South Australia. With initial nameplate capacity of 100MW/129MWh comprised of Tesla's Powerpack system technology, at the time of completion it was the world's largest utility scale battery. The fast-ramping capability of the Tesla Powerpacks used at the HPR enables the facility to dispatch large amounts of power quickly and reliably. This supports the South Australian electricity grid and means 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 processes and methodologies to be employed to implement and demonstrate the innovations to be realised 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

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

which commenced with small-scale bench testing of the Tesla Powerpack 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 are particularly valuable because they provide flexibility. They can respond faster than other energy storage or generation technologies and help maintain grid stability by ramping up or down in fractions of a second.

This can have 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 response that HPR is required to provide.

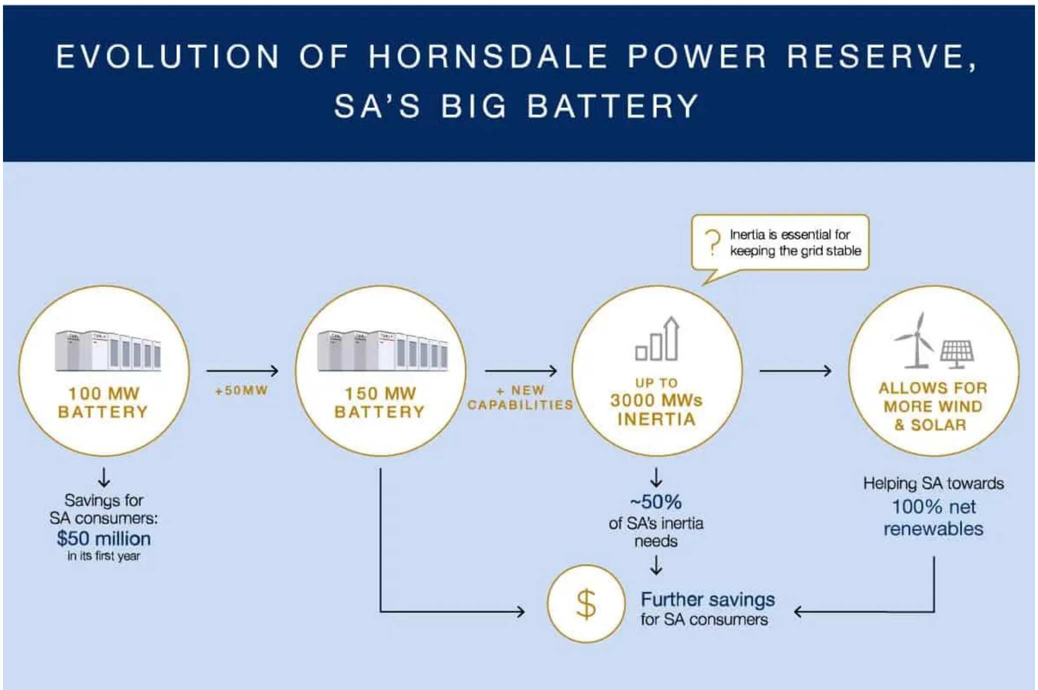

Figure 1 - Evolution of Hornsdale Power Reserve

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 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)

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

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

earlier. As such, it is important to consider the entire nature of an inertial response and not the quantity alone when comparing different technologies.

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's Powerpack system 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*.

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

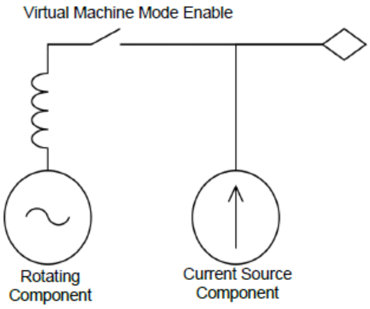

Figure 2: Virtual Machine Mode representation

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.

The machine characteristics such as inertia, and stator damper 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.

3.4. Inertial Constant

The inertial constant "H" represents the ratio of the synchronous machine's rotor kinetic energy to the machine's apparent power rating. Larger generators with more physical mass (and/or rotational velocity) typically have larger inertia constants. In typical synchronous generators this ranges between 3 and 12. For example, if there was a 500MVA (and MW assuming unity power-factor for simplicity) generator with a H equal to 5, it could provide 2500MW.s of inertia. The same generator with a H equal to 10 could provide 5000MW.s.

Tesla inverters implement an inertial response synthetically via microprocessor-based control. This allows selection of inertial parameters to suit the grid conditions in which it is installed.

Synchronous machines have typical overload ratings of 5-10pu, whereas for Tesla's inverter this value is limited to 1.2pu. Thus, the transient response to a grid disturbance for an inverter operating with VMM, compared with a synchronous machine with the same inertial constant, will differ. Transient current will saturate (reach maximum output) at a lower value during the inverter response, and this is a physical limitation of the types of internal components used within inverter-based generators. Excluding saturation, the response will be very similar.

The implemented settings at HPR will provide ~2,070 MW.s of inertia, with an overall equivalent H constant is 11.02MW.s/MVA.

A key indicator of frequency stability is the Rate of Change of Frequency (RoCoF), which is the time derivative of the power system frequency. For a given elevated RoCoF event, the *Swing Equation* can be used to describe the rotor dynamics of synchronous machines, and thus the inertial response expected for machines with prescribed rotor and damping inertia values.

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = \Delta P_{pu}$$

$$\frac{d\delta}{dt} = \omega = 2\pi \times f \Rightarrow \frac{d^2\delta}{dt^2} = 2\pi\frac{df}{dt}$$

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

Where:

H = inertial constant (MW.s)

P_pu = overload rating (pu)

ω = rotor angular velocity

4. Scope of Testing

4.1. Test Plan Overview

In consultation with ARENA, the South Australian Government (DEM), Neoen and Tesla, a test plan was developed for the implementation of VMM at HPR, with a view to providing utility-scale virtual inertia services to the SA grid. The test plan for the rollout of VMM involved a staged approach which evolved over time as challenges were faced and solutions derived.

As part of the planned full-scale VMM roll-out, it was critical for physical inverter behaviour to be validated against modelled behaviour. This forms part of the process for alteration of an existing generating system under National Electricity Rule 5.3.9[5]. This was achieved firstly via lab bench testing, and secondly through a dual inverter trial at HPR.

On 13/02/2021, after several months of testing, providing supporting documentation and consultation with ElectraNet and AEMO, approval was granted to implement VMM on two (2) inverters. The implementation of VMM took place on 15/02/2021. Careful monitoring programs of the inverters, and entire facility, were in place to ensure compliance was maintained, and the trial did not pose any significant risk to grid security.

During this dual-inverter trial, several significant events that occurred in the NEM (such as the failure of Callide C-4 Power Station on 25/05/2021) were captured and analysed, with differing inertia settings, to help validate the accuracy of the modelled behaviour.

This validation of the model during both steady state and dynamic changes in the power system allowed the modelling for the connection modification (under NER 5.3.9) to proceed in earnest. Moreover, these events provided a demonstration of the inertial response to significant frequency disturbances.

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[5] S5.3.9 – Applicants must submit a Connection Application/Alteration Form to AEMO to begin the process of proposing to alter an existing generating system. The Altering of a Generating System procedure is a formal process under Clause 5.3 and is commonly referred to as the 5.3.9 Process.

Table 1 - Test schedule

#	Test	Description
1	Desktop Scoping	An initial technical deep dive with AEMO on firmware implementation of virtual machine mode, impacts on current operation, understanding of the optimum range of inertia for integration into the SA system, and key data channels was investigated.
2	Test Bed GridSim concept demonstration	A 90kVA Chroma Amplifier GridSim, located at a Tesla USA facility, is utilized. The GridSim is a full 4-quadrant AC power source that emulates characteristics of a stiff grid. The GridSim is set to nominal 480V, 50Hz. Voltage and frequency deviations are induced, and inverter response waveform captured via a PicoScope Oscilloscope. The Power System Computer Aided Design (PSCAD) model is set up with a stiff grid source, to mimic GridSim operation.
3	Test Bed GridSim data analysis	A detailed presentation of high-resolution waveform data was prepared and provided to AEMO from the test bed, including a comparison with predicted responses.
4	HPR limited dual inverter rollout	Following agreement with AEMO on the inertial response, dual HPR inverters were upgraded. This test required liaising with AEMO and ElectraNet to request an exemption.
5	HPR full-scale pilot demonstration	Following completion of the expansion and AEMO agreement, a full implementation of the firmware was rolled out at full 150MW Generator scale. The outcomes of the rollout were confirmed through hold-point testing and validated using real system events in the 3 months following.

5. Modelled vs Actual

During both the dual-inverter trial and again following full-scale implementation, data obtained from real system events was able to be evaluated against the models to validate their accuracy. Significant grid events occurring in the 3-months following full-scale roll-out were evaluated to determine that HPR’s performance was consistent with the modelled results.

5.1. Analysis of Sensitivity of H Constants

In discussions with AEMO and ElectraNet, for the 5.3.9 connection alteration submission to proceed, any change in inertia constant selected would require a considerable re-work of modelling to be submitted. As such, to move ahead, preliminary modelling studies were completed with varying inertia constants and the results shared with project stakeholders.

In one of the study cases, the modelling analysed the impact the selection of inertia constant would have on the V-SA Heywood Interconnector. A credible contingency along the SA-VIC interconnector, a 2-phase fault on the Southeast - Tailem Bend 275 kV circuit, was used to study the performance. Scenarios were run with three different settings (refer to Table 2) that would deliver different effective H constants (all with HPR commencing at zero output). The impact on the inter-connector power-flow was also monitored for all contingency scenarios studied under

S5.2.5.5[6] and S5.2.5.12[7] to assess the performance under all conditions, and inform decisions taken to select final settings.

Studies have shown that for VMM, the damping inertia and other associated parameters are equally as important as the H constant value itself. This can be seen in Table 2 where there is significant variance between the H constant and the effective H constant. As such, for the purposes of discussing inertia in this context, the terms equivalent (or effective) are used.

Table 2 - Varying effective H constants evaluated

Setting	H Constant	Effective H Constant	Total Inertia
VMM 1	1	11.02 MW.s/MVA	2,070 MW.s
VMM 2	5	27.50 MW.s/MVA	5,165 MW.s
VMM 3	10	41.80 MW.s/MVA	7,850 MW.s

The results of the modelling showed that greater effective H constants resulted in increased active power responses at HPR (see Figure 3), and improved damping at Heywood interconnector (see Figure 4).

Active power recovery time was one of the key factors considered when selecting the final inertia settings, with longer active power recovery time being the trade-off for better damping. The optimal inertia settings were selected to achieve better interconnector damping without significant degradation to post fault active power recovery time. Based on the study results, settings to achieve an effective H = 11.02 MW.s/MVA was selected to achieve optimal performance.

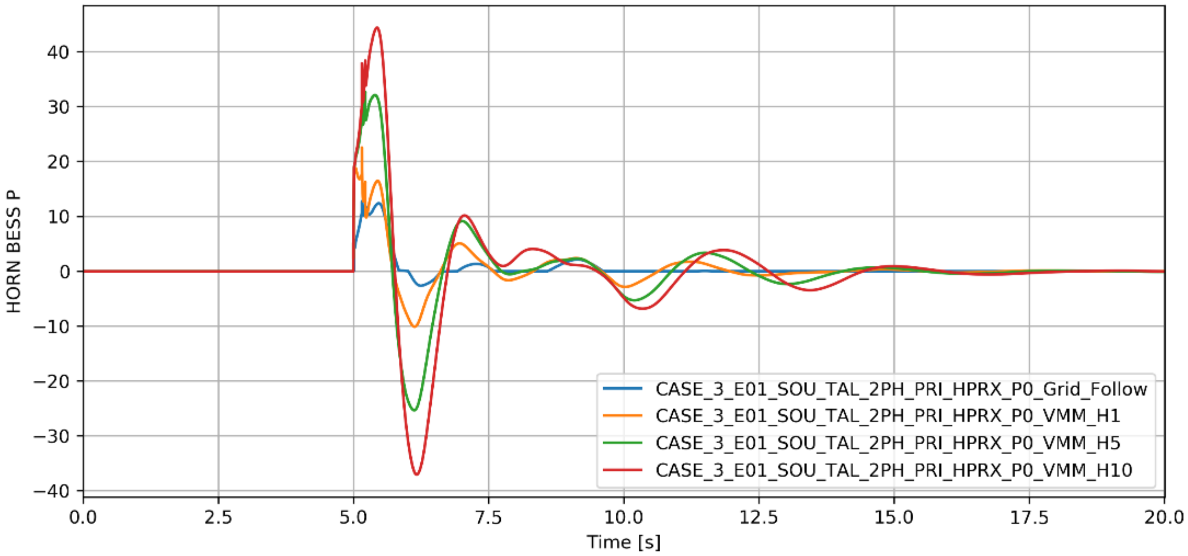

Figure 3 - HPR active power during simulated fault with different inertia settings

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[6] S5.2.5.5 is the standard for the Generating System Response to Disturbances following Contingency Events, with disturbances including credible contingency events; three-phase fault in a transmission system, two-phase-to-ground, phase-to-phase or phase-to-ground fault in the transmission system; and three-phase, two-phase-to-ground, phase-to-phase or phase-to-ground fault in a distribution network.

[7] S5.2.5.12 is the standard for impact on network's inter-regional or intra-regional power transfer capability.

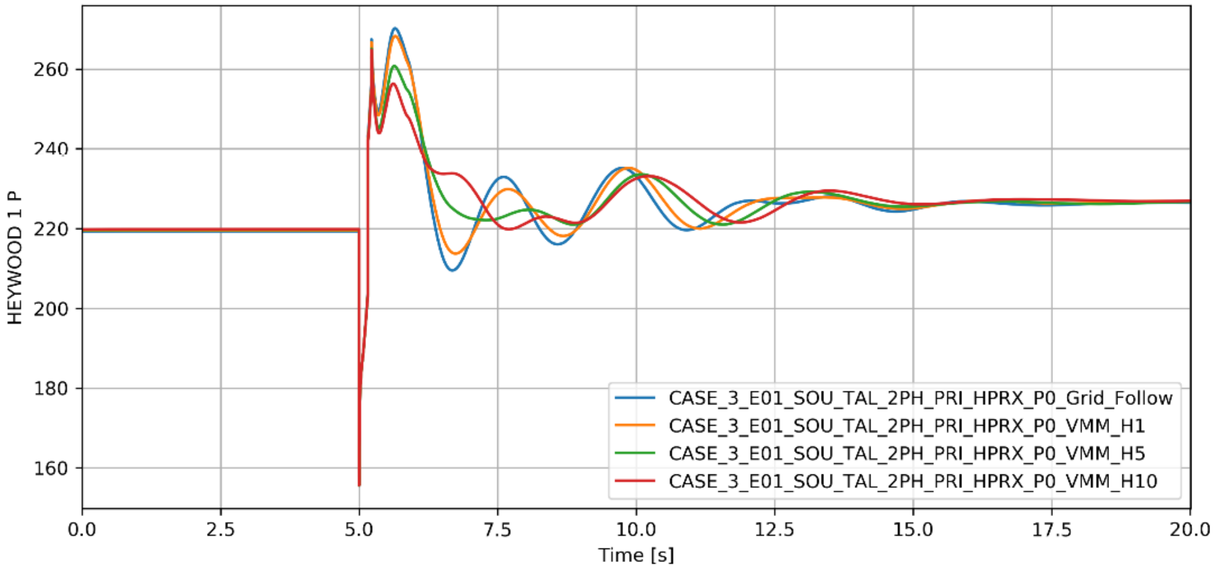

Figure 4 - Heywood Interconnector flow with different inertia settings

5.2. Frequency Control Behaviour During Contingency Event

A key interest with synthetic inertia was how the control system would transition from an inertia-based response to a traditional frequency droop-based response (FCAS).

Following acceptance of the 5.3.9 submission, VMM was permanently enabled on the full 150MW facility on 22/07/2022, along with a suite of hold-point tests that confirmed the intended behaviour.

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.

Model overlays for this event again demonstrate good alignment between model and actual performance.

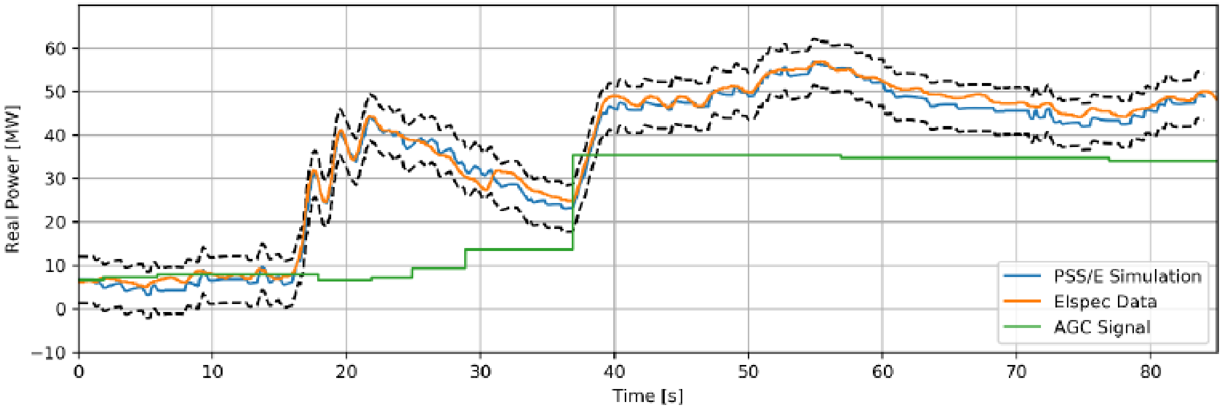

Figure 5 - Actual and modelled response during a grid event (dashed lines showing 10% tolerance from model)

Tesla were able to further break down the elements of the model and demonstrate that the actual response overserved at HPR is an aggregated response of VMM and FCAS.

VMM is responding proportional to RoCoF, while FCAS is responding proportionally to the frequency deviation from a nominal 50Hz. It is worth noting that the system is also following a moving AGC target from AEMO, and this signal is being used as a reference point from which to provide a response.

Focusing on the first drop in frequency in Figure 6, it can be observed that VMM response is largest (moving from -1.2 to +12 for a Δ13.2MW) at the time of greatest RoCoF (-0.16Hz/s).

Shortly thereafter, at the nadir of the first frequency drop, RoCoF decreases, but the FCAS response provides the dominant contribution to the overall response.

To further substantiate the modelled effective H constant of H = 11.02 MW.s/MVA, taking the swing equation:

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

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

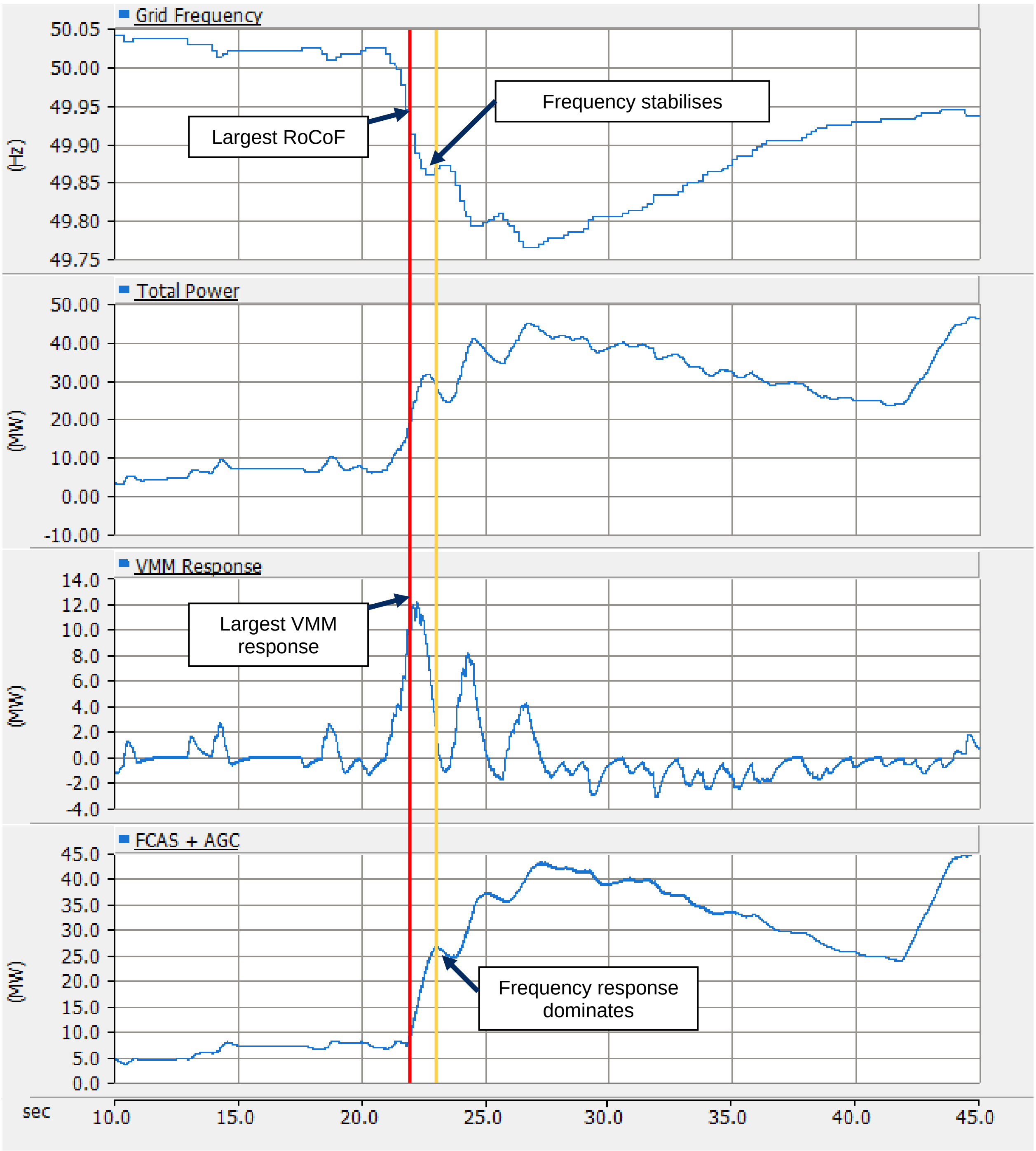

Figure 6 - Aggregated and individual VMM + FCAS responses

6. Conclusions and Lessons Learnt

6.1. 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 the summation aggregation of both the VMM and traditional frequency droop, and there is no switched transition from one response to the other.

6.2. Regulatory

1. Having successfully navigated the regulatory process for implementing VMM, HPR has effectively paved the way 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.
2. The success of this project has allowed Neoen to put forward several other grid-forming projects utilising the same (or similar) technology as HPR.

6.3. Economic

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

6.4. Social

3. No social impacts of any significance observed.

7. 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
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
SEL	Schweitzer Engineering Labs
US	United States
USA	United States of America
VMM	Virtual Machine Mode