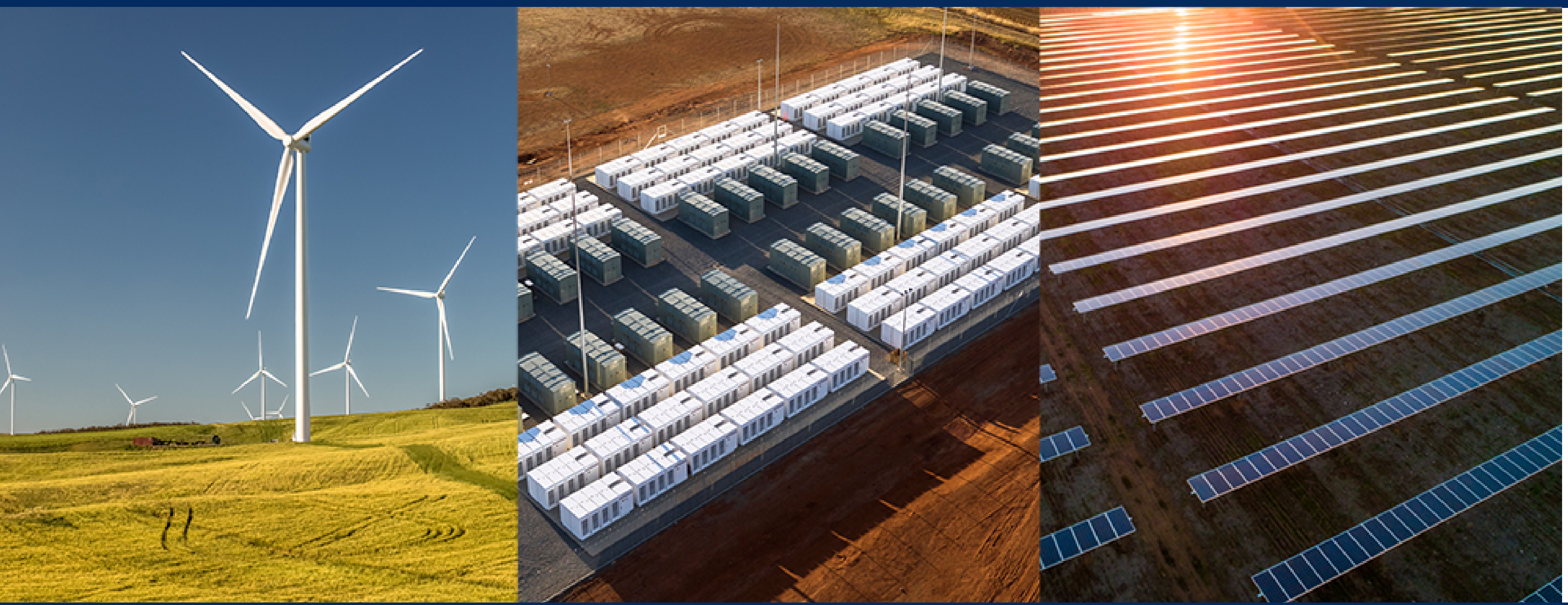
HORNSDALE POWER RESERVE EXPANSION



VIRTUAL MACHINE MODE TEST SUMMARY REPORT

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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 so far towards 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 validate the model for the full-scale connection alteration studies.

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

[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.

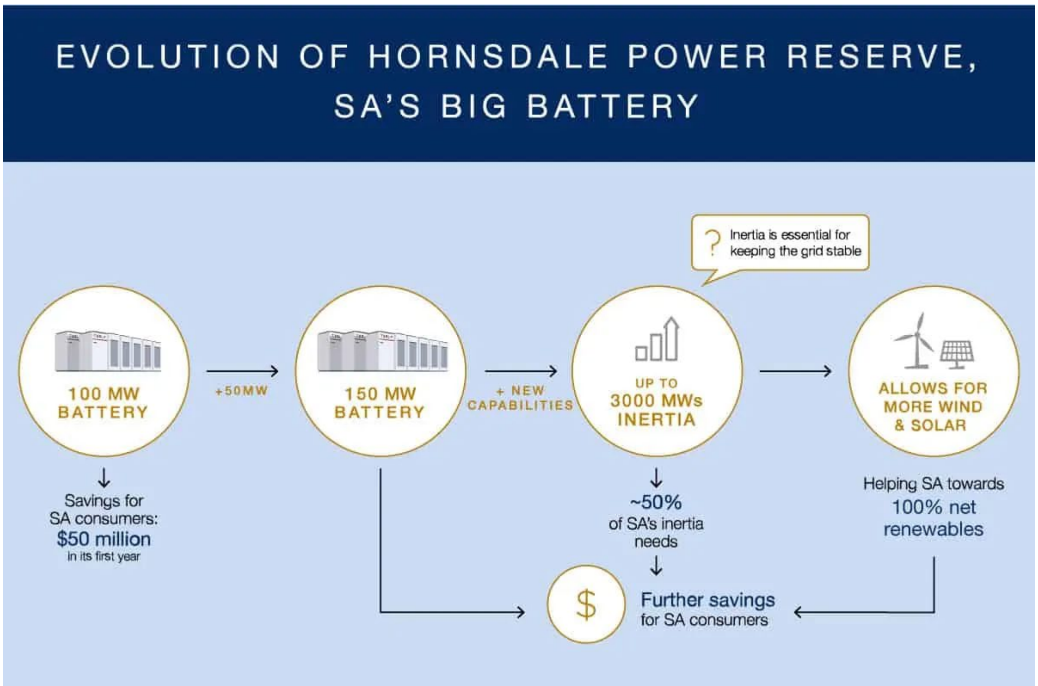

Figure 1 - Evolution of Hornsdale Power Reserve

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)

[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.

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

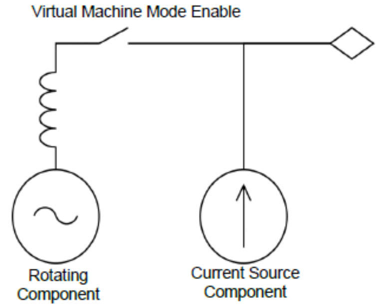

Figure 2: Virtual Machine Mode representation

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. In typical synchronous generators this ranges between 3 and 12.

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 at a lower value during the inverter response. Excluding saturation, the response will be very similar.

Studies have shown that for VMM, the damping inertia and associated parameters are as equally important the H constant itself, and thus the focus should not be on the H constant alone when assessing the inertia being delivered.

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.

Following challenges associated with the implementation of the tests at a Melbourne facility, the testing plans evolved to incorporate the use of a Grid Simulator (GridSim), located in California USA. Grid simulators enable the simulation of specific grid conditions such as programmed voltage and frequency disturbances. Commonly used in Tesla product testing in the USA, Grid Simulators are able to output and input power in accordance with specific testing needs.

It was also agreed to expand the planned single inverter trial to a dual inverter trial, with the aim of gathering additional data by running separate inertial constants simultaneously.

Table 1 - Test plan

#	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 will be investigated.
2	Test Bed GridSim concept demonstration	A 90kVA Chroma Amplifier GridSim is 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 will be 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 will be 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 will be rolled out at full Generator scale.

5. Testing Results

The testing program was undertaken in several rounds, with ongoing improvements incorporated into the GridSim and model alignment. Moreover, as the inverter trial progressed, data obtained from real system events was also able to be evaluated against the models to give further confidence in their accuracy.

5.1. Grid Simulator Testing – Round 1

Testing was undertaken in late 2020, just prior to the VMM inverter trial commencing, to compare inverter responses under different configurations of operation. These tests aimed to demonstrate how the different modes of operation interact and how they are all accurately reflected in PSCAD models.

5.1.1. Setup and Configuration

Tests were undertaken to compare inverter responses under different configurations of operation:

1. Iq Injection and frequency-watt response only
2. Iq Injection, frequency-watt and VMM mode

Configuration (1) represents an inverter operating with smart inverter features enabled. Each inverter responds with a reactive power injection proportional to voltage deviation and a real power response proportional to frequency deviations. At HPR, the frequency-watt feature is enabled.

The VMM implementation project proposes to update all inverters at HPR so that both frequency-watt and VMM are enabled. Configuration (2) tests the combination of smart inverter features with VMM. These bench tests aim to show how the different modes of operation interact and how they are all accurately reflected in PSCAD models.

Under lab test conditions, Tesla inverter hardware was subjected to grid disturbances and the response recorded. This response is compared with modelled output of PSCAD simulation under the same disturbance to verify model accuracy.

The GridSim is set to nominal 480V, 50Hz. Voltage and frequency deviations are induced, and inverter response waveform captured via a PicoScope Oscilloscope. The PSCAD model is set up with a stiff grid source, to mimic GridSim operation.

Disturbances applied under each operating configuration are described in Table 2.

Table 2 - Test disturbances applied

Disturbance	Description
Voltage disturbance	The voltage waveform generated by the GridSim and the PSCAD source is initially at nominal voltage, then is stepped down to 0.7pu for 0.5s, then back to 1pu. The initial inverter current is a 35A discharge, designed to illustrate how disturbance responses are superimposed onto direct commands.
Frequency Disturbance	The voltage waveform generated by the GridSim and the PSCAD source is at nominal voltage and initially nominal frequency. The frequency is ramped down at 4Hz/s to 48Hz where it remains for 2s and is then ramped back to 50Hz at the same rate. The second test similarly starts at nominal voltage and frequency, then is ramped up at 4Hz/s to 52Hz where it remains for 2s, and is then ramped back to 50Hz at the same rate. Initially, the inverter is responding to a 30kW charge command designed to illustrate how disturbance responses are superimposed onto direct commands.

5.1.2. Results

Test results from Configuration (1) show near identical match between the PSCAD trace, and at PicoScope GridSim trace for both voltage and frequency disturbances.

As shown in Figure 3, following the voltage disturbance, the current ramps over ~2 cycles in accordance with the RMS based reactive current injection control algorithm. Note that in these figures, GridSim test is represented by ‘Channel_x’ signals, and PSCAD by ‘Vx’ signals.

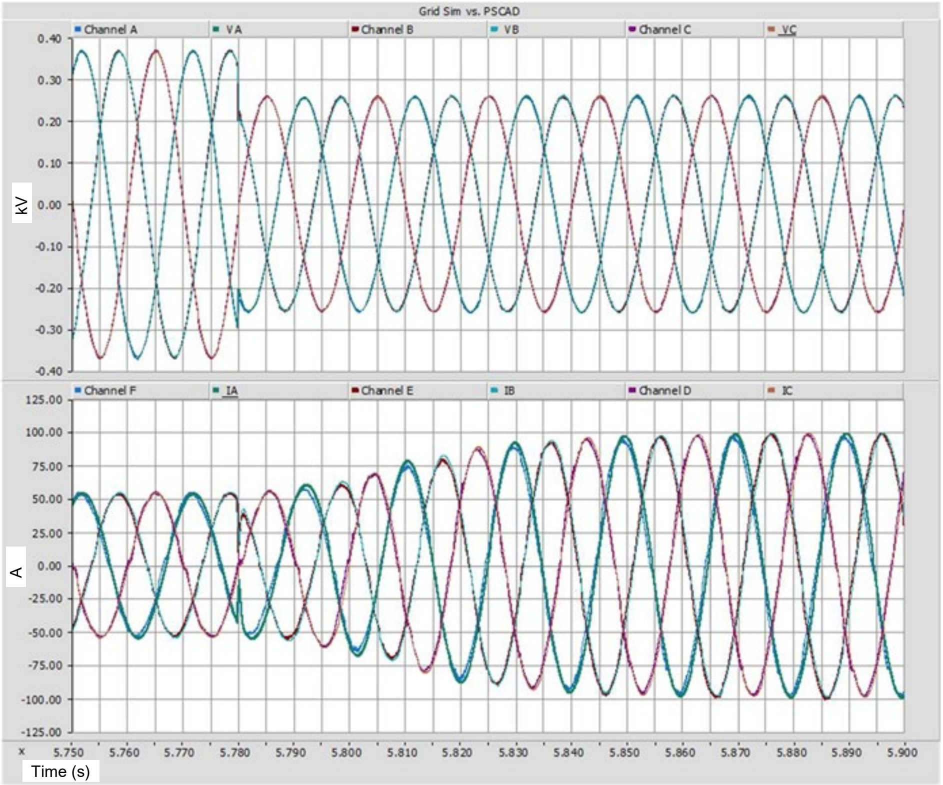

Figure 3 - Iq Injection + Freq-Watt Only, Voltage Step Down (1.0pu to 0.7pu)

Figure 4 shows the response following a frequency disturbance. The response to change in frequency begins multiple cycles after the frequency ramp begins in accordance with the rms based frequency-watt response.

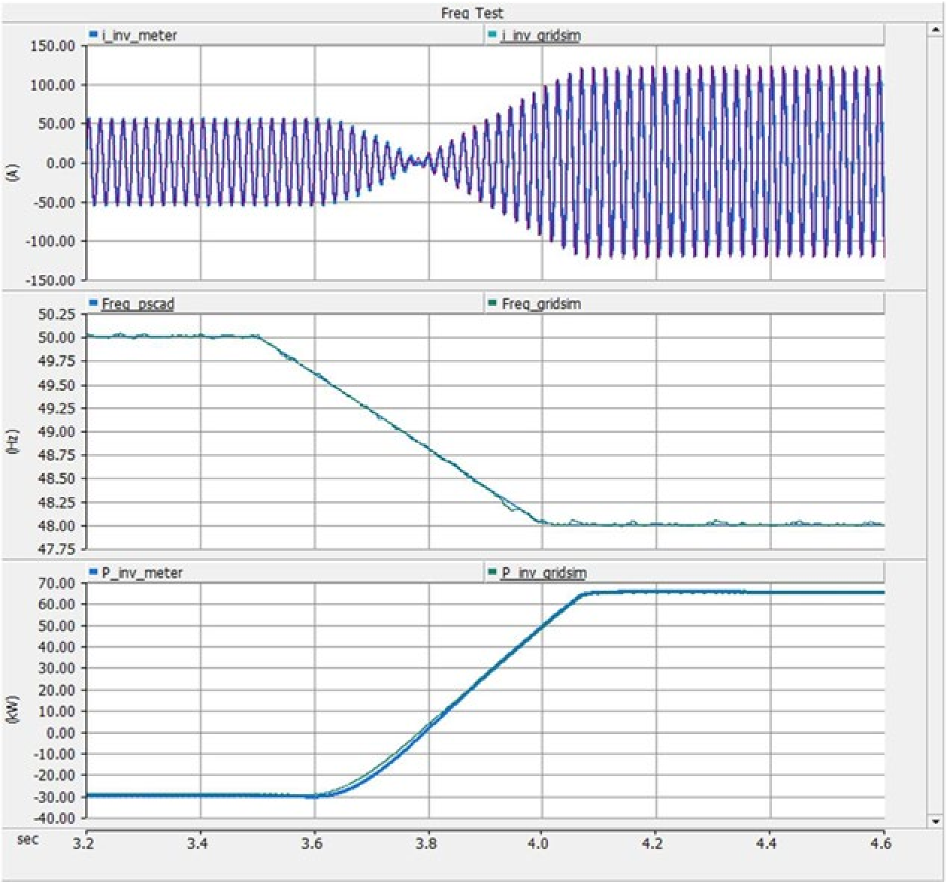

Figure 4 - Iq Injection + Freq-Watt Only, Frequency Ramp Down (50Hz to 48Hz)

For the voltage disturbance, Figure 5 shows near identical PSCAD and PicoScope GridSim traces. Slight discrepancies in peak current on each phase of system test trace are due to minor non-linearities in Rogowski coils.

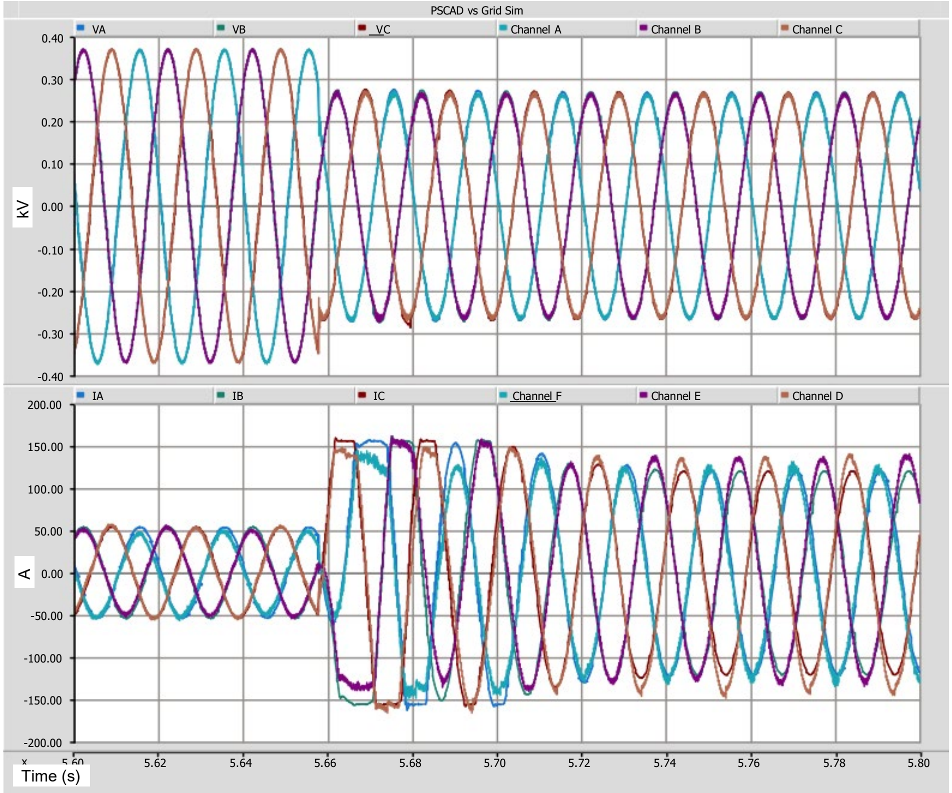

Figure 5 - Iq Injection + Freq-Watt + VMM, Voltage Step Down (1.0pu to 0.7pu)

Tests for the frequency 50Hz to 52Hz ramp up test (Figure 6), and 50Hz to 48Hz ramp down test (Figure 7) yielded similar aligned results between the PSCAD and PicoScope GridSim traces.

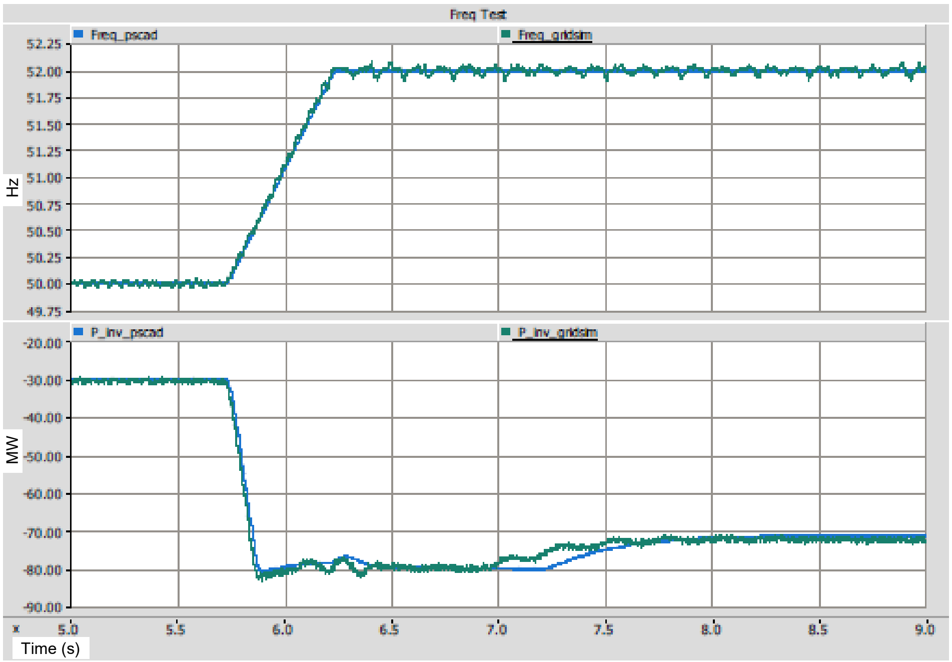

Figure 6 - Iq Injection + Freq-Watt + VMM, Frequency Ramp Up (50Hz to 52Hz)

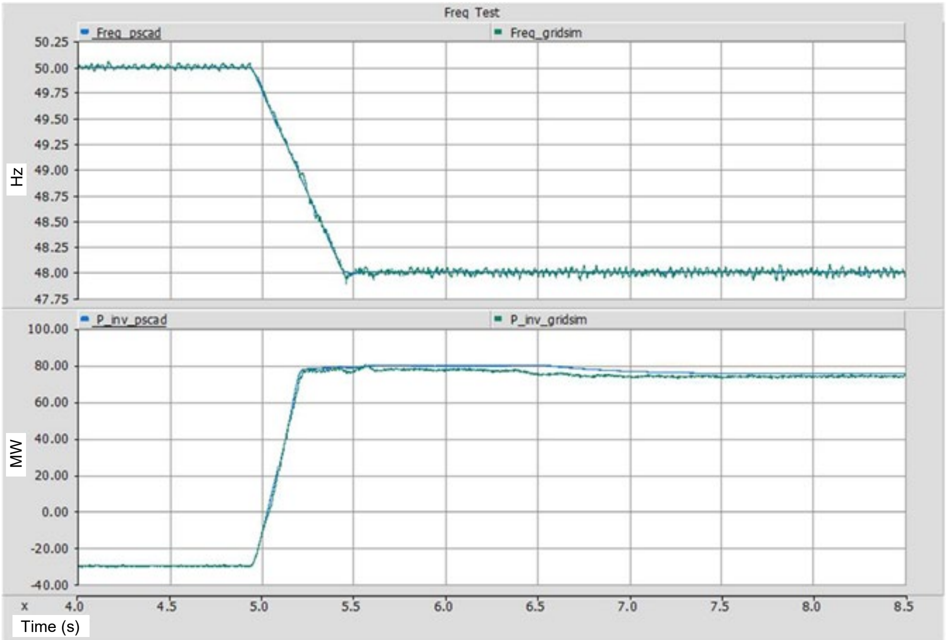

Figure 7 - Iq Injection + Freq-Watt + VMM, Frequency Ramp Down (50Hz to 48Hz)

5.2. Grid Simulator Testing – Round 2

Further benchmarking tests undertaken to validate the behaviour of VMM against the PSCAD model. The benchmarking effort presented herein focuses on VMM only, with the chosen test conditions to reflect the range of operating scenarios that drive specific machine responses from the inverter. Tesla Firmware Engineers considered the test plan appropriate to validate the firmware against simulation model.

Consistent with the PSCAD RUG, the machine model operates in isolation to the control logic loops of smart inverter and site level control functions. Thus, these functions were justifiably turned off during test to benchmark only VMM response. Behaviour under other configurations (Iq injection + frequency-watt) were covered in Round 1 testing.

Alignment of hardware and PSCAD model response in these representative conditions shows that the model accurately represents real world behaviour.

5.2.1. Setup and Configuration

Tesla power-stages each contain a Control Board which drives power-stage behaviour, including VMM response. During the hardware test the Control Board is subject to hardware-in-loop (HIL) testing, a methodology for testing complex embedded systems, to demonstrate Tesla inverter hardware response to emulated grid conditions. HIL testing allows grid behaviour to be digitized and controlled within the Typhoon Real-time GridSim and interfaced with the Control Board under test.

The PSCAD model is subject to the same grid conditions for comparison of hardware and PSCAD model inverter response. Both hardware and model represent a single power-stage rated at 71.5kVA, 480V and 50Hz.

Both the PSCAD model and the Control Board utilise the same settings. Voltage and current waveforms are captured by the scope during HIL testing and played back in PSCAD with small time offset to phase-match PSCAD voltage. For best comparison, waveforms captured from HIL tests are examined to determine point-on-wave (POW) instant where disturbance or step change was applied. The same POW timing was applied in PSCAD model. PSCAD master library multi-meter is used to calculate P and Q for both Grid sim HIL and PSCAD results.

To benchmark virtual machine response only, smart inverter functions (Iq injection + frequency-watt) were disabled. The inertia constant used for Round 2 testing was as per Table 3.

Table 3 – Virtual Machine Mode Settings for Round 2 Testing

VMM Parameter	Description	Value	Unit
Inertia Constant	Stored kinetic energy at synchronous speed in megajoules over generator MVA rating	1	MW.s/MVA

5.2.2. Results

Test results showed excellent correlation between the GridSim (HIL) and PSCAD modelling, over a wide range of tests. The full suite of tests can be seen in Table 4, with a sample of representative tests included within this report.

Table 4 - HIL vs Model Benchmark Tests

Description	Values	Test #
Active power set point change	1pu to 0	1
	1pu to -1pu	2
Reactive power set point change	0 to 0.5pu	3
	0 to -0.5pu	4
Response to frequency disturbance	50Hz to 49.5Hz (step change)	5
	50Hz to 50.5Hz (step change)	6
	50Hz to 49Hz @ 4Hz/s	7
	50Hz to 51Hz @ 4Hz/s	8
	50Hz to 49Hz @ 0.125Hz/s	9
	50Hz to 51Hz @ 0.125Hz/s	10
Response to bus angle shift	+ 30 deg	11
	- 30 deg	12
Response to voltage disturbance	1pu to 0.9pu with Q BW = 5Hz	13
	1pu to 0.9pu with Q BW = 0.5Hz	14
	1pu to 0.7pu	15
	1pu to 0.2pu	16
	1pu to 1.1pu	17
	1pu to 1.2pu	18
Response to frequency and voltage step	V to 0.7pu and F to 49Hz @ 4Hz/s	19
3ph to ground fault	Fault Z = 0.1 ohm	20
	Fault Z = 0.4 ohm	21
	Fault Z = 1.5 ohm	22
Phase to Phase fault	Fault Z = 0.1 ohm	23
	Fault Z = 0.4 ohm	24
	Fault Z = 1.5 ohm	25
Single line to ground fault	Fault Z = 0.1 ohm	26
	Fault Z = 0.4 ohm	27
	Fault Z = 1.5 ohm	28

Figure 9 demonstrates more complex testing whereby a simultaneous frequency and voltage disturbance were introduced, and yielded equally impressive results, with excellent alignment between model and GridSim.

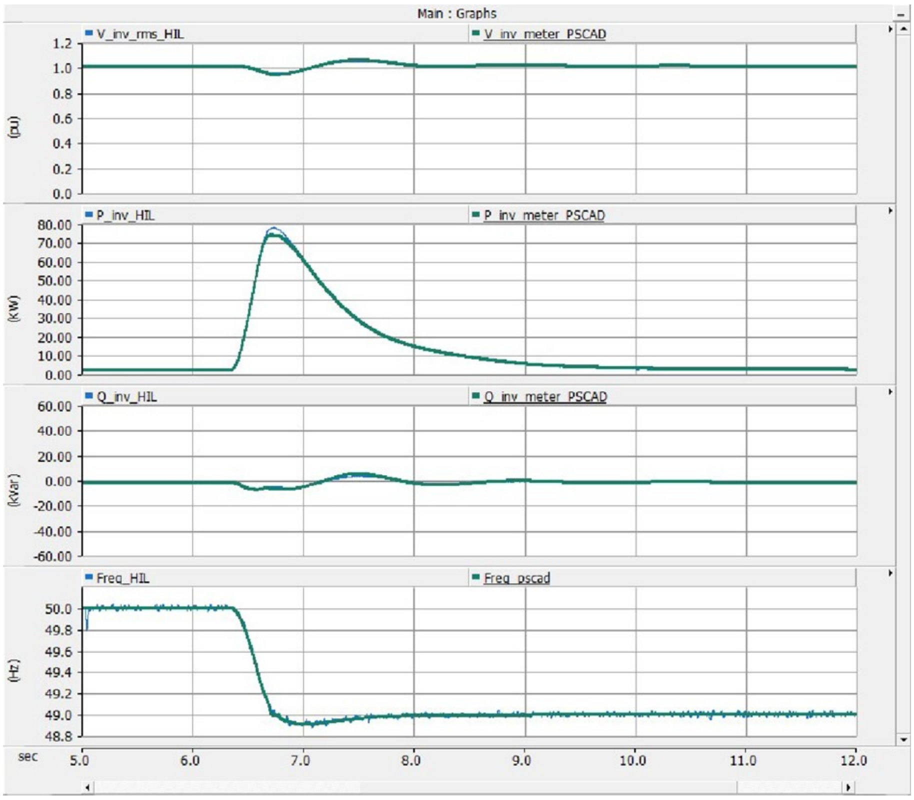

Figure 8 - Test # 7: Frequency ramp from 50Hz to 49Hz @ 4Hz/s

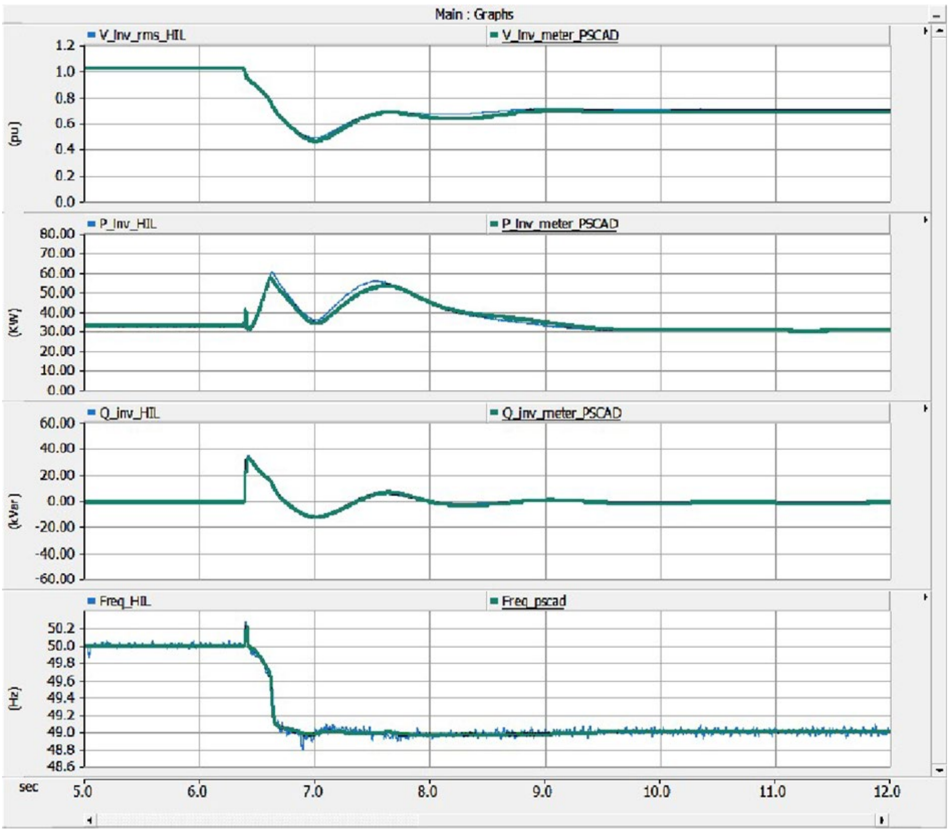

Figure 9 - V+F disturbance: 1pu to 0.7pu and 50Hz to 49Hz @ 4Hz/s

5.3. Dual inverter trial

As part of the planned full-scale VMM roll-out (refer section 6 for details of the larger process), it was critical for physical inverter behaviour to be validated against modelled behaviour. This was achieved firstly via lab bench testing, as described in *Grid Simulator 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.

Despite challenges in the capturing of event data, several critical events that occurred in the NEM were captured and analysed, with differing inertia settings, to further validate the accuracy of the modelled behaviour.

Ultimately, this real-world validation of the model gave great confidence and allowed the modelling for the connection modification (under NER 5.3.9) to proceed in earnest. Moreover, it demonstrated a real inertial response to a significant frequency disturbance.

5.3.1. Setup and Configuration

During the dual inverter trial, VMM was enabled on two inverters. Meters at the trial inverters' low voltage (LV) terminals captured the response to a grid disturbance when VMM was active. Meters at the 275kV Point-of-Connection (PoC) captured the disturbance response from the whole BESS.

It should be noted that, since <1% of HPR inverters were VMM enabled, the overall site response can be considered to represent the grid following response. Thus, the trial enables clear comparison of VMM and Grid Following response to the same disturbances.

Metering consisted of Schweitzer Engineering Labs SEL-735 Power Quality and Revenue Meter being installed on each trial inverter, configured for event triggering. Additionally, inverter #2 also had a permanently installed Elspec Power Quality Meter (PQM) gathering data continuously.

The inertial constant of one inverter will be set to H=5, which is on the lower end of the proposed range. The other inverter will be set with the effective inertial constant of H=50, the upper limit of the proposed range. Additionally, the firmware of the trial inverters was updated to match that installed in the GridSim facility.

Table 5 - Initial inverter settings

VMM Parameter	Inverter #1 (S1T3P1)	Inverter #2 (S2T4P1) [Elspec]
Inertia Constant (H)	5	50
On_grid_machine_enable	1	1

The settings in Table 5 were trialled from 15/2/2021, through until 27/5/2021 at which point they were revised. The basis of the revision was primarily to swap the inertia constant of H=5 to the inverter with the permanent Elspec PQM installed and gather additional data.

Table 6 - Final Inverter Settings

VMM Parameter	Inverter #1 (S1T3P1)	Inverter #2 (S2T4P1) [Elspec]
Inertia Constant (H)	50	5
On_grid_machine_enable	1	1

5.3.2. Results

The dual inverter trial has faced numerous challenges, specifically around capturing events using the high-resolution SEL-735 meters installed. The initial plan was for SEL meters to trigger on high rate of change of frequency or current. The observed reality is that this method of triggering was not reliable, and either the settings were too sensitive, and the meter cache filled up with nuisance data, or the settings were not sensitive enough to capture events.

A more robust event triggering system was in development which utilises an internal Powerpack signal to recognise that VMM event has occurred and trigger event capture. Significant testing of this method was completed at the GridSim facility in the US, but ultimately the SEL meters were not successful in capturing events. Nonetheless, with an Elspec PQM installed on one of the inverters, data was still being captured.

The first significant event was captured on 21/05/2021 and can be seen in Figure 10. The disturbance response at Point of Connection (PoC) was captured in Figure 10 (left) and represents the system in grid following mode. It can be observed the active power response is proportional to the magnitude of frequency deviation from nominal, in line with frequency-watt droop parameters.

Figure 10 (right) shows that the VMM enabled inverters responded with active power injection proportional to the RoCoF, with peak output being reached prior to the frequency nadir. This was a clear inertial response captured at HPR.

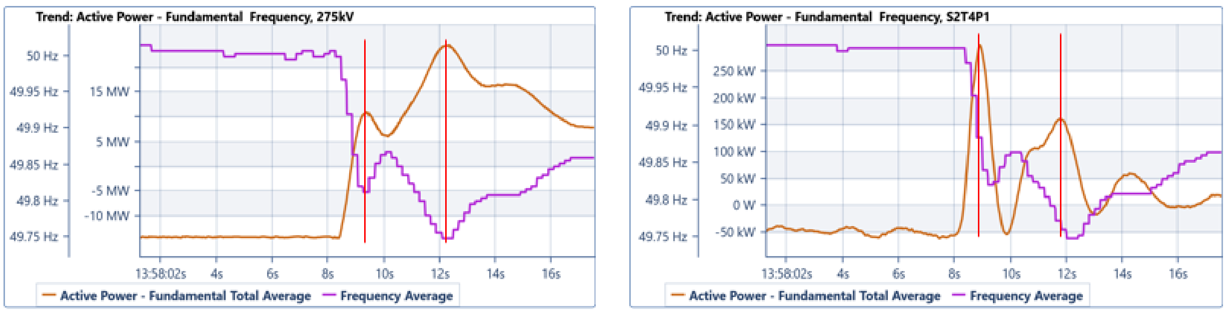

Figure 10 - 275kV Point of Connection (left) and Trial Inverter (right) responding to frequency event (H=50)

On 25/5/2021, a series of events unfolded in Queensland involving the trip of multiple generators and high voltage transmission lines following an initial event at CS Energy's Callide C Power Station[5].

The two distinct contingency events were observed at HPR in SA as a 49.7Hz nadir at 13:44, and a subsequent 49.6Hz nadir at 14:06.

Analysis of meter data shows a clear inertia response from trial inverters during RoCoF events.

For analysis purposes, this report focusses on the deeper event at 14:06 (NEM). The disturbance response at Point of Connection (PoC) was captured in Figure 11 (left) and represents the

[5] https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2021/final-report-trip-of-multiple-generators-and-lines-in-qld-and-under-frequency-load-shedding.pdf?la=en

system in grid following mode. It can be observed the active power response is proportional to the magnitude of frequency deviation from nominal, in line with frequency-watt droop parameters.

Figure 11 (right) shows that the VMM enabled inverters responded with active power injection proportional to the RoCoF, with peak output being reached prior to the frequency nadir.

Figure 11 - 275kV Point of Connection (left) and Trial Inverter (right) responding to the Queensland frequency event (H=50)

The trial inverter meter data was overlayed with the PSCAD modelled response for the same disturbance. The results between the modelled response and the trial inverter were extremely close, giving full confidence in the model behaviour (see Figure 12).

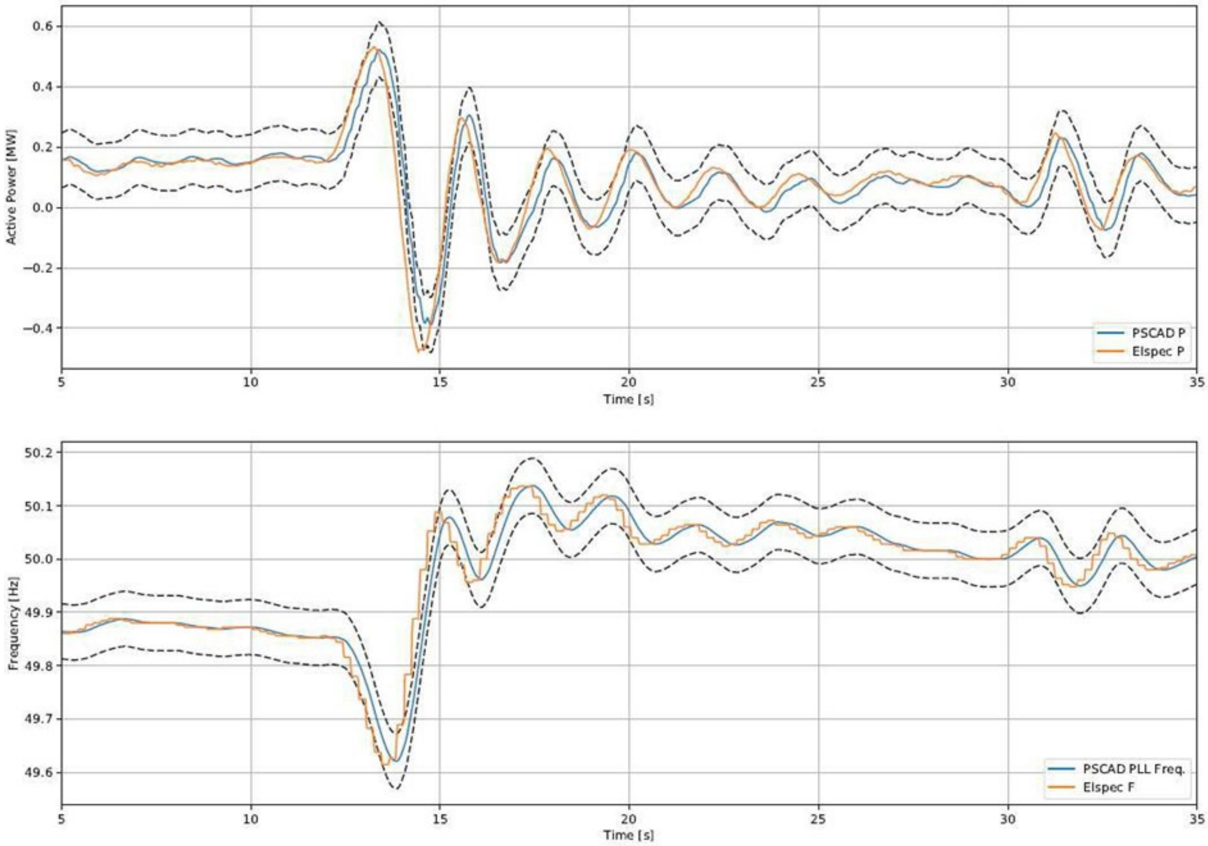

Figure 12 - VMM trial inverter response overlayed with modelled response

6. Modelling and inertia constant selection for 5.3.9 studies

The process for completing a full-scale roll-out of VMM at HPR is to submit 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.

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 complete suite of modelling to be submitted. As such, to move ahead, preliminary studies were completed with varying inertia constants and the results shared with AEMO and ElectraNet.

The amount of response is proportional to the Rate of Change of Frequency (RoCoF). There are two sources of inertia response:

- Rotor inertia
- Damping inertia

The rotor inertia is an equivalence of the rotational inertia (i.e., the kinetic energy stored in rotor at the synchronous speed) in a synchronous machine. Rotor inertia is determined by the inertia constant H.

In addition to rotor inertia, Tesla inverter has a feedback damping loop to improve the control stability. This damping loop also provides an inertial response to system disturbance. The inertia contribution is determined by three parameters, damping (D), P follower time constant (Td), and grid nominal frequency (F).

The total inertia is the summation of the two sources.

The proposed settings are expected to provide 2,070 MW.s of inertia, and the overall equivalent H constant is 11.02MW.s/MVA.

From the *Swing Equation*, 41.4 MW of inertia response is expected from the inverter for a 0.5 Hz/s RoCoF event, and this is consistent with modelling results shown in Figure 13.

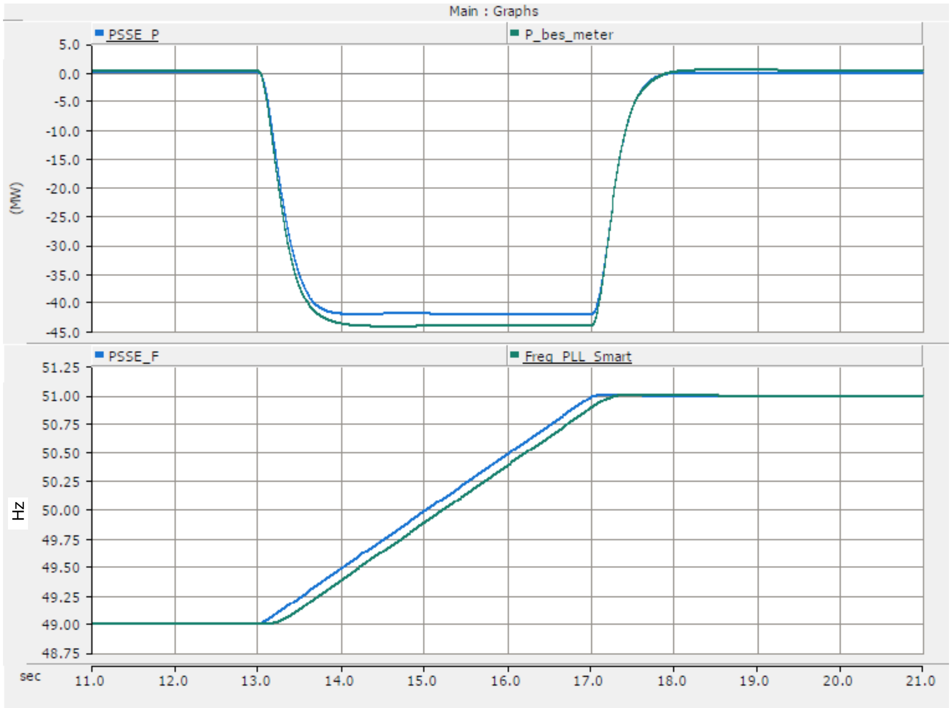

Figure 13 - PSS/E and PSCAD VMM response to a 0.5 Hz/s RoCoF event

7. Conclusions and Lessons Learnt

7.1. 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 testing performed in Melbourne was not able to demonstrate the differences in performance of Tesla's standard grid-following inverter firmware and its virtual machine firmware due to limitations of the facility.
3. The testing performed at US Grid Simulator facility showed excellent response traces, between the model and hardware for all of the different disturbance scenarios tested.
4. When selecting an internal constant, the damping inertia and associated parameters are as equally important the H constant itself, and thus the focus should not be on the H constant alone.
5. The use of event triggered meters was not successful, and continuous monitoring is the preferred approach for this type if project.
6. As expected, more aggressive inertia settings have a longer duration response. As such, the response can be slower than some of the minimum requirements within the GPS and have therefore required some negotiation.

7.2. Regulatory

1. Prior to being granted permission to commence the dual inverter trial, extensive bench testing and modelling was undertaken to ensure there would be no adverse impacts arising from the small-scale trial at HPR.

2. VMM is essentially a new performance characteristic that has yet to be implemented into the NEM on a large grid scale BESS such as HPR. This has required an extensive testing and modelling program for all stakeholders to fully understand not only the response of HPR itself, but how that response interacts with other parts of the grid. To meet these requirements, a System Strength Full Impact Assessment (FIA) is being undertaken.

3. The process for completing a full-scale roll-out of VMM at HPR is to submit a proposal to alter a connected generating system under the National Electrical Rules (NER) Clause 5.3.9. The 5.3.9 process, and commissioning is expected to conclude in Q2, 2022.

7.3. Economic

1. Economic impacts are currently in line with expectations.

7.4. Social

1. No social impacts of any significance observed.

NEOEN

8. 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