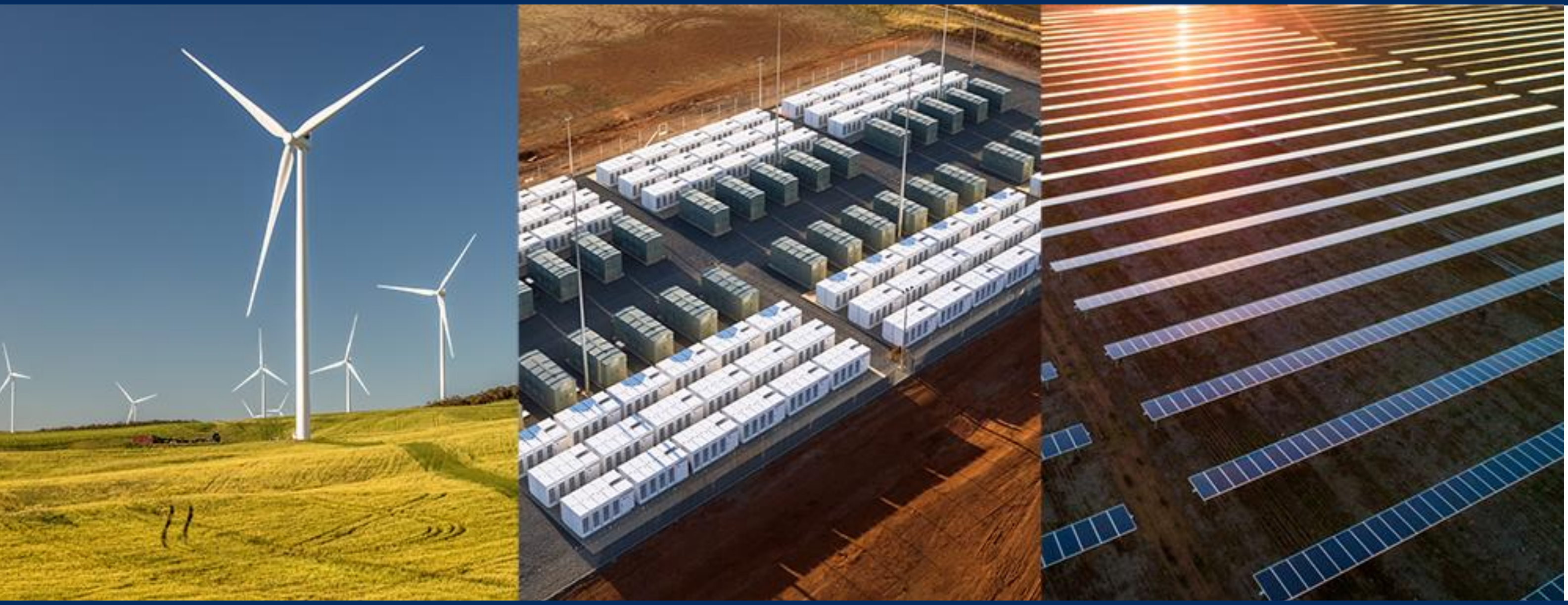
HORNSDALE POWER RESERVE EXPANSION



PROJECT SUMMARY REPORT – FULL INERTIA TRIAL

Revision	1
Released	15/12/2023
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.

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1. Project Stakeholders

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 collaboration 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 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 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 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.

Batteries (coupled with advanced inverters) are particularly valuable to the grid due to the types of services and grid support they can 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.

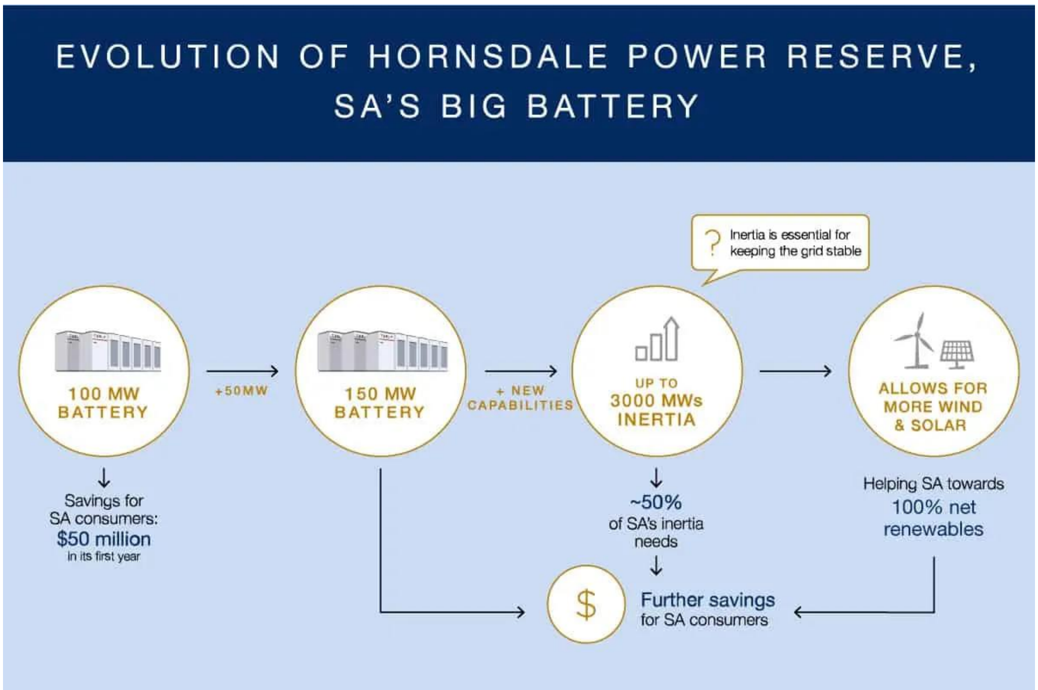

Figure 1 - Evolution of Hornsdale Power Reserve

The Australian Energy Market Operator (AEMO) identified an inertia shortfall in its December 2018 National Transmission Network Development Plan and noted that the South Australian grid requires 6,000 megawatt-seconds (MWs) to maintain a secure operating level of inertia and that the expanded Hornsdale Power Reserve, can potentially provide up to 3,000MWs of inertia (depending on the parameters selected).

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. 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 earlier.

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[1].

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 rotating component runs in parallel with the conventional current source component as show in Figure 2.

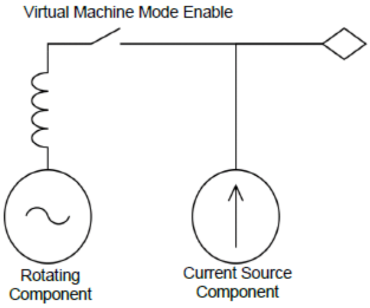

Figure 2: Virtual Machine Mode representation

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.

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

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.

Typically, characteristics such as inertia and damping are tuneable via the adjustment of programmable parameters, unlike a synchronous condenser machine, which has fixed characteristics inherent to the physical machine design.

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.

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)

ΔP_{pu} = inertial response

ω = rotor angular velocity

δ = angular position

$\frac{df}{dt}$ =rate of change of frequency (RoCoF)

f_{nom} = nominal frequency, 50Hz

4. Regulatory Treatment

4.1. Crown Sponsorship

The Project was granted Crown Sponsorship as it was deemed to have the potential to benefit South Australia and is considered public infrastructure. The Expansion was endorsed as a development of public infrastructure. This meant it was exempt from the requirement to obtain Development Approval.

4.2. Generator Performance Standard (GPS) Changes

Clause 5.3.9 of the National Electricity Rules (NER) outlines the required procedure for generators proposing to alter their generating system. Given HPR was already grid-connected and in operation, all the performance settings had been agreed upon in the connection process and an assessment was required to determine what effects VMM would have on these existing settings. The assessment looked at the performance impact of the VMM upgrade to the existing HPR with respect to the affected clauses of the GPS according the NER clause 5.3.9.

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 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.

This process required several factors to align, being the laboratory test results, the models, and the results of a pilot trial conducted on two inverters in operation at HPR. It was only once these results were gathered and analysed that AEMO and the TNSP could assess the impact on the grid. Figure 3 provides an overview of the process that was underwent to obtain a new connection agreement.

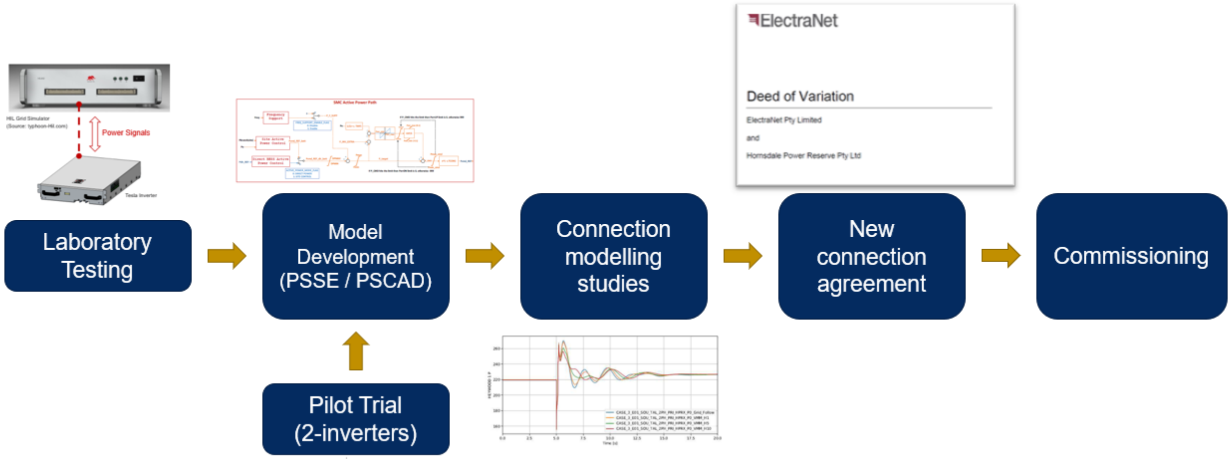


Figure 3 - Overview of VMM implementation process

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.

5. Community Consultation

As part of the HPR Expansion project, a Community Relations Plan was developed. This document identifies the community relations approach going forward for Neoen’s wind and battery facility (as expanded) at Hornsdale. It outlines the overall framework across the phases of the project lifecycle (from development through construction to operations) and proposed plans. It also provides a summary of the key stakeholders including landholders, neighbours, local community and local government.

Neoen understands that the continued success of the Hornsdale Wind Farm and Power Reserve is dependent to a large extent on the development of genuine, open and ongoing relationships with key stakeholders and members of the local community. We recognise the importance of ensuring a "no surprises" dynamic with the local community and are committed to developing and nurturing long-term relationships between our team and the various project stakeholders, evidenced in the process outlined in Figure 4 for community relations.

DEVELOPMENT				CONSTRUCTION		OPERATIONS	
1 SITE SELECTION	2 FEASABILITY	3 PLANNING & APPROVALS	4 POST DA LODGEMENT	5 PRE-CONSTRUCTION	6 CONSTRUCTION	7 OPERATION	8 DECOMMISSIONING
• Undertake host landowner engagement (one-on-one) • Social Feasibility Scan • Initial stakeholder mapping	• Engage with neighbours (one-one-one), decide on neighbour benefit options • Council & MPs briefings • Engage with Traditional owners • Establish stakeholder register • Mapping of political context	• Develop Community Relations Plan (CRP) & Social Risk Matrix • Launch website including project email, 1800#, job interest register & feedback survey • Hold community information session(s) • Undertake council briefings • Develop Community Benefit-sharing Scheme • Hold host landowner dinners & updates	• Update website with progress & news • Email newsletter to stakeholders & subscribers • Presentation to local business & community groups • Host landowner dinner & updates • Develop complaints register	• Hold Local Employment & Supplier networking session • Finalise Community-Benefit-sharing Scheme • Update website with progress & news • Email newsletter to stakeholders & subscribers • Organise start of construction event for host landowners • Introduce Construction Manager & EPC Contractor to key stakeholders	• Regular host & neighbour communication • Community updates via briefings, website & newsletters • Manage complaints register • Establish Community Benefit-sharing Scheme • Introduce Asset Manager to key stakeholders	• Organise community celebration event • Website updates & news • Email newsletter to stakeholders & subscribers • Manage complaints register • Delivery of Community Benefit-sharing Scheme • Facilitate site visits, educational tours & open days	• Landowner & council briefings • Update website • Communicate decommissioning process • Engagement with landcare groups

Figure 4 - Activities involved in community relations from development of a project through to operations

As a condition of ARENA funding, Neoen is required to provide a copy of the Community Relations Plan to ARENA and to keep ARENA informed of progress on the implementation of the Plan. Further, Neoen is required to notify ARENA of all submissions, complaints and questions arising from community consultation and responses provided by Neoen.

The key bodies involved in consultation included:

- Local Government – Northern Areas Council
- State Government – Stuart Electorate
- Federal Government – Division of Grey
- Local business and community organisations
- Local media
- Landowners
- Near-neighbours
- Traditional owners – indigenous community
- Schools, TAFEs and universities

Neoen conducts annual HPR Open Days, involving members of the local council and communities surrounding Jamestown. Following the implementation of VMM, a presentation was given to the local community to help make them aware and informed of the latest changes their local battery is undergoing, seen in Figure 5.

Figure 5 - Annual open day held at HPR in 2023, presenting on the benefits of virtual inertia

6. Stakeholder Log

As the inertia trial was a purely software/firmware based rather than requiring any physical works on site, stakeholder consultation was limited to the relevant interactions with AEMO and ElectraNet.

6.1. VMM Working Group

A VMM working group was established to manage the bench testing and dual inverter trial. This working group included key project managers from Neoen, Tesla, ElectraNet and AEMO. Once the 5.3.9 was submitted, the working group focus was then adjusted to complete the necessary technical due diligence of the 5.3.9 submission package. The group met on a regular basis to work through the assessment process, with minutes captured for each meeting and supplied to ARENA.

6.2. 5.3.9 Issues Tracker

In addition, an issues tracker documented all the items that arose from the 5.3.9 submission technical due diligence that needed to be resolved. The issues tracker was a working document for all key stakeholders that addressed issues across multiple facets, including:

- Connection studies
- GPS
- Modelling (PSSE / PSCAD)
- Voltage control

Once all issues were closed in the tracker and agreed by all parties, conditional approval was granted under Clause 5.3.10 of the NER whereby the TNSP and AEMO accept the newly updated GPS, and advise the generator that they can commence commissioning of the updated settings.

7. Management Plans

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 (as seen in Table 1) involved a staged approach which evolved over time as challenges were faced and solutions derived.

The overall project plans were then developed to manage the various elements of the test plan and keep all stakeholders informed and aligned.

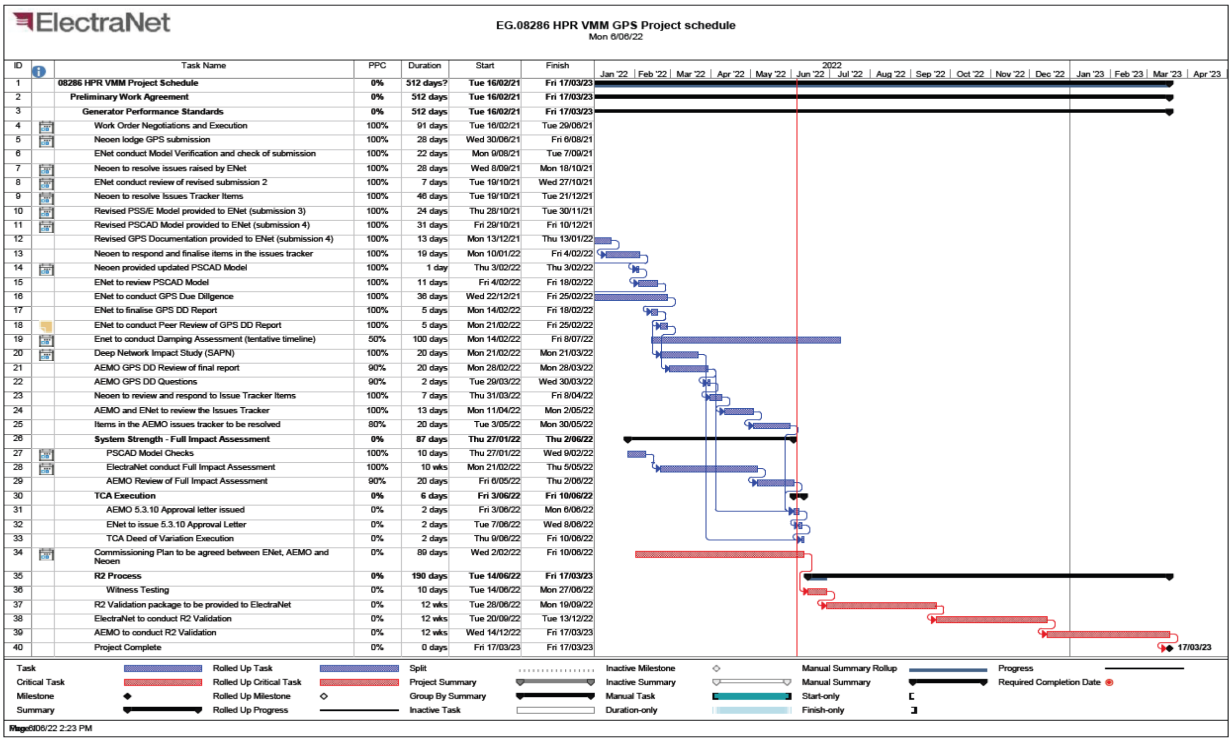
Table 1 - ARENA / South Australian Government test plan

#	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 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.

7.1. Project & Risk Management Plans

Inherent in the 5.3.9 process is the necessary framework to identify and mitigate risks posed to the grid and other generators by proposed settings changes to the generating system generators. Aside from the modelling undertaken by the proponent as part of the 5.3.9 submission package, once submitted, the TNSP and AEMO undertake their own extensive modelling and assessments to ensure the proposed changes to not pose unacceptable risk to the grid. Thus the process undertaken to implement VMM via the 5.3.9 mechanism was largely a risk management process in itself (confidence needed to be built in the models, test results and real-world data before final implementation would be approved).

The overarching management of the project was based upon the project schedule provided by ElectraNet shown in Figure 6.



ElectraNet

EG.08286 HPR VMM GPS Project schedule
Mon 6/06/22

ID	ℹ	Task Name	PPC	Duration	Start	Finish
1		**08286 HPR VMM Project Schedule**	**0%**	**512 days?**	**Tue 16/02/21**	**Fri 17/03/23**
2		**Preliminary Work Agreement**	**0%**	**512 days**	**Tue 16/02/21**	**Fri 17/03/23**
3		**Generator Performance Standards**	**0%**	**512 days**	**Tue 16/02/21**	**Fri 17/03/23**
4	📅	Work Order Negotiations and Execution	100%	91 days	Tue 16/02/21	Tue 29/06/21
5	📅	Neoen lodge GPS submission	100%	28 days	Wed 30/06/21	Fri 6/08/21
6		ENet conduct Model Verification and check of submission	100%	22 days	Mon 9/08/21	Tue 7/09/21
7	📅	Neoen to resolve issues raised by ENet	100%	28 days	Wed 8/09/21	Mon 18/10/21
8	📅	ENet conduct review of revised submission 2	100%	7 days	Tue 19/10/21	Wed 27/10/21
9	📅	Neoen to resolve Issues Tracker Items	100%	46 days	Tue 19/10/21	Tue 21/12/21
10	📅	Revised PSS/E Model provided to ENet (submission 3)	100%	24 days	Thu 28/10/21	Tue 30/11/21
11	📅	Revised PSCAD Model provided to ENet (submission 4)	100%	31 days	Fri 29/10/21	Fri 10/12/21
12		Revised GPS Documentation provided to ENet (submission 4)	100%	13 days	Mon 13/12/21	Thu 13/01/22
13		Neoen to respond and finalise items in the issues tracker	100%	19 days	Mon 10/01/22	Fri 4/02/22
14	📅	Neoen provided updated PSCAD Model	100%	1 day	Thu 3/02/22	Thu 3/02/22
15		ENet to review PSCAD Model	100%	11 days	Fri 4/02/22	Fri 18/02/22
16		ENet to conduct GPS Due Dillgence	100%	36 days	Wed 22/12/21	Fri 25/02/22
17		ENet to finalise GPS DD Report	100%	5 days	Mon 14/02/22	Fri 18/02/22
18	🗒	ENet to conduct Peer Review of GPS DD Report	100%	5 days	Mon 21/02/22	Fri 25/02/22
19	📅	Enet to conduct Damping Assessment (tentative timeline)	50%	100 days	Mon 14/02/22	Fri 8/07/22
20	📅	Deep Network Impact Study (SAPN)	100%	20 days	Mon 21/02/22	Mon 21/03/22
21		AEMO GPS DD Review of final report	90%	20 days	Mon 28/02/22	Mon 28/03/22
22		AEMO GPS DD Questions	90%	2 days	Tue 29/03/22	Wed 30/03/22
23		Neoen to review and respond to Issue Tracker Items	100%	7 days	Thu 31/03/22	Fri 8/04/22
24		AEMO and ENet to review the Issues Tracker	100%	13 days	Mon 11/04/22	Mon 2/05/22
25		Items in the AEMO issues tracker to be resolved	80%	20 days	Tue 3/05/22	Mon 30/05/22
26		**System Strength - Full Impact Assessment**	**0%**	**87 days**	**Thu 27/01/22**	**Thu 2/06/22**
27	📅	PSCAD Model Checks	100%	10 days	Thu 27/01/22	Wed 9/02/22
28	📅	ElectraNet conduct Full Impact Assessment	100%	10 wks	Mon 21/02/22	Thu 5/05/22
29		AEMO Review of Full Impact Assessment	90%	20 days	Fri 6/05/22	Thu 2/06/22
30		**TCA Execution**	**0%**	**6 days**	**Fri 3/06/22**	**Fri 10/06/22**
31		AEMO 5.3.10 Approval letter issued	0%	2 days	Fri 3/06/22	Mon 6/06/22
32		ENet to issue 5.3.10 Approval Letter	0%	2 days	Tue 7/06/22	Wed 8/06/22
33		TCA Deed of Variation Execution	0%	2 days	Thu 9/06/22	Fri 10/06/22
34	📅	Commissioning Plan to be agreed between ENet, AEMO and Neoen	0%	89 days	Wed 2/02/22	Fri 10/06/22
35		**R2 Process**	**0%**	**190 days**	**Tue 14/06/22**	**Fri 17/03/23**
36		Witness Testing	0%	10 days	Tue 14/06/22	Mon 27/06/22
37		R2 Validation package to be provided to ElectraNet	0%	12 wks	Tue 28/06/22	Mon 19/09/22
38		ElectraNet to conduct R2 Validation	0%	12 wks	Tue 20/09/22	Tue 13/12/22
39		AEMO to conduct R2 Validation	0%	12 wks	Wed 14/12/22	Fri 17/03/23
40		Project Complete	0%	0 days	Fri 17/03/23	Fri 17/03/23

Figure 6 - HPR VMM Generator Performance Standards project schedule

A Risk Management Plan was developed as part of the HPR Expansion project to identify and evaluate the risks that would be encountered throughout the life of the project, and to plan appropriate control measures, from the project's late development stage to its decommissioning. These principles were held consistent for both the construction and commissioning of the expansion, and then on to the VMM project. Through an effective risk management framework and approach which is tailored to the specifics of the project, this plan aimed to minimise the project's exposure to risks and in doing so:

- Increase the likelihood of achieving the project objectives;
- Add and protect value within the project;
- Integrate risk management processes into all critical aspects of the project (internal and external); and
- Ensure that critical project stakeholders are kept informed and/or consulted as appropriate.

An appropriate risk management approach and structuring tools have been established to support internal systems at every level of Neoen's organisation.

The relevant local organisations, selected contractors and consultants to ensure that the project enjoyed sufficient market knowledge to manage all possible risks related to financing, constructing, operating and maintaining a grid scale renewable asset.

7.2. Environmental and Safety Management Plans

7.2.1. During Construction and Commissioning

A crucial component of the HPR expansion project was the adherence to an environmental management plan, which gave particular focus to the construction phase of the project. This plan addressed all environmental considerations up to the commissioning of the plant and integration into the grid.

The safety and environmental plans that pertained to the construction of HPRX include:

- Construction environmental management plan
- WHS management plan
- Traffic management plan
- Equipment safety assessments

During construction, there was a commitment toward avoiding, reducing or controlling environmental impact. This included (but is not limited to) the following assessments and processes:

- Soil management
- Flora and fauna management
- Waste management
- Weed management
- Water / air quality / dust management
- Management of chemicals and hazardous materials
- Noise and vibration management

Several management plans were required for the commissioning of this project, though largely pertain to the construction of the 50MW Expansion of HPR, however these fall outside the scope of this report. The VMM component of the project was strictly firmware/software changes thus was managed remotely from off-site.

Industrial sized battery facilities such as HPR help the renewable energy industry perform three primary functions:

1. Network Frequency Control and Ancillary Services (FCAS) support;
2. Smoothing of renewable energy generation profiles;
3. Network voltage support during network transient or short-term (contingency) events.

Designs considerations were made for all site equipment to ensure the inverters ability to perform the functions listed above was unhampered. In particular, a critical assessment was conducted on the medium and low voltage cables to ensure they were adequately sized to accommodate the inverter currents from the new expanded facility.

7.2.2. Ongoing Operations

Once commissioned, the ongoing management of the site while in operations is governed by the Safety, Reliability, Maintenance and Technical Management Plan. This plan provides a means for assessment of safety, technical, and environmental compliance of the site for the remainder of its operational life, and is reviewed and audited annually by the Essential Services Commission of South Australia (ESCOSA).

There are no specific environmental risks associated with VMM, and no requirements outside of those identified in the ongoing review of the SRMTMP.

8. Performance Parameters

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[2] and S5.2.5.12[3] 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 7), and improved damping at Heywood interconnector (see Figure 8).

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. In summary, a higher effective H constant results in a larger active power response, but slows the recovery and settling times post fault.

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[2] 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.

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

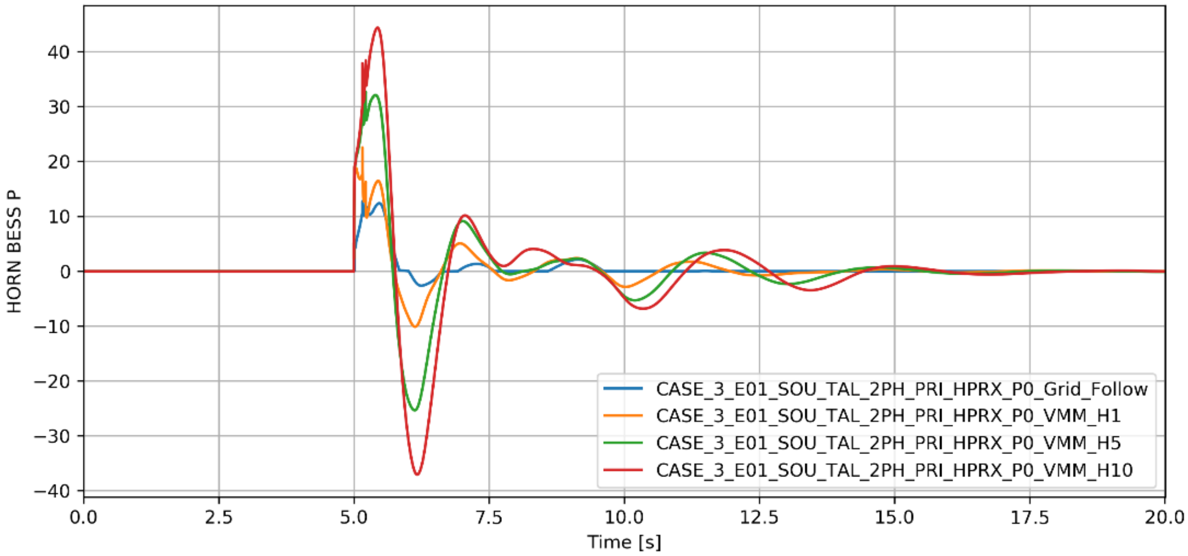

Figure 7 - HPR active power during simulated fault with different inertia settings

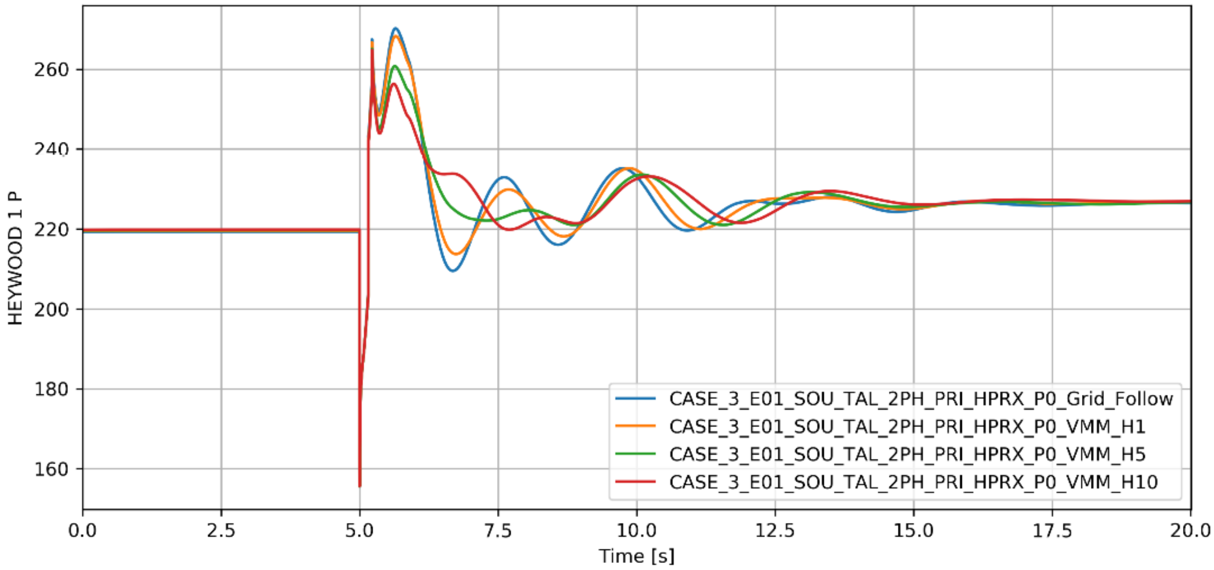

Figure 8 - Heywood Interconnector flow with different inertia settings

9. Shutdown Period – Installation

During the various phases of implementation, HPR was required to be offline for a total of 33 hours across the 2 months of commissioning. The shutdown periods and associated activities are displayed in Table 3.

Table 3 - HPR shutdown period for VMM implementation

Date & Times	*Commissioning Phase*
12/05/2022 10:20 - 15:00	Outage to prepare IT systems for VMM upgrade
25/05/2022 11:20 - 13:31	Outage to prepare IT systems for VMM upgrade
07/06/2022 09:05 - 15:25	Outage to implement VMM firmware upgrade
15/06/2022 10:50 - 18:43	Virtual Machine Mode testing.
27/06/2022 10:10 - 15:15	Virtual Machine Mode testing.
22/07/2022 10:00 - 17:50	Virtual Machine Mode enablement.

10. Commissioning and Testing Plan and Results

10.1. 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 4 – Hold point 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
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.

10.2. Test Results

Testing was conducted on 14/6/2022 and again on 27/6/2022. All testing was witnessed by AEMO and ElectraNet, 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 9 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).

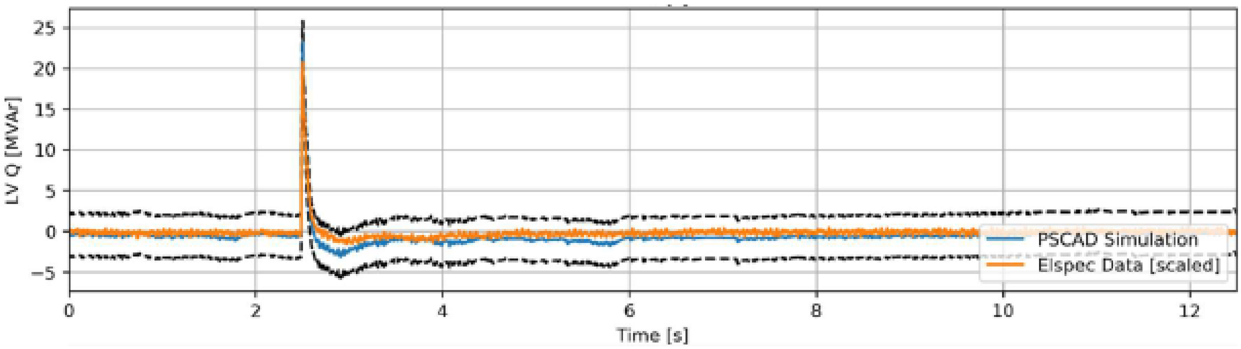

Figure 9 - Example of recorded (Elspec) data and model (PSCAD) overlay

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.

10.3. Enablement

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 was 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.

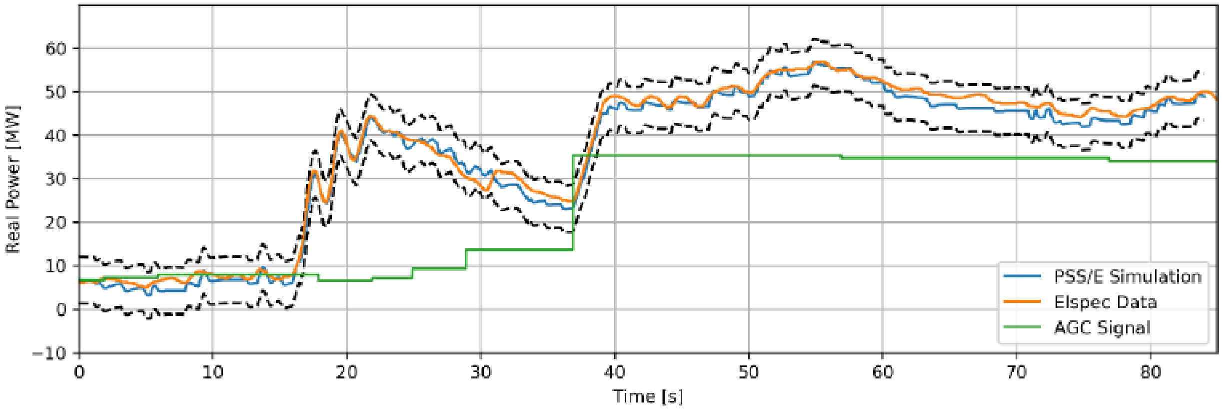

Figure 10 - Actual and modelled response during a grid event

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 (as per Section 3.4), an expected VMM response is calculated as ~13.2MW.

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

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

Figure 10 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.

11. Variations to Plan

This project faced many challenges along its course, with several modifications to elements of the project deliverables, as well as factors influencing the resources available.

The pioneering nature of this project, combined with the existing critical support services HPR provides to the grid, resulted in the TNSP and AEMO taking additional caution (relative to many other projects) when making decisions in relation to VMM (and HPR in general). Each change, test and trial faced challenges in gaining approval to proceed resulted in delays to the project.

11.1. Dual inverter trial

Learnings throughout the dual inverter trial from all parties led to several delays in finalisation. These learnings included:

- An additional benchmark testing step was required by AEMO in order to give confidence that the VMM model being used was representative of actual inverter behaviour.

- Event capture using the high-resolution SEL-735 meters installed was initially planned to be triggered on high rate of change of frequency or current. This method of triggering was found to not be reliable. These triggering challenges diverted resources away from benchmarking tests (as it utilised the same resources) in order to resolve the data capture issues.
- Data manually captured from the trial inverters revealed harmonics on the inverter's current waveform that were not visible in the GridSim testing. Additionally, a ~5Hz envelope (frequency wobble) was also observed on the inverters output current waveform. A revised test plan had to be devised to better understand this observation, however since it required various inverter settings being changed AEMO review and approval was required to proceed.
- Selection of an inertial value ("H" constant) to be taken forward into the project needed to be determined to ensure the value ultimately implemented in the project is the optimal setting. Significant delays are attributed to this factor as sufficient and appropriate event data relied on events occurring in the grid which were out of the project's control.

11.2. 5.3.9 Process

AEMO/ElectraNet's network development and planning teams indicated that the consideration of VMM in operation at HPR would not be progressed until after the initial 150MW 5.3.9 process and commissioning was completed.

Secondly, 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 had to be completed with varying inertia constants and the results shared with AEMO and ElectraNet.

The evolving complexity (in the time since the project was originally conceived) of grid connection studies, (and similarly 5.3.9 studies) meant that the duration of the 5.3.9 works had to be extended in project plans. New generators were added into the network across the project's lifespan, which required updates to the model base-case requirements provided by ElectraNet. Each additional project added takes a significant amount of time to build into the model.

11.3. Commissioning

The time taken between commissioning (hold-point) tests required updating to more accurately reflect experiences on other projects. The test-report-review cycle between each hold-point was perhaps not accurately reflected in past schedules developed.

12. Conclusions and Lessons Learned

12.1. Technical

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.

In discussions with AEMO, an important consideration has arisen when quantifying the inertia contribution from inverter-based technology, and the amount of headroom that is available.

In the case of traditional synchronous generators, the amount of inertia available is inherently linked to the mass and velocity of the rotating elements, whereas in an inverter the amount of inertia available is limited to the available power between the maximum output limit and the current active power output.

As the active power setpoint increases, the inertia contribution from an inverter starts to reduce due to lower available headroom before the plant hits its maximum operating limit.

The magnitude of the response, and the headroom needed, is dependent on the inertia settings and the extent of the frequency deviation. This will be a key focus going forward for other grid-connected batteries intending to provide this service.

12.2. Regulatory

12.2.1. Alteration of a connected generating system

HPR was already providing critical grid services into a vulnerable region, so the TNSP and AEMO were extremely cautious about modifying such a critical asset. This resulted in testing and modelling requirements increasing beyond what was anticipated at project conception.

As discussed in Section 6, generators proposing to alter a connected generating system or a generating system for which performance standards have been previously accepted by the Network Service Provider and AEMO must do so in accordance with NER Clause 5.3.9.

HPR submitted its 5.3.9 application on the 6/8/21 and received approval via NER Clause 5.3.10.

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 size.

The success of this project has allowed Neoen to put forward several other grid-forming projects utilising the same (or similar) technology as HPR.

12.2.2. Inertia and frequency control service

Inertia is one option in a suite of mechanisms to meet frequency stability needs within the NEM. From a frequency control perspective, the ability to manage reducing levels of synchronous inertia through other frequency control mechanisms is technically well understood. The optimal mix of solutions is largely a question of economic efficiency.

Whilst there is no market in place for inertia, the Australian Energy Market Commission (AEMC) has made a final rule to introduce two new market ancillary services in the NEM under the existing frequency control ancillary services arrangements.

The new market ancillary services allows for fast frequency response (FFR) to be procured by the Australian Energy Market Operator (AEMO) in the form of very fast (1-second) services to help control power system frequency following sudden and unplanned generation or power system outages, known as contingency events.

This new market is designed such that a higher volume of Very Fast FCAS will be procured from the market when there is less inertia in the system.

Registered capacities are now 85MW across all contingency markets, following completion of the necessary studies and having made the required submissions to AEMO.

12.3. Economic

No market currently exists for inertia services. As such, there has been no meaningful impacts associated with the delivery of the enhanced services at HPR, aside from grant funding received and expenditure required to implement the service.

13. 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
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 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 Electricity Market
NER	National Electricity Rules
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
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
VFFCAS	Very Fast Frequency Control Ancillary Service