HORNSDALE POWER RESERVE EXPANSION

HPR OPERATIONS REPORT – H1 2023

Revision	1
Released	20/10/2023
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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2. Executive Summary

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

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

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

This report details the first half of 2023 operations and marking 1-year since the implementation of Virtual Machine Mode (VMM) at HPR.

3. Background

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

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

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

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

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

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

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

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.

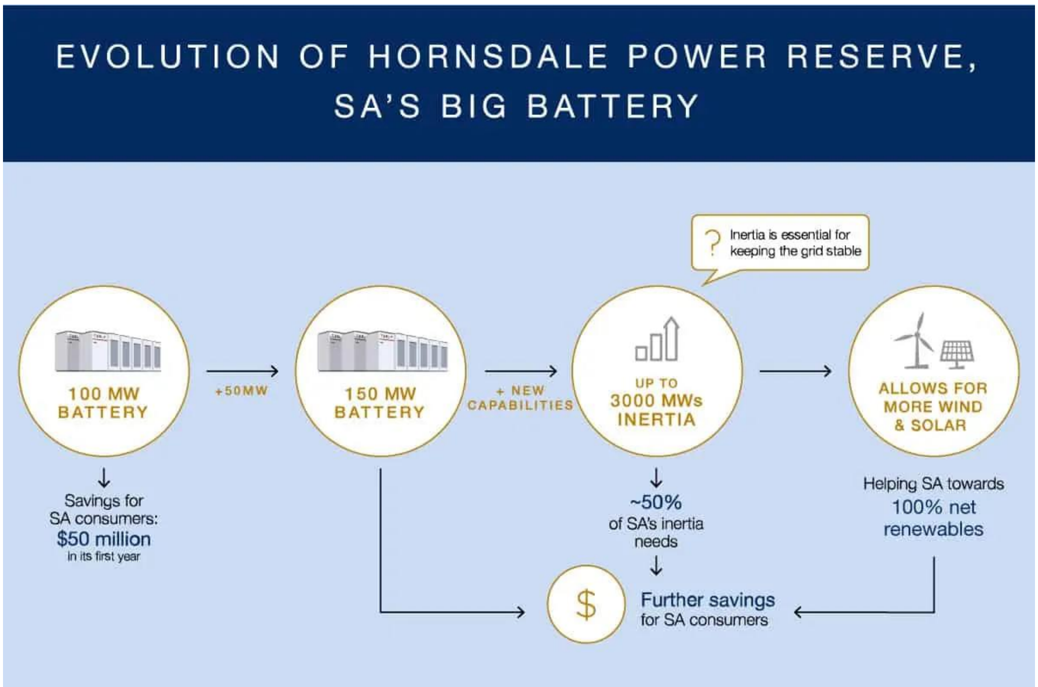


Figure 1 - Evolution of Hornsdale Power Reserve

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. 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 MWs 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.

As such, when comparing different technologies, it is important to consider the entire nature of an inertial response, along with the advantages and disadvantages each technology brings, rather than the quantity alone. This topic is expanded upon in Section 4.2.2.

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.
- Successful integration of VMM across the full expanded 150MW capacity at HPR

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[2].

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*.

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

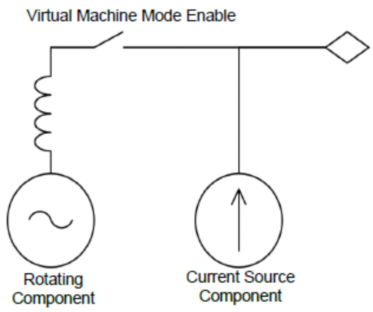


Figure 2: Virtual Machine Mode representation

Like more traditional grid-following 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.

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.

4. Performance and services

4.1. Operational Status

VMM was enabled on 22/7/2022 and has remained continuously in service since that time. Performance has remained consistent with expectations with no adverse impacts detected.

Registered FCAS capacities remain as per the previous report and can be seen in Table 3 below.

Table 1 - Registration data for each ancillary service HPR dispatchable units are registered to provide

DUID	EFFECTIVE DATE	BIDTYPE	MAX CAPACITY
HPRG1	20/09/2022	RAISE5MIN	85
HPRG1	20/09/2022	RAISE60SEC	85
HPRG1	20/09/2022	RAISE6SEC	114
HPRL1	20/09/2022	LOWER5MIN	85
HPRL1	20/09/2022	LOWER60SEC	85
HPRL1	20/09/2022	LOWER6SEC	114

4.2. Results of Key BESS Services Delivered

The first half of 2023 provided limited opportunities for HPR to demonstrate its suite of enhanced inverter capabilities to the grid, with relatively few major grid disturbances.

4.2.1. FCAS Performance

Frequency contingency events are routinely analysed for compliance with the Market Ancillary Service Specification (MASS). An example event from 07/05/2023 is presented in Figures 2 and 3. For this event, the minimum local frequency recorded was 49.776 Hz.

Performance of the facility is checked firstly for compliance with its droop settings (see Figure 3, and then with the verification tool available from AEMO[3] (Figure 4.))

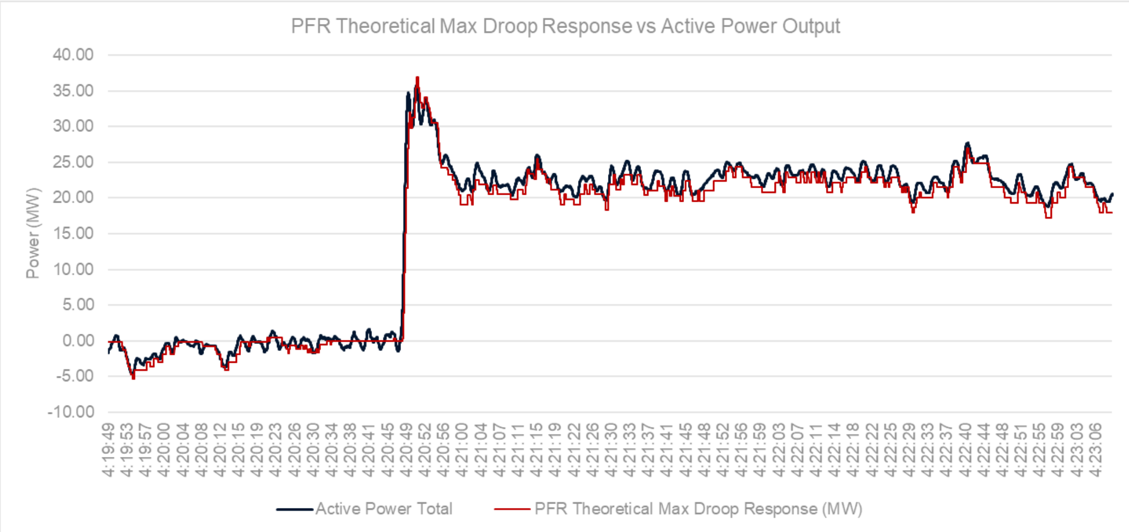


Figure 3 - Active power vs expected frequency droop response.

Droop settings control how active power is injected or absorbed by the facility in response to frequency changes in the grid. For a given frequency event, the expected active power response can be calculated based on frequency data and the relevant droop settings. This is then compared to actual active power data to determine appropriate frequency response behaviour. Figure 3 shows a close alignment of actual with expected response.

Subsequently, the frequency response must also equal or exceed the indicated FCAS availability contained the facility's market bids for the relevant dispatch interval. AEMO provides a verification tool that calculates the expected behaviour based on what has been bid into the market to ensure facilities can check their compliance. Figure 4 shows the facility provided a response beyond the minimum requirement for that interval.

[3] https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/ancillary-services/market-ancillary-services-specification-and-fcas-verification-tool

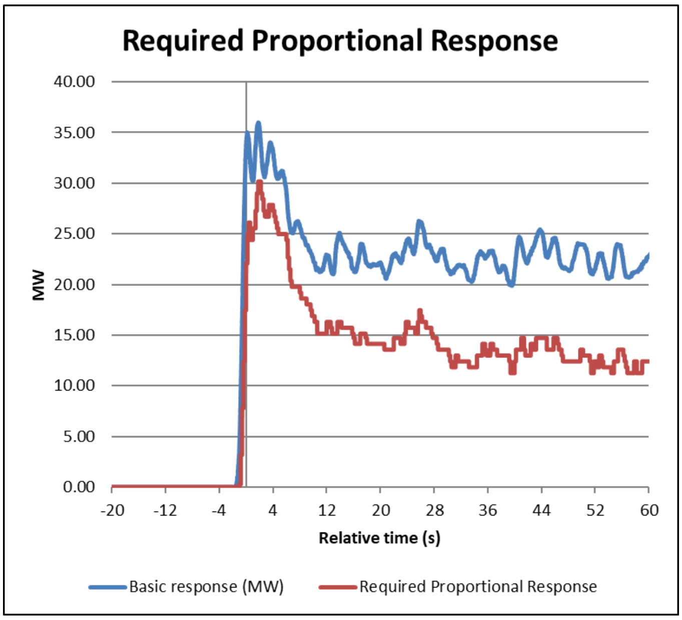


Figure 4 - Actual vs Required response from MASS verification tool.

Analysis indicates that initial performance is greater than the minimum required response, and this is primarily due to VMM responding to the ROCOF prior to the frequency droop response. This performance is as expected and is compliant with the MASS.

4.2.2. VMM

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 maximum output limit and the active power setpoint at that point in time.

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.

AEMO has performed calculations on an example BESS, under various operating conditions and when exposed to different sizes of contingency. As seen in Figure 4, as the active power setpoint approaches 1pu, the inertial response greatly diminishes as there is insufficient headroom to provide a complete response.

In respect to HPR, the facility ordinarily operates at less than 0.53pu, ensuring capacity is reserved for contracted system security services. This reservation ensures significant inertial capability is available over a range of contingency event sizes, however this may not be the case for other BESS facilities in the NEM, meaning the dependability of the inertia will vary from facility to facility.

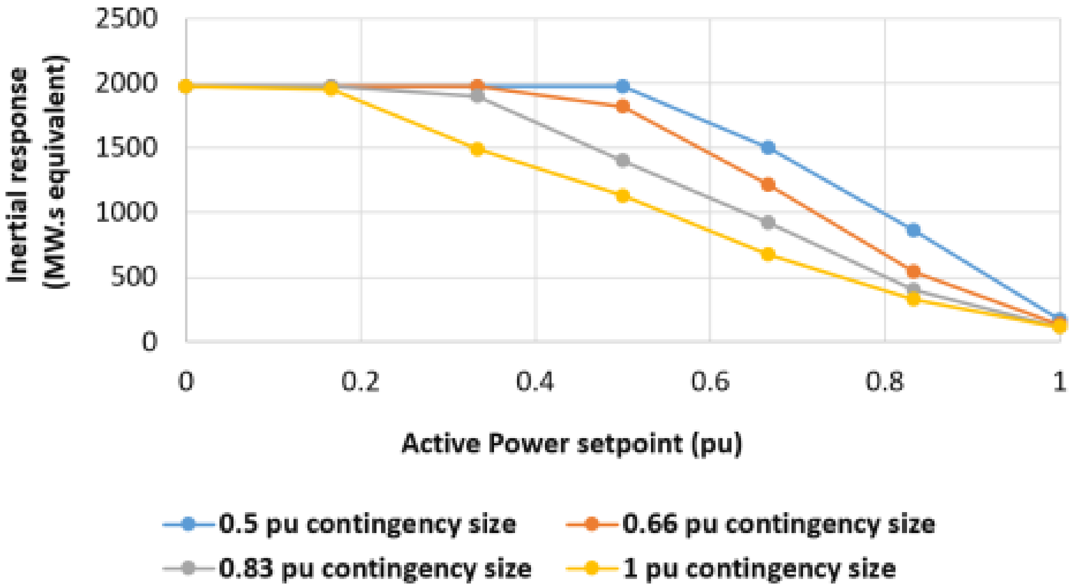


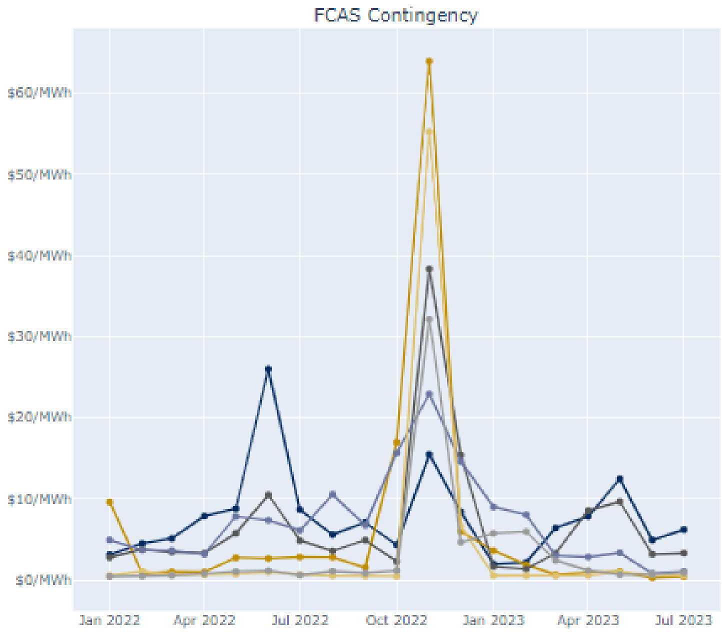
Figure 5 - Inertial contribution calculated for an example BESS under various conditions (image sourced from AEMO[4]).

5. Market Impacts and Regulatory Changes

5.1. Market Impacts

- Currently there is no market in the NEM for the provision of inertia services.
- HPR is consistently one of the largest providers of contingency FCAS in the NEM. In recent months, additional capacity from other providers has come into the market, and this has seen a reduction in HPR's market share.
- Contingency markets for 2023 have been relatively stable and lower in price than previous periods. See average contingency prices in Figure 6.

[4] gfm-voluntary-spec.pdf (aemo.com.au)



	Yearly average
LOWER5MINRRP	4.48 AUD/MWh
LOWER60SECRRP	8.06 AUD/MWh
LOWER6SECRRP	7.93 AUD/MWh
LOWERREGRRP	26.92 AUD/MWh
RAISE5MINRRP	5.27 AUD/MWh
RAISE60SECRRP	7.73 AUD/MWh
RAISE6SECRRP	7.05 AUD/MWh
RAISEREGRRP	28.93 AUD/MWh

Figure 6 - FCAS prices in SA since January 2022 through until July 2023.

5.2. Regulatory Changes

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 (FCAS) arrangements, accompanied by additional reporting requirements.

The new market ancillary services will allow 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.

The rule requires AEMO to:

- Revise the Market Ancillary Services Specification (MASS)
- Commence operation of the Very Fast Frequency Control Ancillary Service (VFFCAS) arrangements by 09/10/2023.

Previously, FCAS providers with the ability to respond more rapidly than the standard frequency ramp, have benefitted in their registration from the ‘multiplier effect’, which allowed registration in the 6-second Contingency FCAS markets at levels that are significantly higher than 100% of their nominal capacity. With the new MASS, the registered contingency FCAS capacity of all providers will be capped to the active power response across the relevant measurement windows.

HPR has completed the necessary studies and made the required submissions to AEMO. A simplified version of this assessment is presented in Figure 7. For clarity, the contribution of inertia is shown on the figure, however for the purposes of registration, the impact has been omitted.

Registered capacities are expected to be 85MW across all contingency markets, however testing and validation are yet to be undertaken.

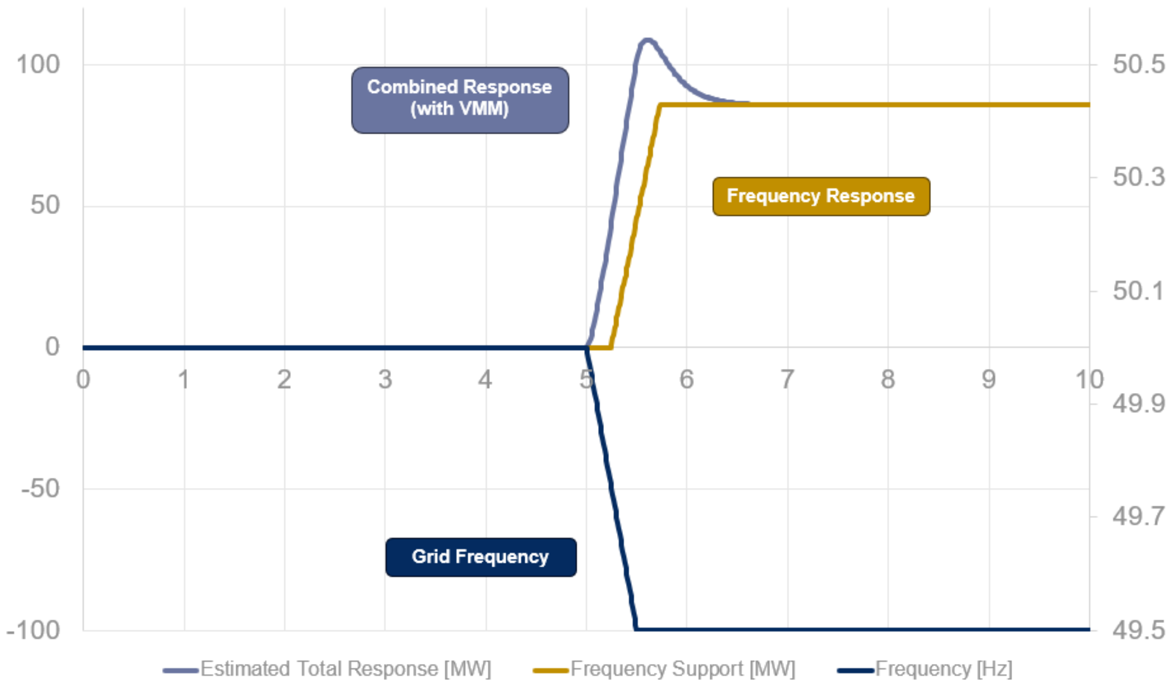


Figure 7 - simplified representation of simulation provided for new frequency markets.

6. Social Impacts

Figure 8 - new viewing area at HPR

7. Emerging Challenges and Opportunities

- The upcoming change to the MASS and the introduction of VFFCAS opens new opportunities for markets that are well suited to inverter-based technologies.

- HPR is in discussions with AEMO and ElectraNet regarding the potential for HPR participating in future Over Frequency Generator Shedding (OFGS) scheme, as well as the South Australia Interconnector Trip Remedial Action Scheme (SAIT RAS).

- Design and implementation of SIPS 2.0 (or WAPS – Wider Area Protection Scheme) is ongoing with AEMO and ElectraNet. This project involves an upgrade of both ElectraNet's scheme, and HPR's corresponding control system.

- AEMO has reviewed the OFGS for South Australia and ElectraNet is progressing the concept design of SAIT RAS, which has to be in service when Project EnergyConnect is commissioned end 2024.

8. Conclusions and Lessons Learnt

8.1. Technical

1. As per Section 4.2.2, whereas with a traditional synchronous generator the amount of inertia available is inherently linked to the masses and velocity of the rotating elements, in an inverter the amount of inertia available is limited to the maximum output limit and the active power setpoint at that point in time.

   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.

8.2. Regulatory

1. With the introduction of VFFCAS, the registered contingency FCAS capacity of all providers will be capped to the active power response across the relevant measurement windows, effectively removing the ability to "bias" the 6-second markets.

8.3. Economic

1. No market currently exists for inertia services.
2. The introduction of VFFCAS will introduce new revenue streams but will remove the past benefits of the ability to "bias" the 6-second markets.

8.4. Social

1. Construction completed of the HPR Viewing Area in March 2023.

9. Glossary of Terms

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