PMU Cost Benefit Analysis for NSW region

August 2022

Looking at installation of further PMUs in the New South Wales region of the NEM

Version control

Version	Release date	Changes
0.2	02/08/2022	Formatting
0.1	10/06/2022	Initial document

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1 Operational Need for Installation of PMUs

Historically oscillatory stability issues in the NEM have been well understood, associated with a few major transmission flow paths, and the limited Phase Monitoring Units (PMUs) we had available were appropriate for monitoring them. However, with more inverter-based generation connected progressively displacing synchronous generation, our current PMU coverage is not adequate and the current operating risks unacceptable.

The increase in inverter-based resources creates two types of oscillatory stability issues. Firstly, there is the interaction of inverters in weakly connected systems, examples are as follows:

- Oscillations that occurred in the West Murray area of the NEM. Generation was constrained between August 2019 and April 2020 at an estimated cost[1] of $17M
- Oscillations observed in the modelling of the Wagga area are delaying the connection of generation in that area
- Oscillations thought to be originating from southern Victoria are found to be impacting power flow across the Basslink interconnector
- Inverter based plant in north Queensland are susceptible to participating in oscillatory behaviour and are required to cease generation under outage conditions
- Concerns regarding oscillatory stability added to the complexity of the analysis associated with connection of wind farms on the 500 kV network in Western Victoria
- A trip of the Ararat-Crowlands 220 kV line and Wemen Solar Farm occurred on 20 August 2020. Additional PMU monitoring could have helped identify the 19 Hz voltage oscillations sooner and assist with efficiently investigating and resolving the issue.

Secondly, the displacement of synchronous generation changes system inertia across the NEM, is creating new operating conditions that that have not previously been observed. These new operating conditions have the potential to exacerbate known oscillatory stability issues and potentially create new issues.

For instance, the power flow across the QNI and Heywood interconnectors are set, in part by an oscillatory stability limit that is impacted by the relative inertia of all mainland NEM regions. The removal from service of synchronous generation has the potential to adversely change these limits. AEMO's ability to model these interarea oscillatory stability issues is not perfect, and it is crucial to have PMUs in place to monitor changes in oscillations.

As incidents are expected to continue to occur, likely consequences for consumers, participants and governments, could include:

- cascading outages
- power system failure requiring system restart
- further constraints that will restrict access to market and may require further (and much more) expensive network investment to remove (which compounds the issue)

[1] The cost is estimated by determining the amount of generation constrained over the period and applying the average cost of replacement energy.

To add to this risk, the NEM will be undergoing major topological changes in the next few years (PEC, Humelink etc), which may affect the oscillatory modes and may introduce new modes.

AEMO currently has extremely limited real-time visibility of existing and emerging power system stability phenomena, primarily related to low system strength, low system inertia and higher penetrations of inverter-based generation2, which is making it increasingly challenging for AEMO to discharge its market and power system security functions.

Low system strength has been shown through theoretical simulations and actual observations to cause instability, such as voltage oscillations. At sufficient magnitudes, or where insufficiently damped, these oscillations will breach power system security limits and cause power quality issues. The problem is exacerbated by increasing inverter-based generation.

In addition, the magnitude of poorly damped inter-area electromechanical oscillations has been increasing due to a reduction of synchronous machines with power system stabilisers online.

Existing SCADA systems are unable to detect and respond to these power system phenomena. To detect oscillations AEMO currently relies on a work-around using existing high-speed monitoring equipment that does not have real-time capability and is not designed to detect oscillatory stability issues. The work around involves downloading data from a number quality of supply meters in the west Murray Region and performing calculations on the data (based on Fast Fourier Transform) to determine if oscillatory issues are present.

This work around pushes AEMO's current high-speed monitoring facilities to their data handling limits while monitoring a single area. AEMO are not able to scale it to observe other areas in Victoria. It is also not capable of providing results in real time. Furthermore, the technology used in the work around is obsolete and devices that fail are not able to be repaired.

PMUs are now the only high-speed data available in Tasmania, following shut-down of TasNetwork's previous high-speed monitoring system earlier this year. Reliability problems are also evident with older high-speed monitoring equipment in some other NEM regions.

Without any visibility of these oscillations as they occur, AEMO is effectively "flying blind". The control room cannot determine whether the power system is secure in real-time and may need to pre-emptively constrain inverter-based generation (as AEMO was forced to do between September 2019 and April 2020 in the West Murray) or direct on synchronous generation (if available in the relevant area). Both actions can have serious market implications that could be avoided or minimised with real-time visibility to facilitate a more targeted system security response.

For further details on these issues refer to Appendix 1.

As shown by examples in Appendix 4, system operators elsewhere have responded to similar growing risks by installing extensive networks of PMUs.

The following is an estimate of the expected costs and benefits of the provision of additional PMUs in the NSW Region to address these issues.

1.1 Cost of PMU procurement, installation, and testing

AEMO has assumed a total cost (procurement, installation, and testing) including establishment of data communication links of $500k to $600k per PMU location for new sites.

For sites where the PMUs are being installed to replace High Speed Monitors the costs will be less as it is likely that much of the existing wiring for inputs can be reused. For such sites, AEMO has assumed a cost of $400k to $500k per site.

These are conservative assumptions which have been adopted solely for the basis of this cost benefit analysis. Based upon preliminary estimates and the known costs of similar projects undertaken overseas (for instance Canada[2] and USA[3]), it is expected that the actual costs will be significantly below these assumptions.

Typical tasks that are covered in this estimate, are (not exhaustive):

- Procurement of PMUs
- Design and install racks, panels, and cubicles at the transmission station
- Modify CT circuits to obtain current signals for PMU
- Install antennae for GPS clock
- Install and terminate cables from the voltage transformers and current transformers to carry measurement data to the PMU
- Install and configure PMU
- Design and install/upgrade communications network infrastructure to transmit synchrophasor data from the PMUs in the field to the phasor data concentrators at the TNSP's central locations
- Install and configure phasor data concentrators
- Configure firewall services and operational IT support

Based upon the above assumption the expected total costs of this project for the NSW Region are

- Costs to be incurred by Transgrid for installation at
  - 18 new sites and
  - 21 sites where PMUs will replace High Speed Monitors

  is $ 17.7 M to $ 21.6 M
- In addition to these costs which would be incurred by the TNSP, AEMO also has costs involved in receiving, analysing, and presenting this data to operational staff. This cost is expected to be of the order of $2 M (about $0.5 K per region).
- Total cost is thus estimated as $18.2 M to $ 22.1 M.

1.2 Expected benefits for installation of additional PMUs in the NSW Region.

The expected benefits in the NSW region analysed here will be in terms of avoided costs of constrained off generation and loss of supply which could be avoided through availability of data from the proposed PMU devices

[2] Project undertaken by the IESO in Ontario refer https://www.ieso.ca/-/media/Files/IESO/Document-Library/engage/pd/phasordata-20210921-quantitative-cost-analysis-pmu-installation-ontario.ashx

[3] DOE Study on costs for projects undertaken by RTOs refer https://www.smartgrid.gov/files/recovery_act/PMU-cost-study-final-10162014_1.pdf

in real time. There are likely to be additional benefits not included in this analysis such as allowing faster commissioning of new interconnectors.

In assessing these expected benefits, AEMO has focused on 3 of the more likely classes of benefits and has assessed

- the impact of an incident
- the likelihood of this incident if this data was not available
- the reduction in likelihood if this data was available.

As these issues that do not exist currently but are rather potential future issues, these estimates are indicative. However such indicative estimates should still be adequate to establish whether or not there is a clear cost – benefit case.

These classes of benefits are as follows

Class 1 Where local sub- synchronous oscillations may arise without warning resulting in the need for significant constraints on local generation in an REZ with lower system strength for an extended period.

This will cover three REZs

- South West REZ (Wagga- Darlington area)
- Central West REZ (Dubbo -Orange area)
- North West REZ (Narrabri – Moree area)

Impact of an event

The cost[4] of such an event has been estimated based upon the event in West Murray area, five solar farms were constrained between August 2019 and April 2020 which cost $5 M to $7 M. The estimated impact has been adjusted to account for the size of REZ compared to the West Murray REZ (refer Appendix 3) as follows:

- South West (SW) REZ - $4.3 M to $6.0 M as REZ is about 85% of size of West Murray REZ
- Central West (CW)REZ -$2.8 M to $3.9 M as REZ is about 55% of size of West Murray REZ
- North West (NW) REZ - $1.3 M to $1.8 M as REZ is about 25% of size of West Murray REZ

Likelihood

Factors influencing likelihood of such an event are

- System conditions – with a steady growth in IBR penetration over the next 20 years we will continue to see large concentrations of generation being installed in remoter parts of the network. It is likely that growth in generation will outpace transmission augmentation meaning issues similar to the one in August 2019 will arise from time to time. Refer Appendix 2 for statistics on prevalence of sub synchronous oscillation issues in the West Murray zone. While actions have been taken to address the constraint, such as fine-tuning solar farm control settings, assigning NMAS to provide additional system strength services and building new transmission lines, AEMO believes that we are likely to see events of a similar magnitude about once in every three years for each REZ.

[4] The cost is estimated by determining the amount of generation constrained over the period and applying the average cost of replacement energy.

- Likelihood of availability of real time PMU information reducing period or magnitude of constraint. – The availability of this information in real time should allow application of constraints to be restricted to periods where there is actual evidence of oscillations and for constraints to be targeted to specific solar or wind farms causing these oscillations. It is thus considered that the availability of real-time PMU data would reduce the magnitude of the impact by about 75%.

The per annum benefits for this class has thus been estimated as follows:

Per annum benefits for Constraint class

Class of Benefit	Impact of event	Per annum probability of Event	Reduction of impact or likelihood due to availability of real time data from PMUs	Per Annum Benefit of real time data from PMUs
1. Constraint				
SW REZ	$4.3 M to $6 M	33% (1 in 3 years)	75%	$1.1 M to $1.5 M
CW REZ	$2.8 M to $3.9 M	33% (1 in 3 years)	75%	$0.7 M to $1.0 M
NW REZ	$1.3 M to $1.8 M	33% (1 in 3 years)	75%	$0.3 M to $0.4 M
Total				$2.1 M to $2.9 M

Where Per Annum PMU Benefit = Impact of event x Probability of Event x PMU reduction of impact

Class 2 Loss of a NSW REZ due to an issue triggered by local sub-synchronous oscillations which could have been avoided if this level of PMU data had been available.

Impact of an event

Assuming an interruption of local load for 4 hours, the expected benefit in terms of avoided cost, assuming a VCR of $20,000/MWh, would be of the order of:

- South West (SW) REZ - $ 8.8 M assuming an average local load of 110 MW (refer Appendix 3)
- Central West (CW)REZ - $ 12.0 M assuming an average local load of 150 MW
- North West (NW) REZ - $ 5.6 M assuming an average local load of 70 MW

Likelihood

Factors influencing likelihood of such an event are

- System conditions – in this case oscillations could arise as in the event discussed from Class 1 but in this case the oscillations could be more severe resulting in cascade tripping and loss of supply. Under present arrangements oscillations do not become known for some time. For instance, recently there was a significant oscillation at Wemen (4% peak to peak) which AEMO did not detect for 24 hours (refer Appendix 2 for further details). AEMO believes that we are likely to see events of a magnitude sufficient to potentially lead to loss of each zone about once in every nine years.
- Likelihood of availability of real time PMU information preventing the loss of the zone. It is considered that availability of this information would allow in some circumstances timely action by AEMO in time to prevent loss of the entire zone. This would reduce the risk of such an event by 50%.

It is thus considered that the availability of real-time PMU data would reduce the risk of such an event from one every nine years to once every eighteen years

Per annum benefits for loss of local load in REZ

Class of Benefit	Impact of event	Per annum probability of Event	Reduction of likelihood due to availability of real time data from PMUs	Per Annum Benefit of real time data from PMUs
2. Loss of local load in REZ				
SW REZ	$8.8 M	11% (1 in 9 yrs.)	50%	$0.5 M
CW REZ	$12.0 M			$0.7 M
NW REZ	$5.6 M			$0.3 M
Total				$1.5 M

Where Per Annum PMU Benefit = Impact of event x Probability of Event x PMU reduction of impact

Class 3 Where *severe sub- synchronous oscillations may arise without warning resulting in loss of QNI interconnection and then to UFLS operation.*

With the large penetration of IBR in Northern NSW and Southern Queensland, there is an increased possibility of inter-region sub-synch oscillations which may not be picked up by existing Psymetrix.

Impact of an event

Assuming an interruption of 1000 MW for average of 1 hour, the expected benefit in terms of avoided cost would be estimated as $20M assuming a VCR of $20,000/MWh.

Likelihood

It has been assumed that the likelihood of a non-credible separation of QNI due to unexpected oscillations would of the order of 1 in 10 yrs.

Reduction to impact or likelihood if PMU real time data available

It has been assumed that the availability of real time PMU data would reduce the likelihood of such an event by 25%.

Per annum benefits for loss of QNI

Class of Benefit	Impact of event	Per annum probability of Event	Reduction of likelihood due to availability of real time data from PMUs	Per Annum Benefit of real time data from PMUs
3. Loss of QNI	$20.0 M	10% (1 in 10 yrs.)	25%	$ 0.5 M

Where Per Annum PMU Benefit = Impact of event x Probability of Event x PMU reduction of impact

These are only three of the potential classes of potential benefits from the availability of real time PMU data. There are a number of others. Such as

- The availability of such data may be able to reduce the likelihood of the need to constrain off distributed PV generation or reduce the magnitude or duration of such constraints
- Also, having access to aggregate DER response for power system disturbance should help in refining power system models over time. Such improved models should help in alleviating constraints. (e.g. the current Heywood transfer equation has a loss of DER term).

These other classes of benefits have not been included in this assessment as they were not able to be estimated qualitatively at this time.

Expected Benefit on a per annum basis.

Taking into account these estimates for the above estimates for each class of benefit, the total expected per annum benefits in terms of avoided costs for the NSW region would be:

Total expected per annum benefits

Class of Benefit		Per Annum PMU Benefit
1.	Constraints	$2.1 M to $2.9 M
2.	Loss of REZ	$1.5 M
3.	Loss of QNI	$0.5 M
Total Classes 1, 2 and 3		**$4.1 M to $4.9 M**

1.3 Meeting the National Electricity Objective

The overall cost benefits of this proposal for the NSW Region are estimated above:

- total cost of about $18.2 M to $22.1 M.
- overall, per annum expected benefit, in terms of expected avoided costs of $4.1 M to $ 4.9 M per annum.

On this basis, this proposal would satisfy the National Electricity Objective in that it would help achieve and efficient operation and use of, electricity services for the long-term interests of consumers of electricity with respect to-

a) price, quality, safety, reliability, and security of supply of electricity; and

b) the reliability, safety, and security of the national electricity system.

A1. Appendix 1 The Importance of Monitoring Stability

Power systems around the world are undergoing technological change and the emphasis on monitoring, modelling and simulations has never been more important. In response to this the need for improved monitoring has been recognised with networks of PMU monitors being installed in many power systems including in the United States, Canada, India, and South Africa.

This especially the case for the NEM since, unlike many other parts of the world with well-connected meshed power systems that still contain many large synchronous generators, the NEM is a very longitudinal power system with synchronous generators being displaced by inverter-based resources (IBRs) at an ever-increasing rate.

Needless to say, the longitudinal nature of the NEM makes it vulnerable to instabilities even without the impact of reduced system inertia due to the increasing penetration of IBRs**. It is noteworthy to emphasise that the interconnected NEM regions are dynamically unstable without power oscillation dampers (PODs) and power system stabilisers (PSSs).**

While Tasmania is not synchronously coupled to the mainland and therefore does not participate in the dominant inter-regional modes, the network topology in Tasmania also gives rise to oscillation modes which constrain network operation if not mitigated.

The need to analyse such phenomena is becoming more critical as power flows are increased in some areas of the network without a corresponding increase of inertia or damping contributions.

Displacement of synchronous generation by IBRs affects the frequency and damping of NEM inter and intra-area modes. Monitoring, modelling, benchmarking, and simulations are crucial in understanding how NEM inter-area modes change and what the impact of that change is on power system security.

In addition to increasing levels of IBRs connections, several interconnectors between NEM regions are in the various implementation stages. New topology will inevitably further change inter and intra-area modes. It is of utmost importance to establish how much the inter-area modes already changed and whether NEM has any damping issues (now or in the future).

It is essential to have a number of PMUs installed in every region to provide sufficient coverage across geography, transmission voltage levels as well as load and generation connections. It is not enough to have, say, one monitoring device per region. Although one PMU may help in establishing the damping and frequency of a particular mode, it will not be sufficient to determine which generator/load is the main participant in a low damping event. To determine generator/load participation, a number of PMUs will have to be strategically placed around the network.

In the future, inter-area modes as we know them, may change their nature and generator participation. It is just a matter of time before the current damping devices become ineffective at damping inter and intra-area modes and will require retuning to account for the changing nature of the modes. Successful tuning of such devices depends solely on the modelling accuracy. Modelling accuracy is achieved through the high-speed data measurements, analysis, and benchmarking.

Most power system oscillations are invisible to RTO due to SCADA sampling. This is because SCADA data typically has a resolution of 2 to 4 seconds whereas PMU data has a resolution of 50 milliseconds. This means that for monitoring of such oscillations the availability of high-resolution real-time data is crucial[5].

The ultimate aim is to have a NEM model that enables accurate and reliable simulation of system performance; this is crucial for secure operation, determination of limit equations and planning for all NEM regions. This cannot be achieved without an extensive, reliable and GPS stamped network of monitoring devices.

The least damped mode of oscillation is the so called QNI mode (or I20).

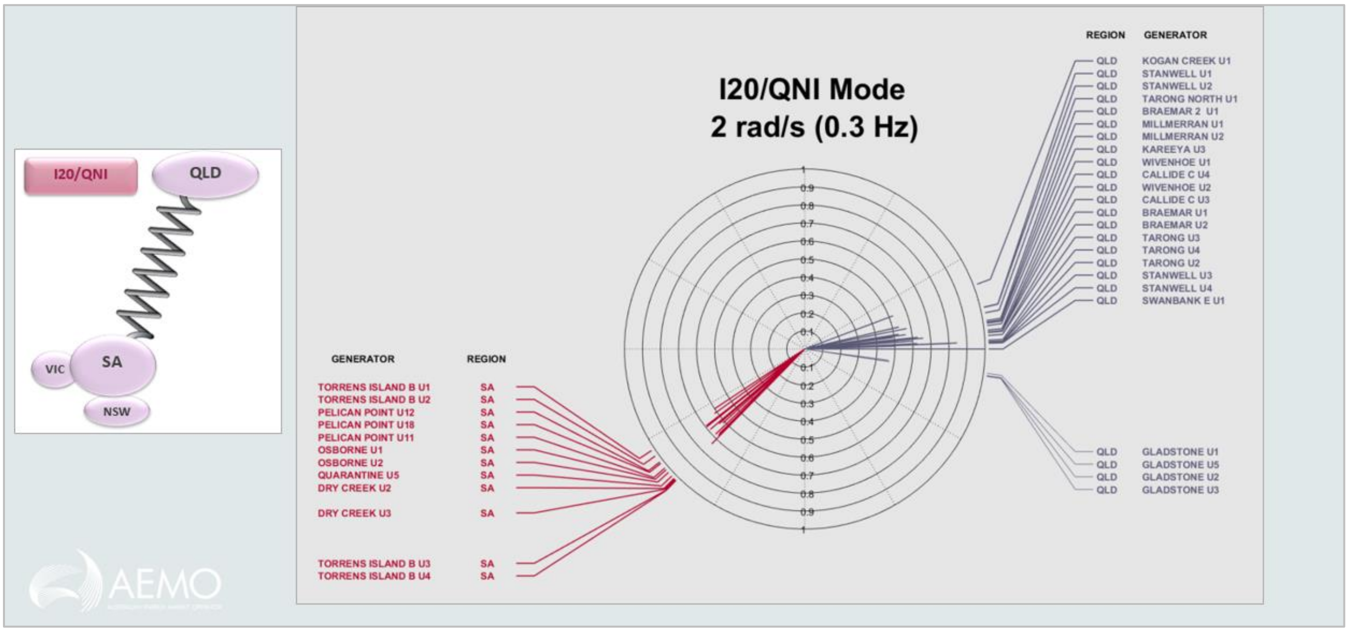

Figure 1: I20/QNI Mode

Historically, the following Power Oscillation Dampers (PODs) and Power System Stabilisers (PSSs) damped the QNI mode:

REGION	PLANT
QLD	GREENBANK SVC U1
QLD	GREENBANK SVC U1
QLD	GREENBANK SVC U1
QLD	SOUTH PINE SVC U1
QLD	GREENBANK SVC U1
QLD	GREENBANK SVC U1
QLD	SOUTH PINE SVC U1
QLD	SOUTH PINE SVC U1
QLD	SWANBANK E U1
QLD	SOUTH PINE SVC U1
QLD	SOUTH PINE SVC U1
QLD	BLACKWALL SVC U1
QLD	BLACKWALL SVC U1
QLD	SWANBANK E U1
QLD	BLACKWALL SVC U1
QLD	BLACKWALL SVC U1
QLD	BLACKWALL SVC U1
SA	PELICAN POINT U11
SA	PELICAN POINT U11
SA	PELICAN POINT U12
SA	PELICAN POINT U12
QLD	GLADSTONE U3
SA	PELICAN POINT U18
SA	PELICAN POINT U18

Figure 2: Region and Plant

These stabilising devices were tuned a number of years ago when IBRs didn't play any significant role in the NEM operation. Additionally, these devices were tuned to optimally damp QNI mode at a frequency of 2 rad/s. This frequency is dependent on the NEM inertia. As inertia is decreasing, the QNI mode frequency has increased. As a result, at a certain point stabilising device will become ineffective. It would be prudent to establish where we are on this curve.

The same reasoning applies to I25 and I35 modes:

[5] Refer https://www.researchgate.net/figure/Comparison-example-between-PMU-measurements-and-SCADA-data-during-a-fast-dynamic-event_fig1_285629258

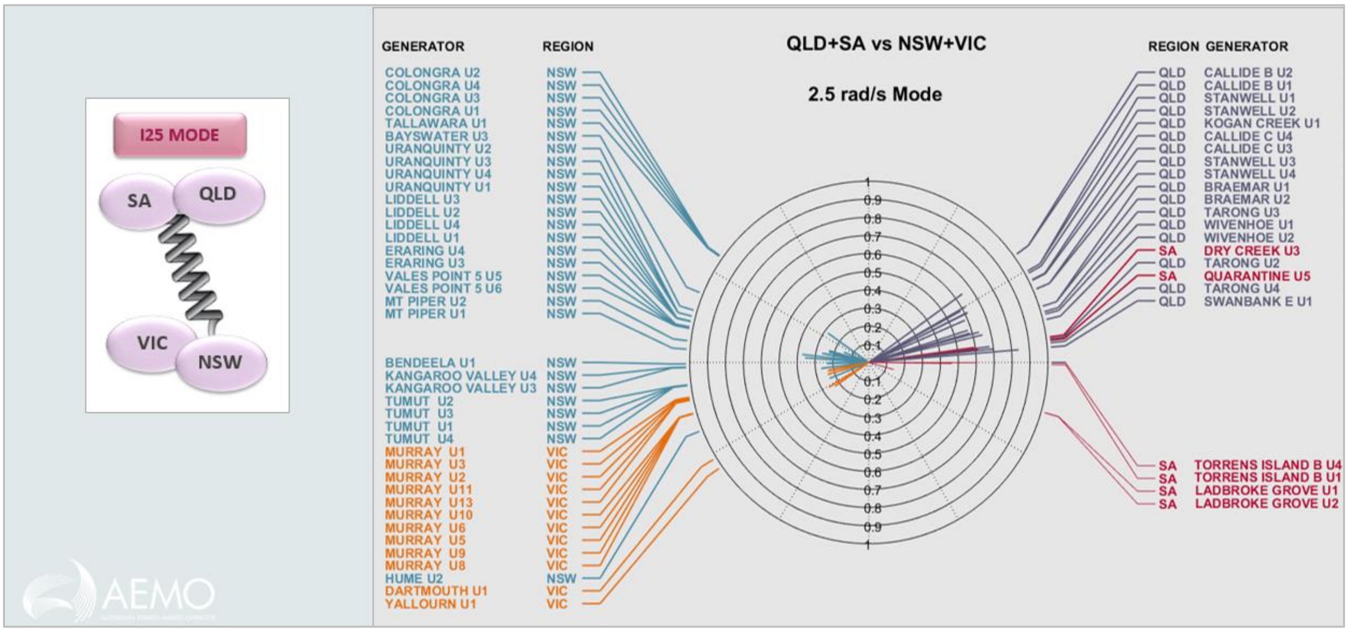

Figure 3: QLD+SA vs NSW+VIC

A2. Appendix 2 Oscillation Events in West Murray Zone

A2.1 Frequency of Oscillation Events in West Murray Zone

The following are the results from October 2020 up to 10 August 2021.

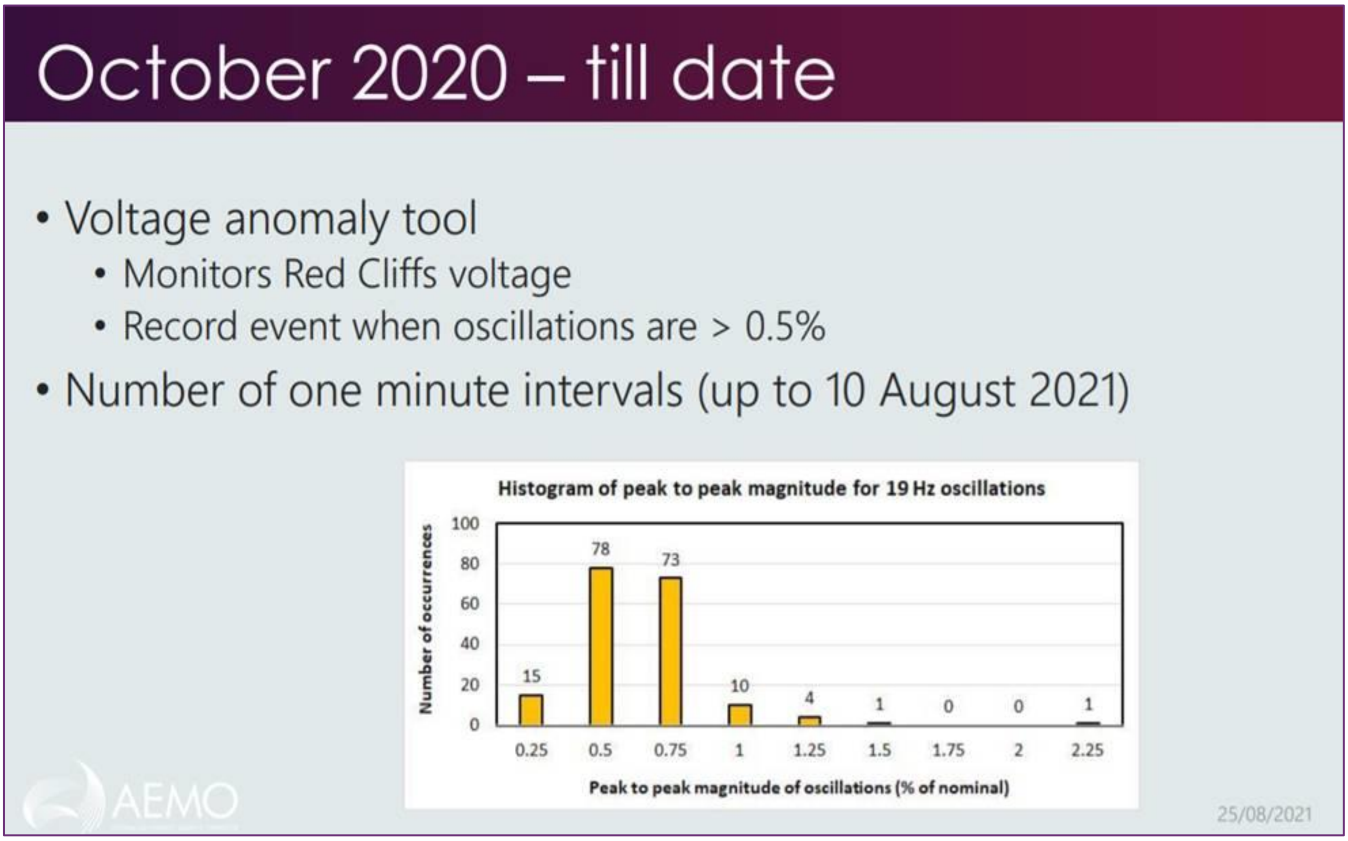

Figure 4: Frequency of oscillation events in West Murray zone

A2.2 Sub-Synchronous Oscillations on 16 November 2021

On the 16th of November there were multiple detections of 20Hz oscillations between 14:40 and 17:12. These were detected after the event using the AEMO voltage oscillation detection tool. The source of the oscillations is still unknown but was likely triggered by an outage of the Wemen 220/66kV transformer on the day.

The magnitude of the oscillations was 0.4% at Redcliffs and 3.9% at Wemen.

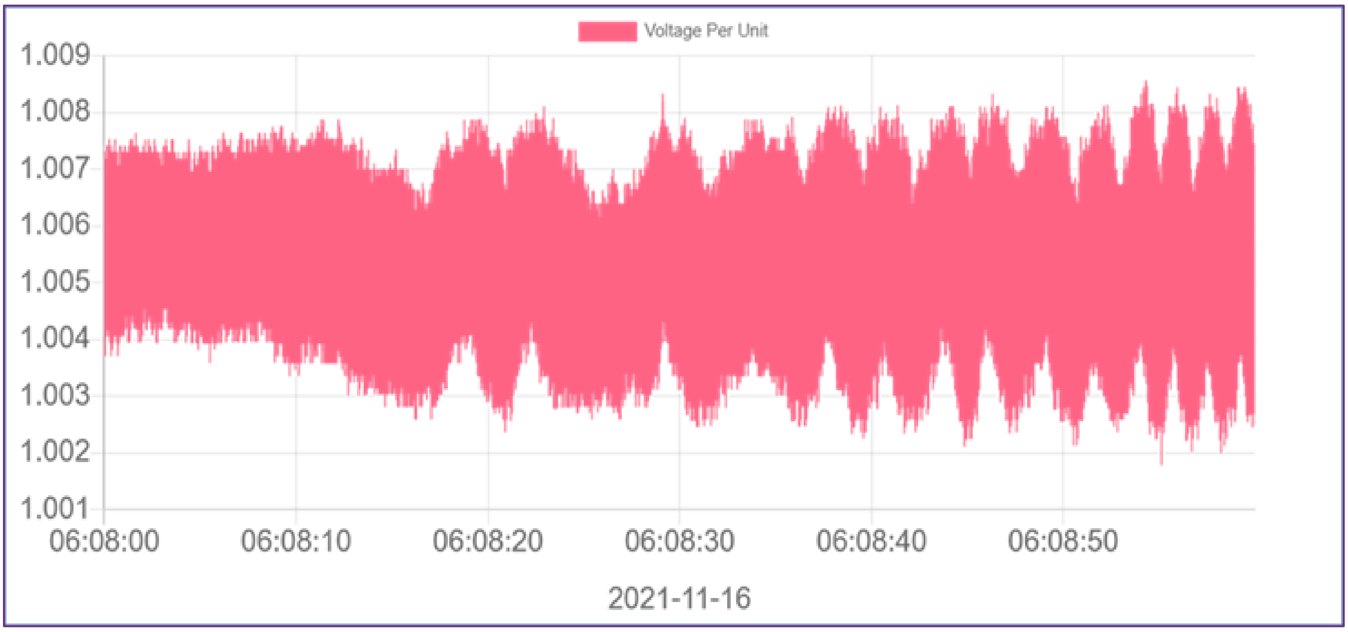

Figure 5: Magnitude of the oscillations at Redcliffs

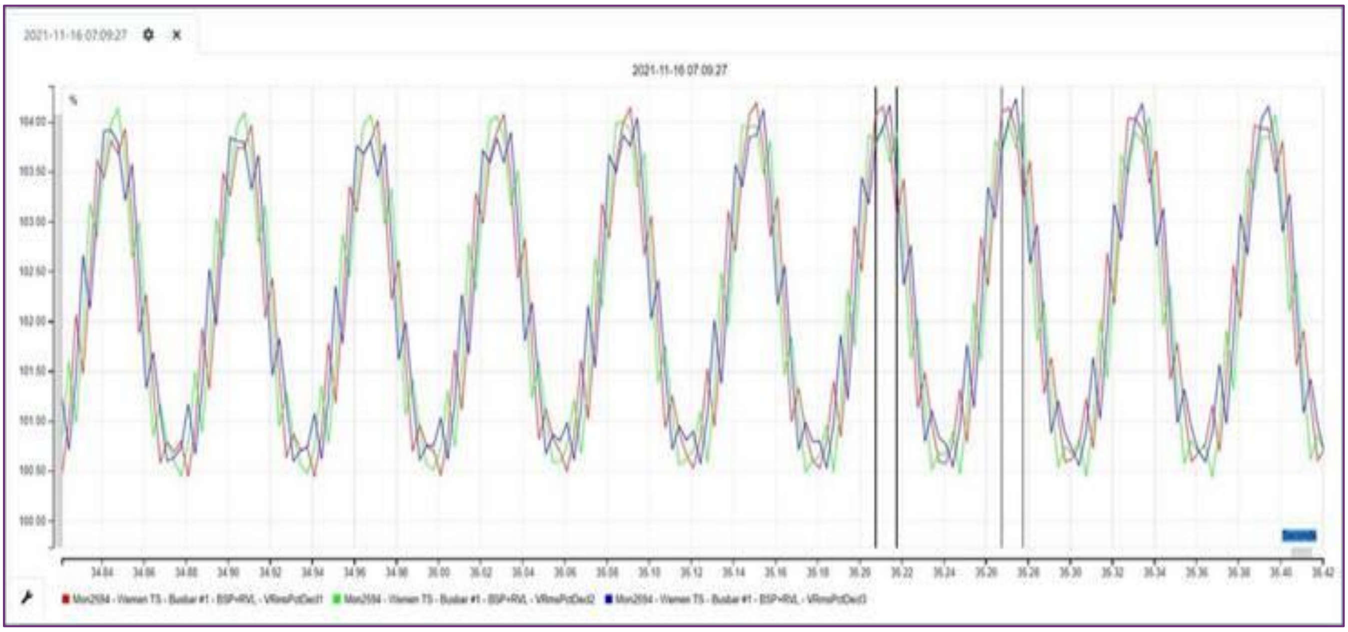

Figure 6: Magnitude of the oscillations at Wemen

A3. Appendix 3 Size of Renewable Energy Zones

The estimates of the generation likely to be impacted for Class 1 Benefits have been estimated from the generation maps

https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/nem-generation-maps

as follows:

- West Murray REZ – 1700 MW – only generation in V2 Murray zone
- North West NSW REZ – 430 MW – only considering Generation connected on 132kV subsystem remote from 330kV connection points
- Central West NSW REZ – 950 MW - only considering Generation connected on 132kV subsystems remote from 330kV connection points
- South West NSW REZ – 1450 MW - only considering Generation connected on 132kV or 220kV subsystems remote from 330kV connection points (excluding Darlington Point)

The estimates of the local load have been estimated from the Transgrid 2021 Annual Planning Report

https://www.transgrid.com.au/media/j2llfv1u/transmission-annual-planning-report-2021.pdf

The average local load has been assumed to be 50% of the annual peak demand as follows:

- North West NSW REZ – about 70 MW – only considering load connected on 132kV subsystem remote from 330kV connection points
- Central West NSW REZ – about 150 MW - only considering load connected on 132kV subsystems remote from 330kV connection points
- South West NSW REZ – about 110 MW - only considering load connected on 132kV or 220kV subsystems remote from 330kV connection points (excluding Darlington Point)

A4. Appendix 4 Initiatives undertaken elsewhere

Initiatives to establishment networks of PMUs have been undertaken by many system operators elsewhere. Some examples of these are:

For South Africa A WAMS contract, awarded in early July 2010, comprised two phases – an initial R10-million design phase and a R21-million production phase involving installation of PMUs at 28 locations on the network around the country. For further details refer https://www.actom.co.za/mv-protection-and-control-divisional-news-wide-area-monitoring-system-for-eskom/.

In North America over the last decade almost 2,000 production-grade PMUs deployed across the United States and Canada, streaming data and providing very high visibility across much of North America's bulk power system. For further details refer Section II in the following report https://www.smartgrid.gov/files/recovery_act/PMU-cost-study-final-10162014_1.pdf

In India one of the largest networks of PMUs is currently being installed. When fully commissioned, it will be the world's largest, comprised of 1,184 Phasor Measurement Units (PMUs) involving 34 control centres across India and 350 substations in the national grid. For further details refer https://www.tdworld.com/substations/article/20971462/india-to-get-wide-area-monitoring-system-ultimately-covering-350-substations

EirGrid has installed a network of 19 PMUs with more to be installed. For further details refer https://www.eirgridgroup.com/site-files/library/EirGrid/Ray%20Doyle.pdf

National Grid (UK) The ESO has established a new policy STC-P 27-1 which mandates all the TOs to install synchronised system monitoring at all their substations to improve the wider system observability by the end of 2026. For further details refer https://www.nationalgrid.com/electricity-transmission/document/132381/download

In Continental Europe there is also an extensive network of PMUs. The following report on a major incident in 2021, shows the key role they play in monitoring and analysing system importance. https://eepublicdownloads.azureedge.net/clean-documents/Publications/2022/entso-e_CESysSep_210724_02_Final_Report_220325.pdf