West Murray Zone Power System Oscillations 2020-2021

February 2023

National Electricity Market

A report on real-time observations from August 2020 to December 2021

Important notice

Purpose

To document real-time observations and subsequent analysis of sub-synchronous oscillations identified in the West Murray Zone from August 2020 through December 2021. It has been prepared by AEMO using information available up to the date of publication, in relation to oscillations occurring up to 28 December 2021.

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All times mentioned in this report are based on Australian Eastern Standard Time (AEST), or Coordinated Universal Time (UCT) + 10, also referred to as Market Time unless otherwise noted.

Version control

Version	Release date	Changes
1.0	17/02/2023	First publication

AEMO acknowledges the Traditional Owners of country throughout Australia and recognises their continuing connection to land, waters and culture. We pay respect to Elders past and present.

Executive summary

The West Murray Zone (WMZ) of the National Electricity Market (NEM) power system spans parts of the interconnected networks in south-west New South Wales and north-west Victoria. Sub-synchronous power system oscillations in the range of 15-20 hertz (Hz)[1] lasting from a few seconds to several minutes have been observed in the WMZ on various occasions, since first identified on 20 August 2020, following a line trip in the WMZ.

The power system oscillations seem to occur both with and without any obvious network disturbances. The magnitude and duration of voltage oscillations are generally low but, in several instances, oscillations have been observed at higher magnitude[2] (range of 1% to 2.2% peak-to-peak Root-Mean-Square [RMS] at the 220 kilovolt [kV] transmission level close to Red Cliffs and Wemen) and longer duration (ranging from a few minutes to 45 minutes).

After the oscillations were first identified in August 2020, AEMO developed a bespoke tool that monitors high resolution power system quantities at Red Cliffs Terminal Station (RCTS) 220 kV and captures intervals with sub-synchronous voltage oscillations. More recently, AusNet and Powercor have installed monitors around Wemen Terminal Station (WETS) that can capture high resolution GPS synchronised data.

Sub-synchronous oscillations are characterized by power system oscillations below the fundamental frequency (50 Hz), including network voltage and current.

This report documents AEMO's analysis of real time observations gathered in relation to five separate instances of poorly damped network voltage oscillations up to a magnitude of 2.2% peak-to-peak RMS at RCTS 220 kV.

Although, the present nature of observed power system oscillations is not an immediate threat to power system security, it is important to comprehensively understand this phenomenon and its relationship with a number of power system elements, as undamped oscillations in the power system are not desirable. They have the potential to cause voltage waveform instability and create resonances, which can lead to uncontrolled tripping and damage of power system equipment. With increasing penetration of wind and solar generation within WMZ, the problems can further be exacerbated under weak grid conditions. While it has not yet been possible to establish a clear cause or causes for oscillations in WMZ, the findings to date indicate a number of potential contributing factors, and other factors that appear to have no clear correlation with the oscillations.

Key findings to date

All evidence to date points to the oscillations being contained in the area to the west of Bendigo and Darlington Point. The largest magnitude of oscillations has been observed around the Wemen area.

The oscillations were observed during an outage of the Red Cliffs to Buronga 220 kV line (OX1 line) and during periods when Murraylink DC (MLDC) was disconnected, indicating the likely source of oscillations within north-west Victoria.

[1] The observed frequency range of 15-20 Hz is based on RMS data. Therefore, the instantaneous three-phase measurements will have oscillations in the range of 50 ± (the observed frequency in RMS plots) Hz, please see note in Appendix A1.

[2] As a reference, 7.5 Hz frequency of voltage oscillation on the Pst=1 curve from Appendix A of IEC 61000-3-7 corresponds to a 0.3% limit on % RMS peak-to-peak voltage change assuming rectangular characteristics and 900 changes/minute.

For a few instances, where a large magnitude of oscillation was observed, AEMO analysed the total reactive power (Q) and RMS voltage (V) relationship of online generating units in the region. It is difficult to draw conclusive findings from these observations alone, and it is also noted that Yatpool solar farm was not commissioned when the oscillations were identified by AEMO on 20 August 2020.

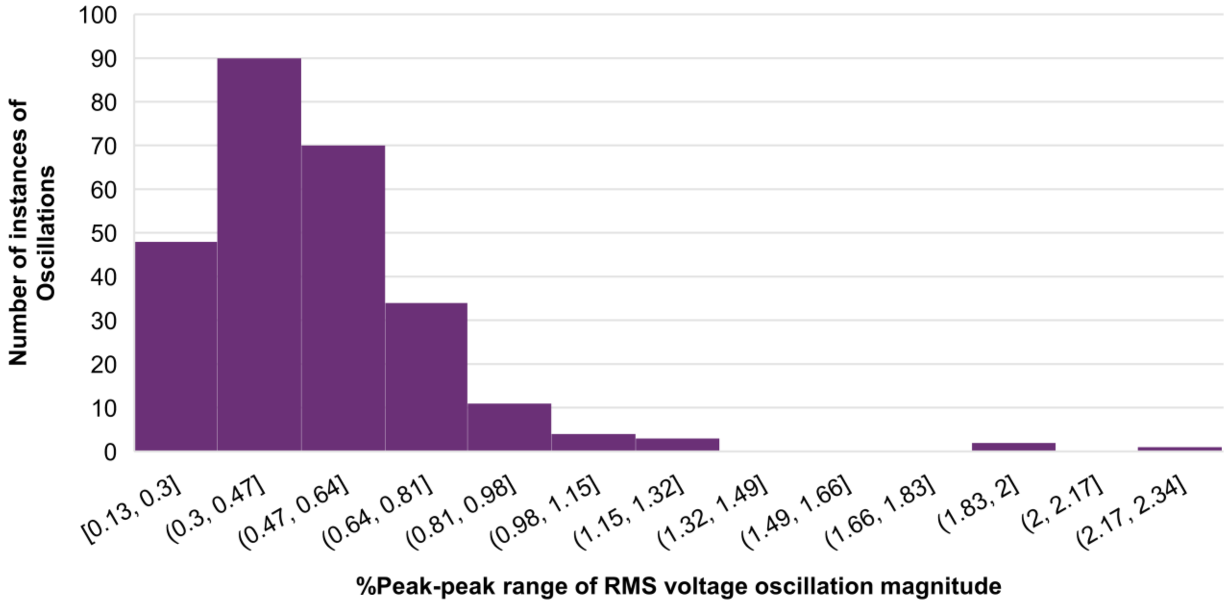
During periods when reduced numbers of inverters from solar farms were online, the oscillations were still present, but the observed magnitude was distinctly lower.

In three of the five cases studied, oscillations were observed when Wemen solar farm was either disconnected, tripped or not generating active power.

For the sub-synchronous oscillations detected on various occasions, load ramping at Wemen, Boundary Bend, Ouyen, Mildura and Merbein zone substations were analysed. However, to-date, no clear correlation has been established between the onset or presence of oscillations and the ramping of loads in the region.

A summary of oscillations observed (from August 2020 to December 2021) at RCTS 220 kV is shown in Figure 1 below.

Figure 1 Summary of oscillations observed at Red Cliffs Terminal Station 220 kV, August 2020 to December 2021



AEMO, in collaboration with AusNet and Powercor, continues to monitor and investigate the oscillations in the WMZ region. Further investigation is ongoing, including installation of additional high-speed monitoring devices across the network and desktop analysis to investigate solutions.

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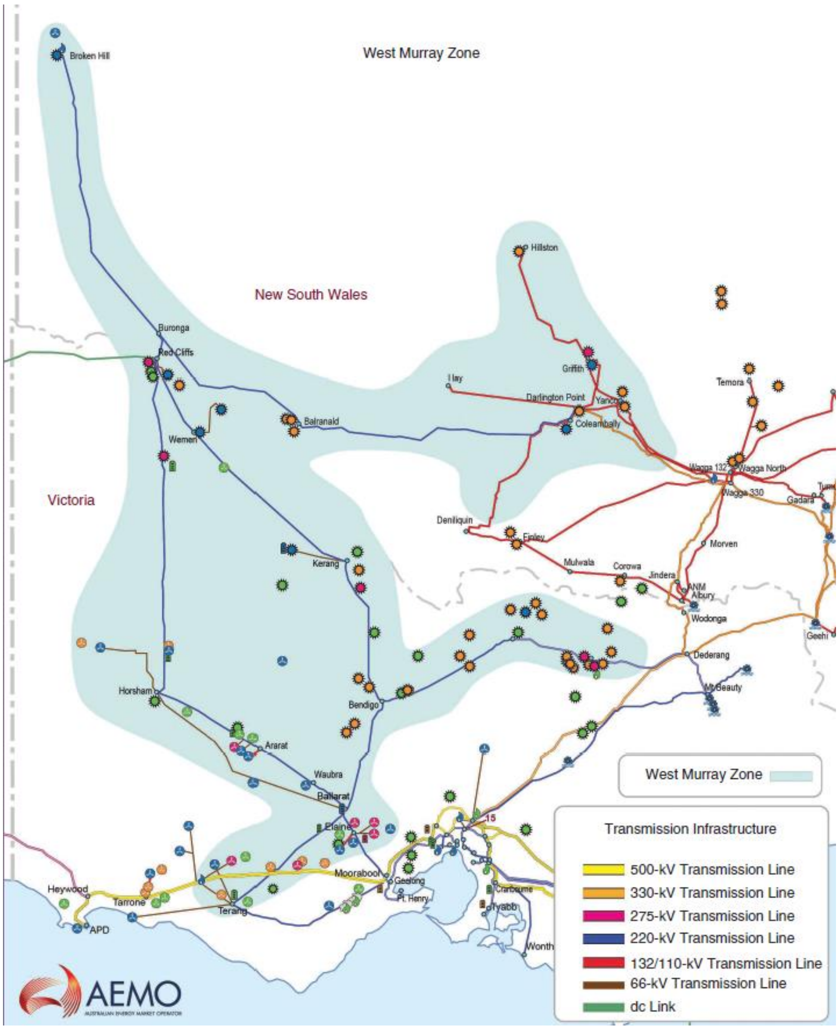
1 Introduction

1.1 Background

The West Murray Zone (WMZ) is an area of the National Electricity Market (NEM) that encompasses the interconnected transmission and distribution networks in south-west New South Wales and north-west Victoria, as indicated in Figure 2[3]. The region has seen unprecedented integration of renewable inverter-based resources (IBR), all using grid-following technology, in the past few years, and several more large-scale IBR connections are expected in the area. The area has been historically low in system strength, owing to low synchronous fault levels due to its remoteness from major synchronous generators in Victoria and New South Wales. These two factors – remoteness to synchronous generation coupled with high penetration of IBR – have resulted in some technical operational challenges in this region. One of these challenges, the occurrence of sub-synchronous oscillations, is the focus of this report.

Figure 2 West Murray Zone



[3] More information on the WMZ is available on AEMO's website at: https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/west-murray

Although the present nature of these oscillations has not posed an immediate system security risk, the presence of undamped oscillations in the power system is not desirable. This can lead to uncontrolled disconnection or tripping of IBR generators due to voltage waveform instability and potentially create system resonant conditions, which could then further damage power system equipment. Moreover, as the penetration of IBR resources continue to increase in WMZ, these problems can be further exacerbated during weak grid conditions. Hence, it is necessary to identify and mitigate undamped sub-synchronous oscillations. This report documents AEMO's analysis of a few key incidents based on real-time observations, where sub-synchronous oscillations have occurred in the WMZ region between August 2020 and December 2021.

1.2 Voltage oscillations in WMZ during 2018-19

In 2019, sustained post-disturbance voltage oscillations with a dominant frequency of 7-12 Hz[4] were observed in electromagnetic transient (EMT)-type simulations in the WMZ.

These oscillations were identified in AEMO's studies[5] to be mainly caused by a few IBR in the area, following the loss of a transmission line.

The simulated oscillations were proven to be real later in 2019, through staged tests on the actual network. AEMO's studies also showed that by limiting the active power dispatch of these IBR alone, the magnitude of oscillations cannot be adequately reduced. Hence, a constraint on the number of online inverters was applied for the IBR involved, which was shown in the simulations to be effective in limiting the magnitude of post-disturbance voltage oscillations to an acceptable level.

In 2020, AEMO – in collaboration with the IBR and Powercor – developed a proposal for tuned inverter control system parameters for the IBR involved, which were shown in the simulations to be able to resolve the voltage oscillations to a large extent. The tuned parameters were implemented on the control systems of the IBR by April 2020, and staged tests on the actual network verified the effectiveness of the tuned parameters in damping the voltage oscillations. Following the implementation of the tuned parameters, the constraint on number of inverters for the above IBR was removed.

Since then, WMZ has observed a further integration of grid-following IBR as well as a few synchronous condensers, installed as system strength remediation measures for some IBR. Despite the tuning solution implemented on IBR and the system strength contribution of the installed synchronous condensers, the WMZ has been experiencing different system strength related issues, primarily intermittent sub-synchronous oscillations in the 15-20 Hz range, with and without any obvious network disturbances.

[4] All frequencies mentioned in this report refer to measurements based on root mean square (RMS) power system quantities, primarily voltage. The instantaneous three-phase waveforms would have frequencies in the range of 50 ± (observed RMS frequencies) Hz, please see note in Appendix A1.

[5] A. Jalali, B. Badrzadeh, J. Lu, N. Modi, and M. Gordon, "System strength challenges and solutions developed for a remote area of Australian power system with high penetration of inverter-based resources," Published in CIGRE Sci. Eng. J., pp. 27–37, Feb. 2021.

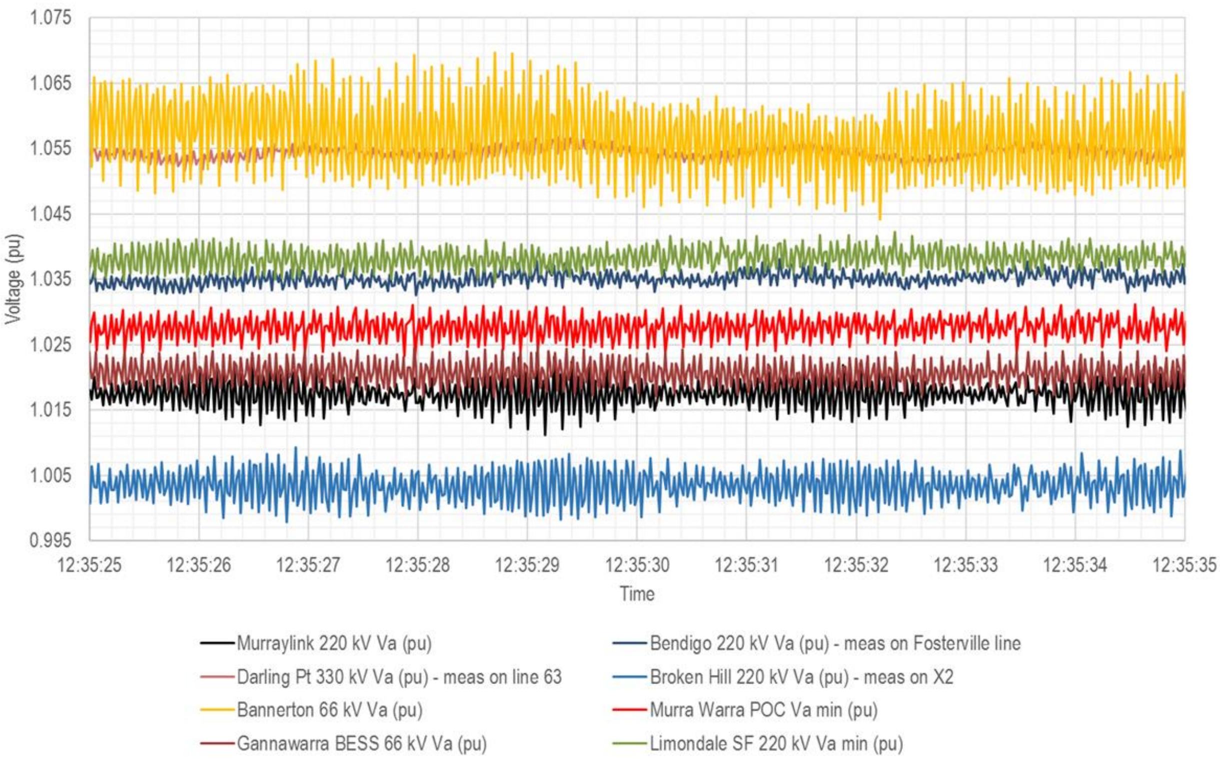
2 20 August 2020 event

2.1 Line trip (no-fault) event on 20 August 2020

This was the first instance, after the mitigation measures were implemented in April 2020, when AEMO again observed sub-synchronous oscillations in the WMZ region. A high-level summary of the event is as follows:

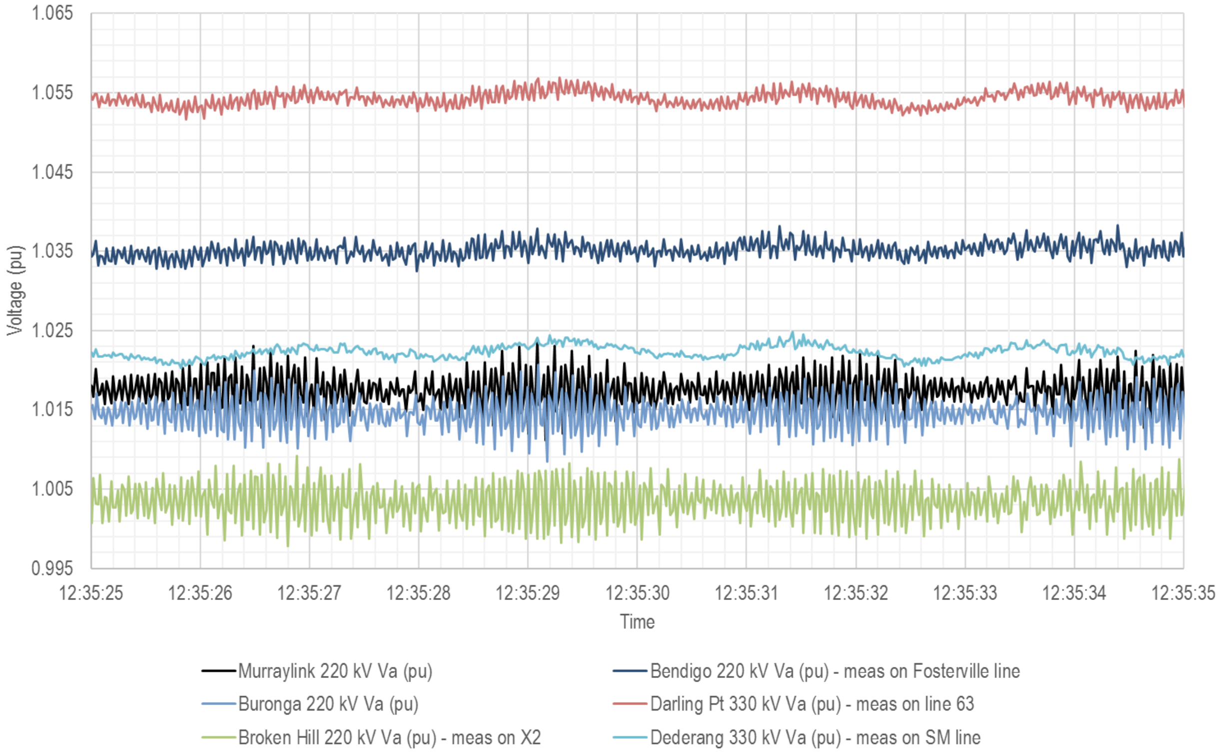
- At 1235 hrs on 20 August 2020, the Ararat – Crowlands 220 kilovolts (kV) line (ARTS-CWTS line) tripped, which resulted in operation of the Generator Fast Trip (GFT) control scheme. The operation of the GFT control scheme tripped the Crowlands and Bulgana wind farms and designated feeders at the Murra Warra wind farm (WF), resulting in the automatic disconnection of 184 megawatts (MW) of generation. The incident also resulted in an unexpected trip of the Wemen solar farm (SF), resulting in loss of another 63 MW of generation. In total, 247 MW of generation output was disconnected as a result of this incident.
- It was confirmed that the trip of ARTS-CWTS line was due to an incorrect line differential protection setting and there was no fault on the line.
- Within a few seconds after the ARTS-CWTS line trip, oscillations around 19 Hz were observed for approximately 30 seconds, with magnitude around 0.65% peak-to-peak RMS at Red Cliffs Terminal Station (RCTS) 220 kV. The maximum magnitude of oscillations occurred at Bannerton 66 kV.
- Analysis of this event helped conclude that the oscillations were mostly contained within the WMZ region (west of Bendigo and Darlington Point), as shown based on magnitude of oscillations observed at Bendigo and Darlington Point in Figure 3 and Figure 4.

Figure 3 West Murray RMS voltages at 1235 hrs on 20 August 2020



BESS: battery energy storage system Va: Phase A to ground average RMS voltage Va min: minimum value of Va in the measurement cycle

Figure 4 West Murray RMS voltage oscillations on 20 August 2020 contained to the west of Darlington Point and Bendigo



2.2 Immediate operational measures

After the event on 20 August 2020, the following measures were implemented:

- Incorrect trip settings for the ARTS-CWTS line were rectified to prevent relay maloperation.
- Wemen SF vector shift protection and anti-islanding scheme settings were disabled to prevent maloperation.

In addition to the above, AEMO started monitoring WMZ with the help of existing monitors. During the monitoring period, oscillations were observed even without any disturbances [6]:

- Measurements around 1520 hrs on 21 August 2020 indicated the presence of 19 Hz voltage oscillations at RCTS 220 kV, with a magnitude of up to 0.7% peak-to-peak RMS (see Figure 5).
- Measurements around 1258 hrs on 2 September 2020 indicated the presence of 19 Hz voltage oscillations at RCTS 220 kV with a magnitude of up to 1.8% peak-to-peak RMS (see Figure 6).

[6] The available data for some quantities only included Va min (minimum) or Va avg (average) quantities. However, the main purpose of Figure 5 and Figure 6 is to highlight the presence of latent oscillations around RCTS 220 kV (including Bannerton and Wemen 66 kV) and Broken Hill 22 kV, even without any disturbance.

Figure 5 West Murray RMS voltage oscillations around 1520 hrs on 21 August 2020

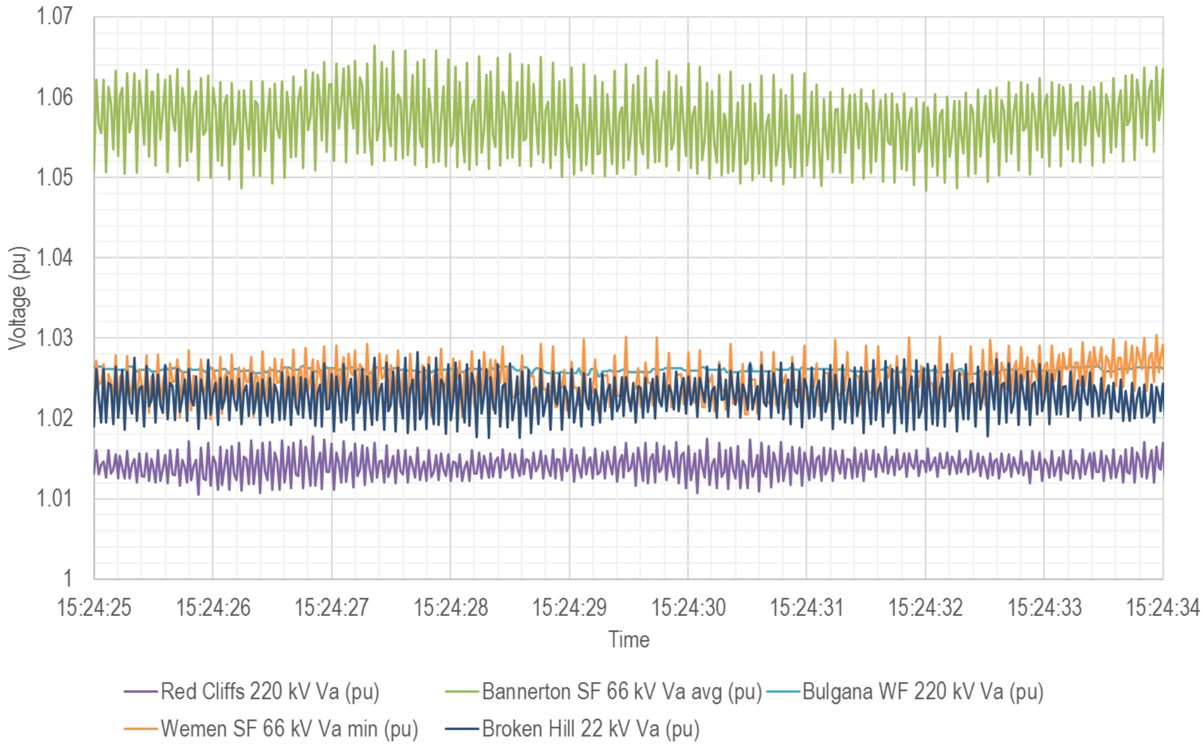
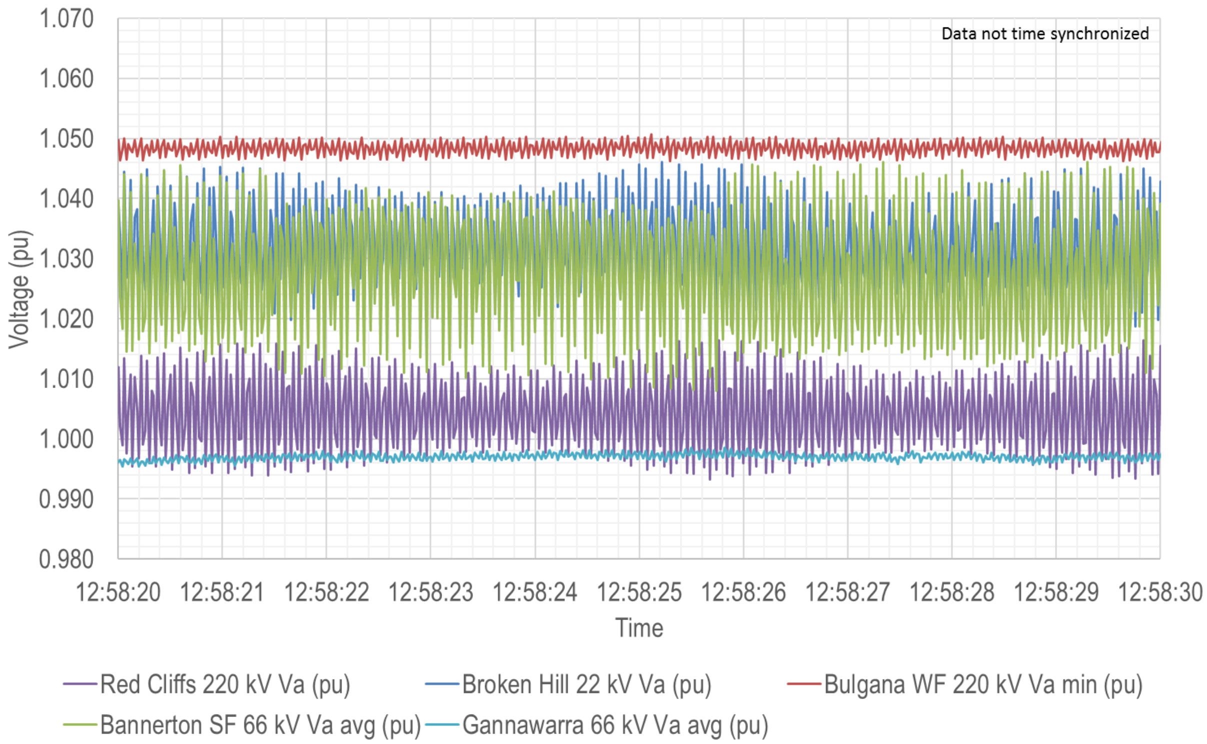


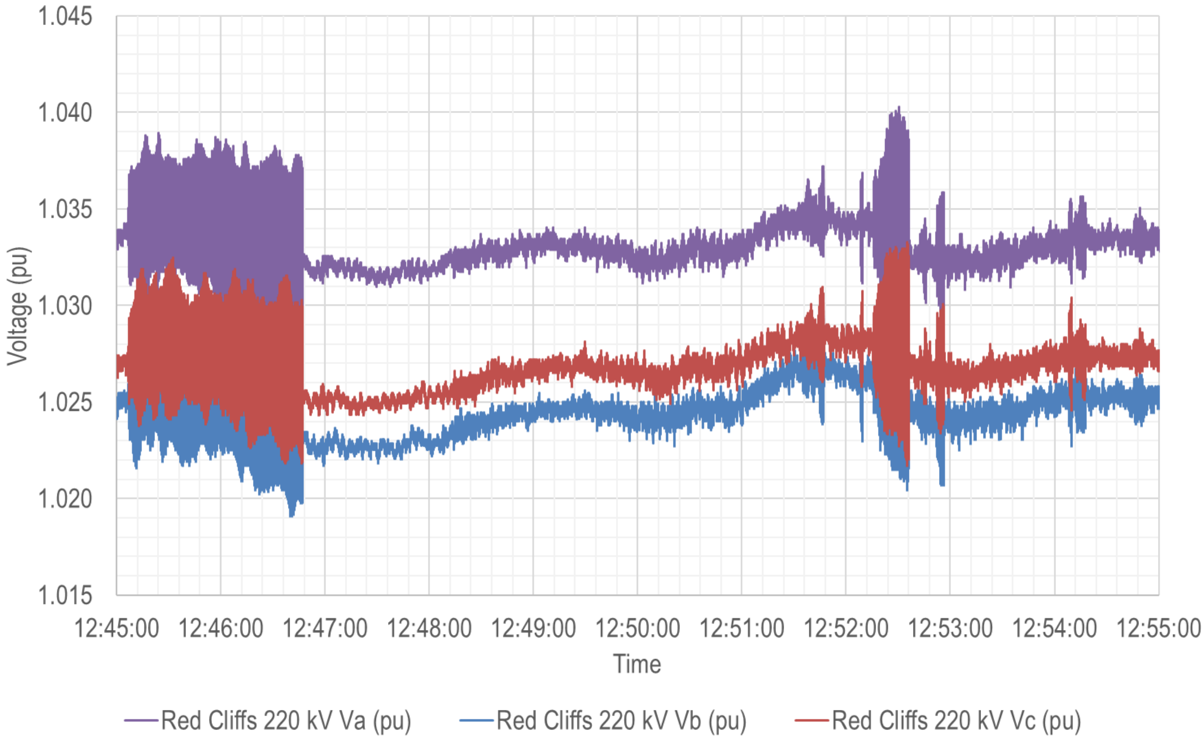
Figure 6 RMS voltage oscillations around 1258 hrs on 2 September 2020



2.3 Impact of Horsham SVC on manual mode

While the investigation of the oscillations was ongoing, Horsham static var compensator (SVC) was placed on manual mode from the evening of 3 September 2020 to isolate whether the SVC control mode was initiating this event. On 4 September 2020, 0.78% to 0.93% peak-to-peak voltage oscillations were observed at RCTS 220 kV, as shown in Figure 7. This helped rule out the role of Horsham SVC automatic voltage controller as a primary source of initiating the oscillations.

Figure 7 Red Cliffs 220 kV RMS voltage oscillations on 4 September 2020 with Horsham SVC in manual mode



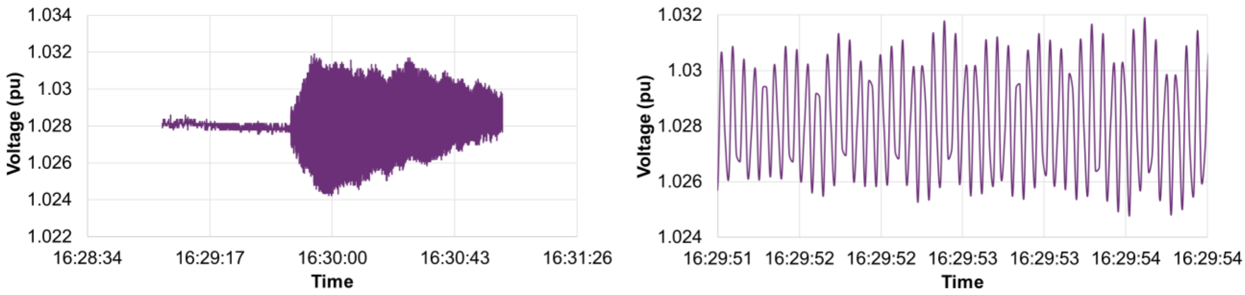
2.4 Murraylink DC (MLDC) out of service

The MLDC station circuit breaker CB6077 status connection to Monash substation was monitored as open (and transferring 0 MW) on a few occasions, as shown in Table 1, yet oscillations were observed. Maximum peak-to-peak RMS voltage oscillations of up to 0.9% with a frequency of approximately 18 Hz were observed at RCTS 220 kV around 1629 hrs on 29 July 2021, as shown in Figure 8, for a duration of 85 seconds with MLDC out of service. This helped rule out MLDC as a primary source of the oscillations.

Table 1 Sub-synchronous oscillations during periods of MLDC CB6077 open (Red Cliffs 220 kV voltage)

Date and time	Frequency of oscillations [Hz]	% Peak-to-peak voltage magnitude (max)	Duration [s]
15/09/2020 16:30:00	18	0.78	40
16/09/2020 13:00:35	20	0.39	17
23/09/2020 10:53:46	20	0.28	20
04/10/2020 11:00:20	20	0.45	160
06/10/2020 10:46:07	20	0.38	40
03/05/2021 15:03:47	19	0.55	28
13/05/2021 10:52:11	19	0.71	185
29/07/2021 16:29:44	18	0.9	85

Figure 8 Red Cliffs 220 kV RMS voltage oscillations around 1629 hrs on 29 July 2021 with MLDC out of service



2.5 Key takeaways

Key observations are:

- Based on the 20 August 2020 event, it is evident that the sub-synchronous oscillations in the 19 Hz range occurred even with the complete tripping of Crowlands WF, Bulgana WF, and Wemen SF. Hence, it is unlikely that these IBR plants initiated the oscillations during this event.
- The magnitude of voltage oscillations at Bendigo 220 kV, Darlington Point 330 kV and Dederang 330 kV were seen to be relatively small compared to the oscillations seen at Buronga 220 kV and Broken Hill 220 kV. Hence, it is likely that the oscillations are contained to the west of Bendigo and Darlington Point. Among IBR locations, the maximum magnitude of oscillations was observed within the 66 kV sub-transmission system around Wemen during this event.
- Further monitoring of latent oscillations also confirmed the presence of these oscillations even without any switching or disturbances in the power system.
- The oscillations were found to exist even during periods when the Horsham SVC was set in manual mode of operation, confirming that the automatic voltage regulator function of Horsham SVC was not the primary source for initiating these oscillations.
- Similarly, the oscillations were also identified during several instances when MLDC was out of service, based on monitoring of real-time RMS voltage measurements at RCTS 220 kV. This confirms that MLDC was not the primary source for initiating these oscillations.

3 25 May 2021 event

On 25 May 2021, there was a planned outage of a 220 kV line between Red Cliffs and Buronga. This line electrically disconnects south-west New South Wales and north-west Victoria. Around 1518 hrs, voltage oscillations of magnitude up to 2.2% peak-to-peak RMS with a frequency of around 16.5 Hz were observed at RCTS 220 kV. These oscillations were observed for approximately 12 minutes. Coincidentally, on 25 May 2021 around 1330 hrs, Queensland experienced a major disturbance with tripping of Callide generator units. Power system restoration was in progress, however, there is no correlation between the Queensland incident and observed voltage oscillations in north-west Victoria.

In addition to the 16.5 Hz oscillations, there was a 0.75 Hz over-riding frequency component (Figure 9) in the overall response (a similar trend was observed during the August 2020 event – see Figure 4). The frequency of 0.75 Hz suggests some latent low frequency power system electromechanical oscillations, which is not an unusual aspect of the NEM power system. Figure 9 shows the observed oscillations at RCTS 220 kV. Figure 10 on the other hand, at Buronga 220 kV and Broken Hill 220 kV, does not show significant voltage oscillations.

Figure 9 Red Cliffs 220 kV RMS voltage oscillations around 1518 hrs on 25 May 2021 for 12 minutes

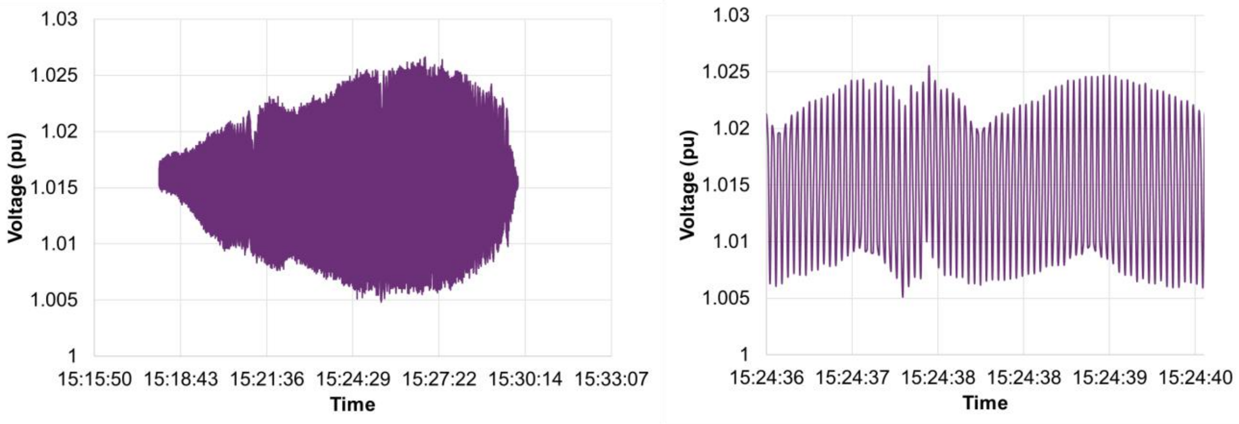
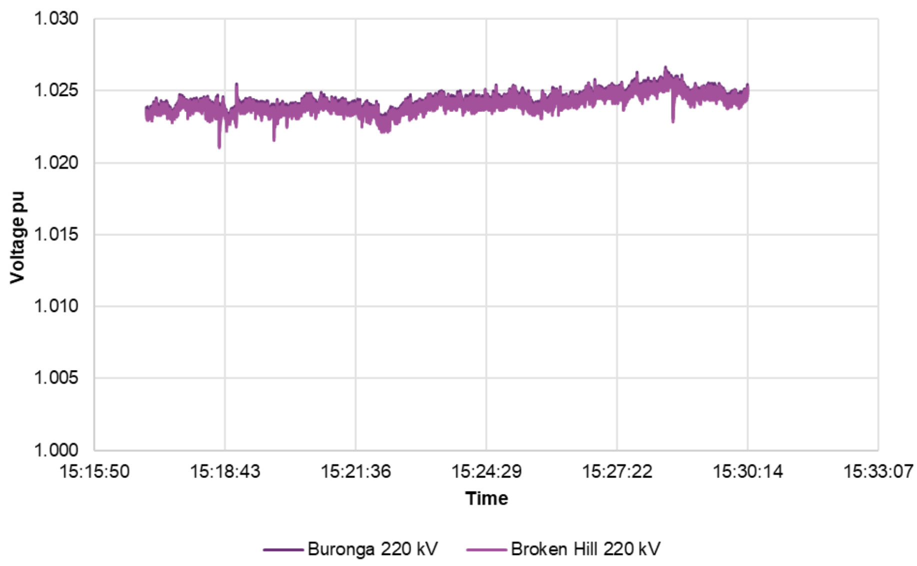


Figure 10 RMS voltage at Buronga 220 kV and Broken Hill 220 kV around 1518 hrs on 25 May 2021



3.1 Key takeaways

The key observation is that the oscillations shown in Figure 9 were observed at RCTS 220 kV bus around 1518 hrs on 25 May 2021, however, no oscillations were observed at Buronga 220 kV or Broken Hill 220 kV, as confirmed in Figure 10. Therefore, the outage of OX1 line during the above timeframe suggests that the sub-synchronous oscillations were likely to be contained in north-west Victoria and that the IBR plants in New South Wales are not the primary source for initiating these oscillations.

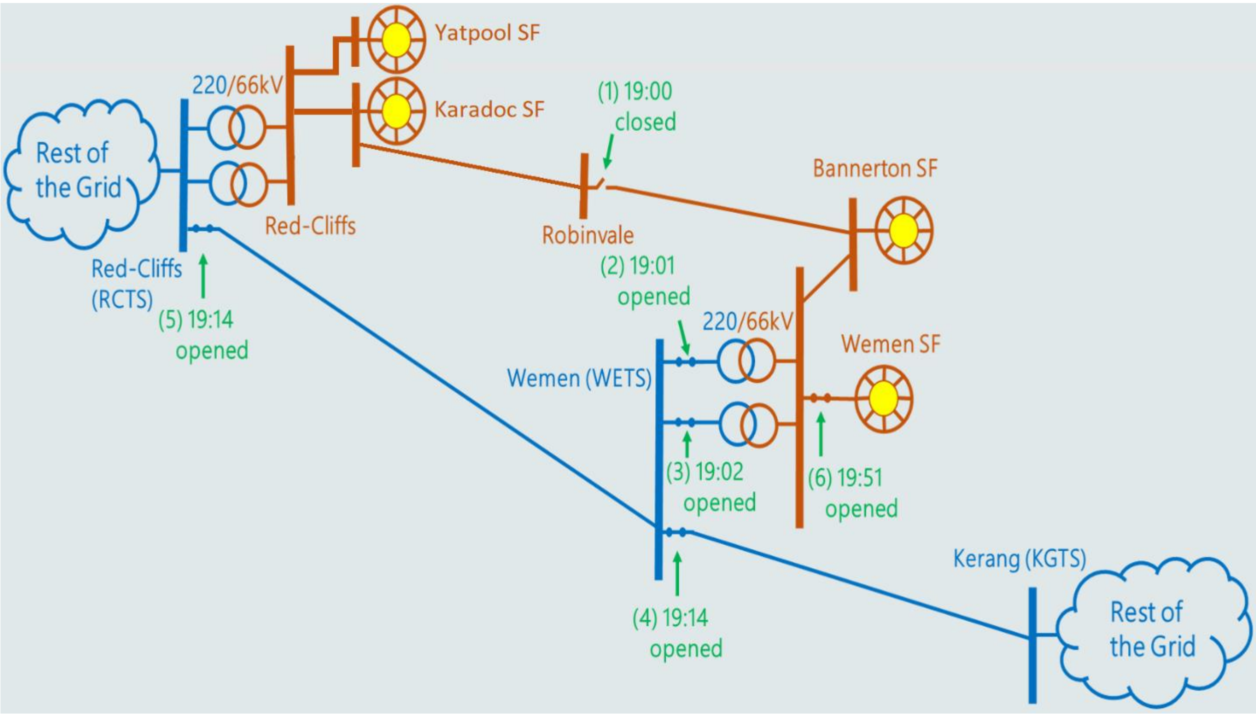
4 11 August 2021 event

At around 1900 hrs on 11 August 2021, the 66 kV breaker connecting Robinvale to Bannerton SF was closed, followed by disconnection of Wemen Terminal Station (WETS) 220/66 kV transformers (B1TR and B2TR) from the 220 kV network as shown in Figure 11. Further to this, the WETS-RCTS and WETS – Kerang Terminal Station (KGTS) 220 kV transmission lines were opened at 1914 hrs.

During this switching event, sub-synchronous oscillations were observed at RCTS 220 kV starting at 1902 hrs. The switching of WETS-RCTS and WETS-KGTS 220 kV transmission lines at 1914 hrs did not have any major impact on the oscillations, as shown in Figure 12 and Figure 13. Wemen SF started to switch out the inverters at 1946 hrs, and at 1951 hrs the Wemen SF 66 kV circuit breaker was opened. The oscillations stopped around 1946 hrs. Wemen SF was in Q-on-Demand mode during this event. Given the time of this incident, Wemen SF was only generating around 2 MW of active power and Bannerton SF was only generating around 0.5 MW.

Oscillations were in the range of 16.5 Hz, with a maximum peak-to-peak magnitude of 0.85% and lasted for 45 minutes as measured at RCTS 220 kV station. Analysis of ELSPEC data (Figure 14 and Figure 15) obtained at 66 kV Point of Connection (PoC) indicated that the Q and V oscillations were mostly in-phase at Wemen SF. However, the Q and V relationship at Bannerton SF was not consistent (in-phase and out-of-phase) during this event. Further, as seen in Figure 16, the magnitude of oscillations at Wemen SF seemed to be higher during this event, around 5% compared to less than 1% at nearby Karadoc SF[7].

Figure 11 Power system single-line schematic around Wemen Terminal Station



[7] The magnitude of oscillations at PoC of Kiamal SF was also verified and found to be around 0.2%, which is much smaller in magnitude than the oscillations observed at Wemen SF during this event. No data was available for Murra Warra WF for this event.

Figure 12 Red Cliffs 220 kV RMS voltage oscillations around 1902 hrs on 11 August 2021

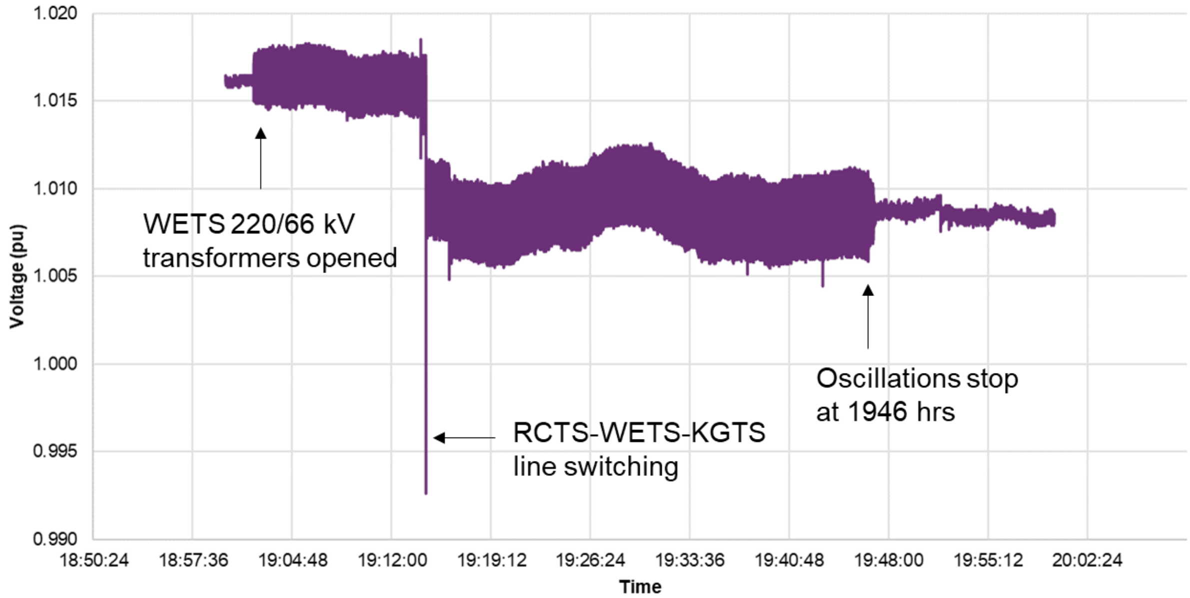


Figure 13 Red Cliffs 220 kV RMS voltage oscillations around 1914 hrs on 11 August 2021

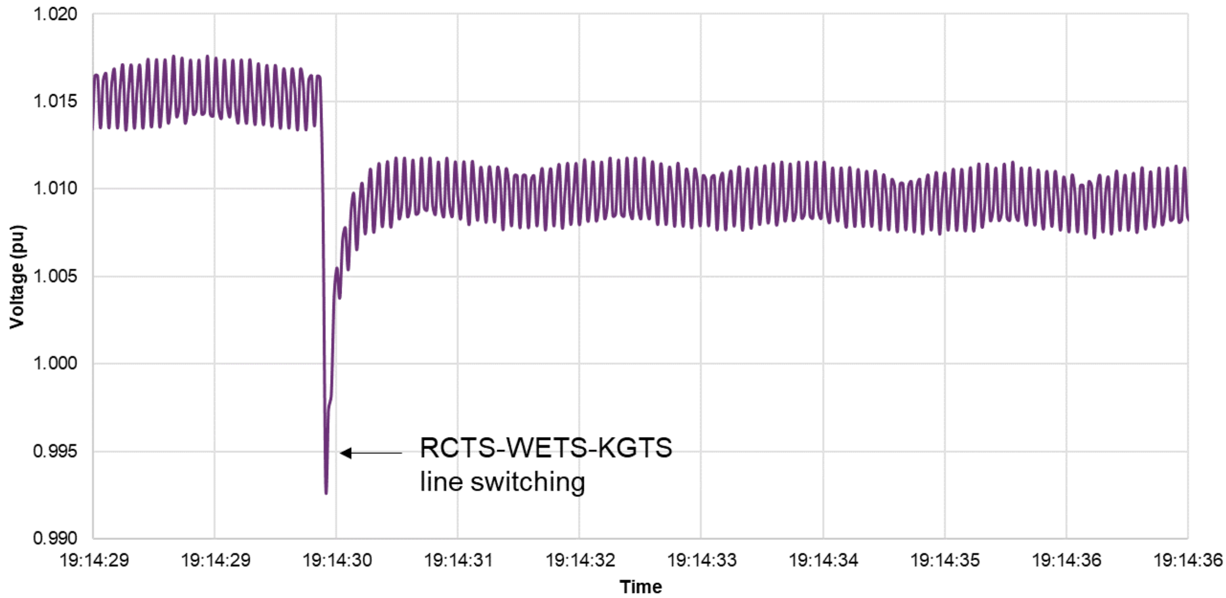


Figure 14 Wemen Solar Farm, 11 August 2021 event, Q and V are in-phase

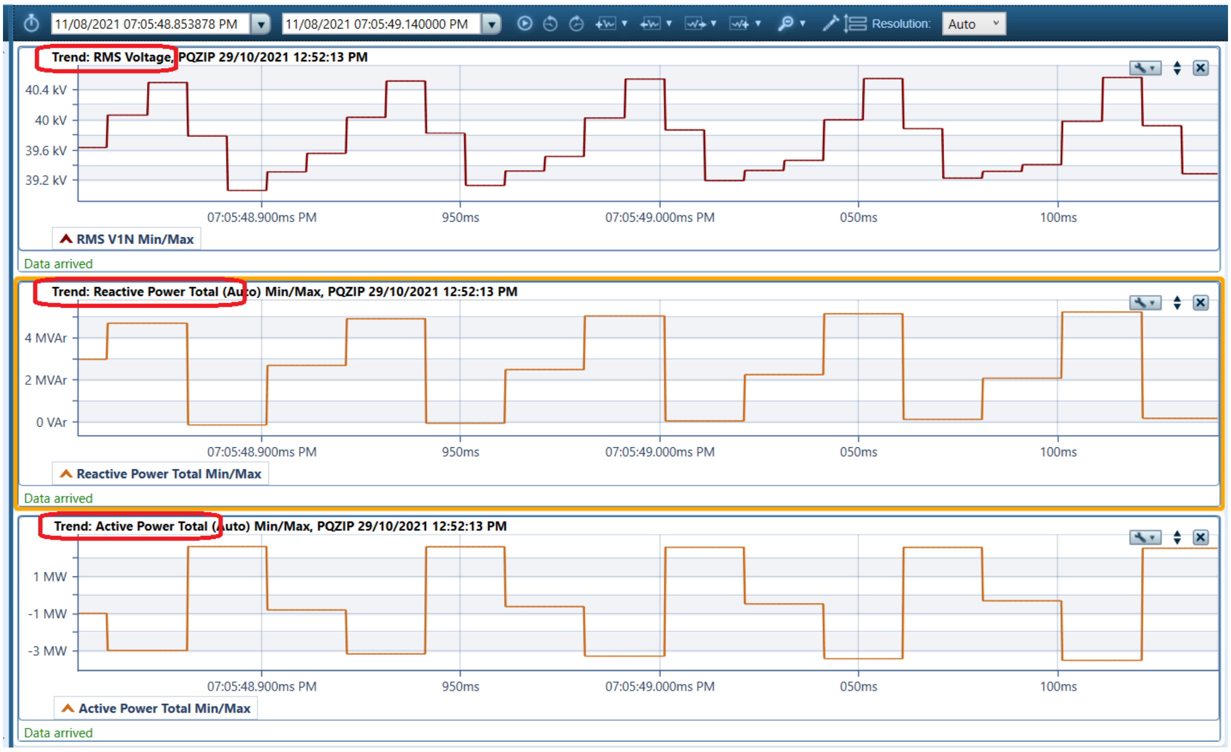
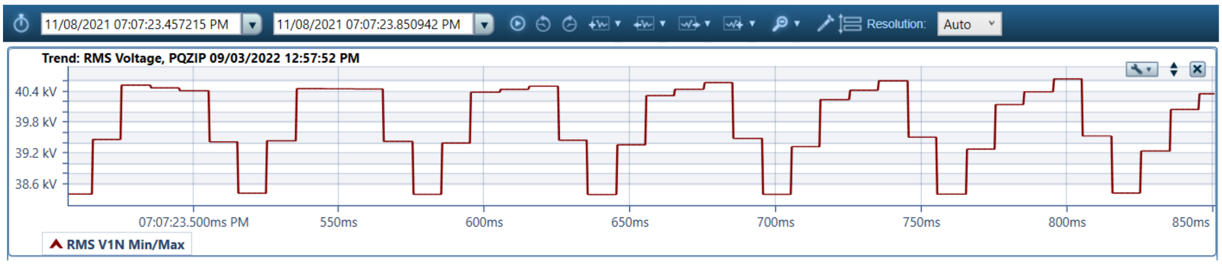


Figure 15 Bannerton Solar Farm, 11 August 2021 event, Q and V relation in and out of phase

Figure 16 Wemen SF and Karadoc SF, comparing the oscillations magnitude, 11 August 2021 event

PoC of Wemen SF (5.5% oscillations magnitude)



PoC of Karadoc SF (<1% oscillations magnitude)

4.1 Key takeaways

Key observations are:

- The opening of the WETS 220/66 kV transformers (B1TR and B2TR) left the Wemen SF and Bannerton SF connected via 66 kV to the RCTS 220/66 kV bus. The opening of RCTS-KGTS-WETS 220 kV lines did not have any major impact on the oscillation magnitudes. As Gannawarra SF and BESS are connected near KGTS 220 kV the disconnection of this line likely removes the contribution or role (if any) from Gannawarra SF and BESS to the ongoing oscillations.
- Given the time of the day, around 1900 hrs on 11 August 2021, most of the solar plants in the area were generating less than a few MW and were moving from normal feed-in operation, when generating active power, to Q-on-demand or Q@night mode.
- Wemen SF had inverters online, however considering the time of day of this event, they were all being switched out and completely offline at 1946 hrs, which was coincident with the reduction seen in the oscillations at RCTS 220 kV. Bannerton SF was confirmed to have only four inverters online during this event. However, this does not necessarily indicate that Wemen SF was the primary source for the oscillations; as highlighted during the 20 August 2020 and 16 November 2021 events, the oscillations at RCTS 220 kV continued despite tripping of inverters at Wemen SF during those events.
- The response of wind plants in the region, such as Bulgana WF and Crowlands WF, did not show any significant oscillations (< 0.1% magnitude peak-to-peak RMS) in the voltages obtained at their respective PoC.
- Analysis of ELSPEC data obtained at 66 kV PoC of Wemen and Bannerton SF indicated that the Q and V oscillations were in-phase at Wemen SF, however the relation was not as consistent with Bannerton SF during this event. Also, the magnitude of oscillations seen at the PoC of Wemen SF and Bannerton SF was higher during this event than oscillations observed at PoC of nearby Karadoc SF.

5 16 November 2021 event

At around 0605 hrs on 16 November 2021, sub-synchronous voltage oscillations in the range of 18 Hz were detected at RCTS 220 kV and lasted for approximately 37 minutes, with the maximum peak-to-peak voltage magnitude of 1.94%, as shown in Figure 17.

At around 0613 hrs, as seen in Figure 18, it was confirmed that 35 inverters at Wemen SF tripped. They subsequently started going through their internal checks and started returning to service between 0615 hrs and 0640 hrs. The entire plant was operational by 0645 hrs.

WETS 220/66 kV transformer B2TR was out of service for maintenance during this event, which resulted in reduced system strength around Wemen and Bannerton area.

ELSPEC data obtained at 66 kV PoC of Wemen SF and Bannerton SF was analysed for two different snapshots – one before the tripping of Wemen SF inverters at around 0610 hrs (Figure 19 and Figure 20), and a second snapshot at around 0627 hrs (Figure 21 and Figure 22) after the tripping of Wemen SF inverters. Analysis of this data indicated that Bannerton SF presented in-phase behaviour between Q and V oscillations during the 0610 hrs snapshot, however, the response was both in-phase and out-of-phase for the 0627 hrs snapshot. The response of Wemen SF was both in-phase and out-of-phase.

From the evening of 17 November 2021, AEMO applied a constraint of 38% of inverters online (around 15 inverters) at both Wemen and Bannerton SF, while one of the WETS 220/66 kV transformers was out of service for maintenance. During this period, after applying the constraint, no significant oscillations were observed.

Figure 17 Red Cliffs 220 kV RMS voltage oscillations, 0600 hrs to 0700 hrs on 16 November 2021

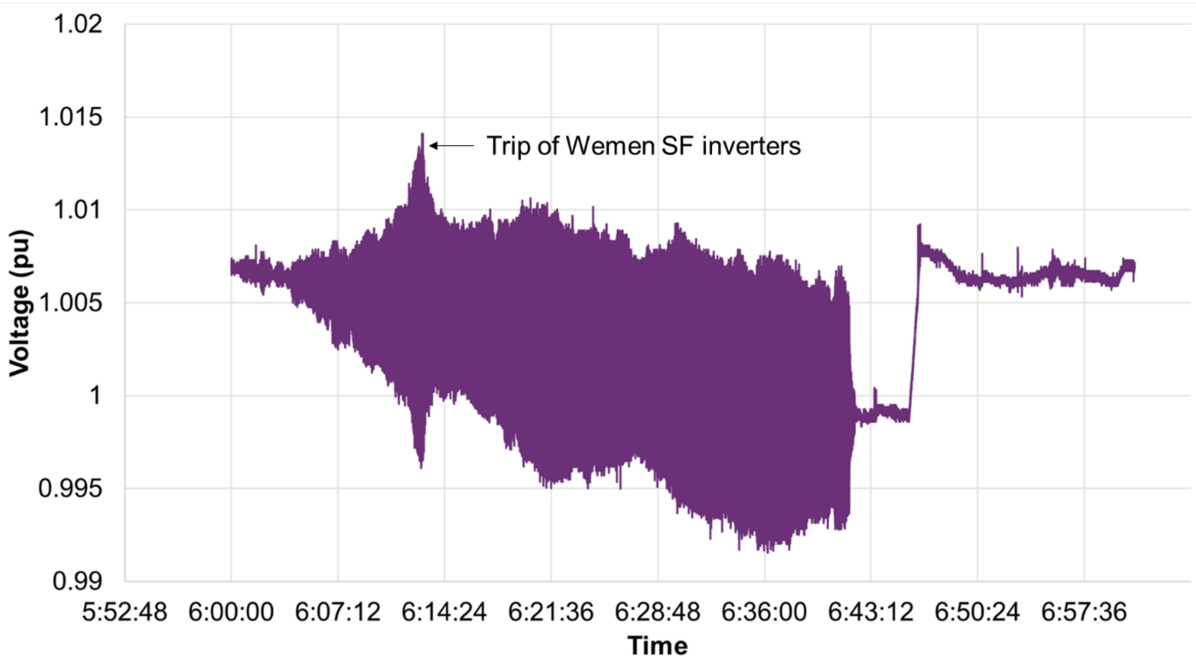


Figure 18 Solar plant MW output, 0600 hrs to 0700 hrs on 16 November 2021

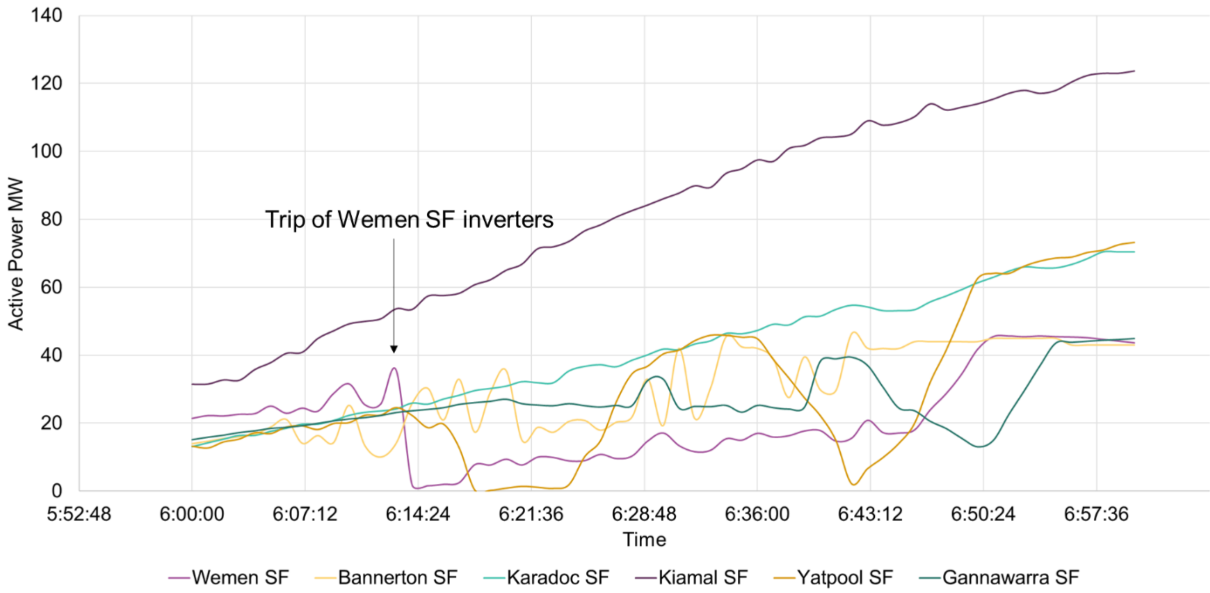


Figure 19 Wemen Solar Farm, 0610 hrs on 16 November 2021, Q and V (both in-phase and out-of-phase)

Figure 20 Bannerton Solar Farm, 0610 hrs on 16 November 2021, Q and V (in-phase)

Figure 21 Wemen Solar Farm, 0627 hrs on 16 November 2021, Q and V (both in-phase and out-of-phase)

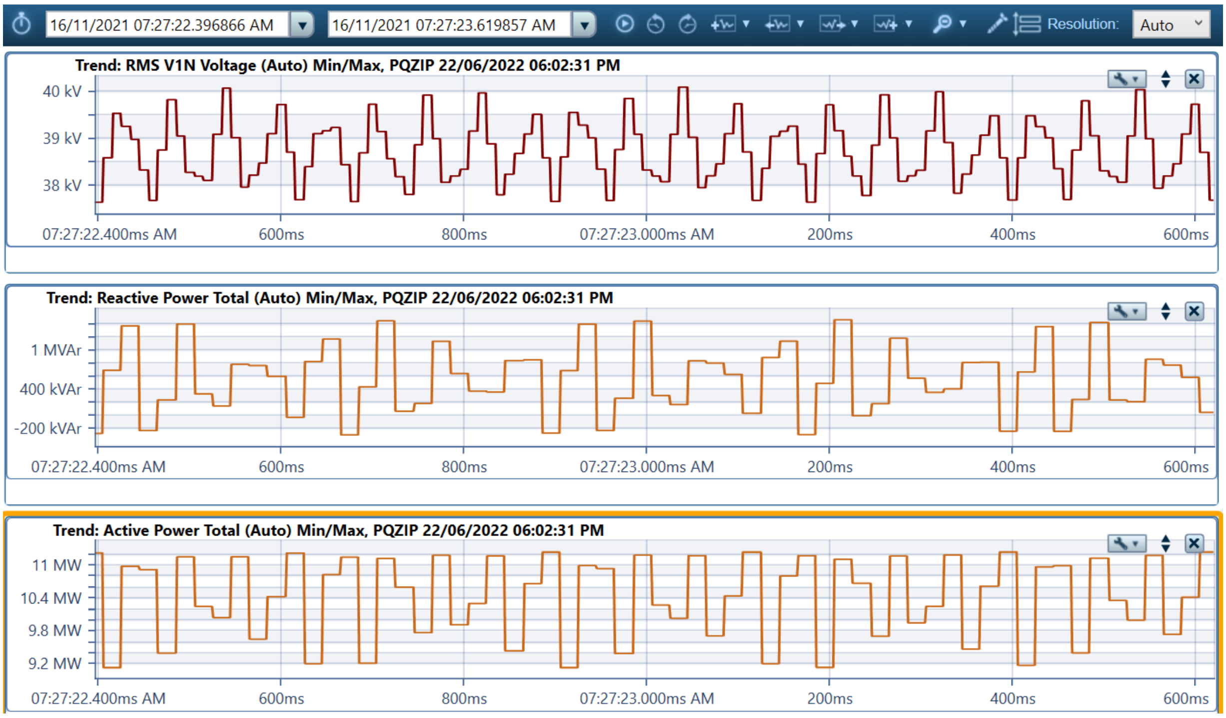
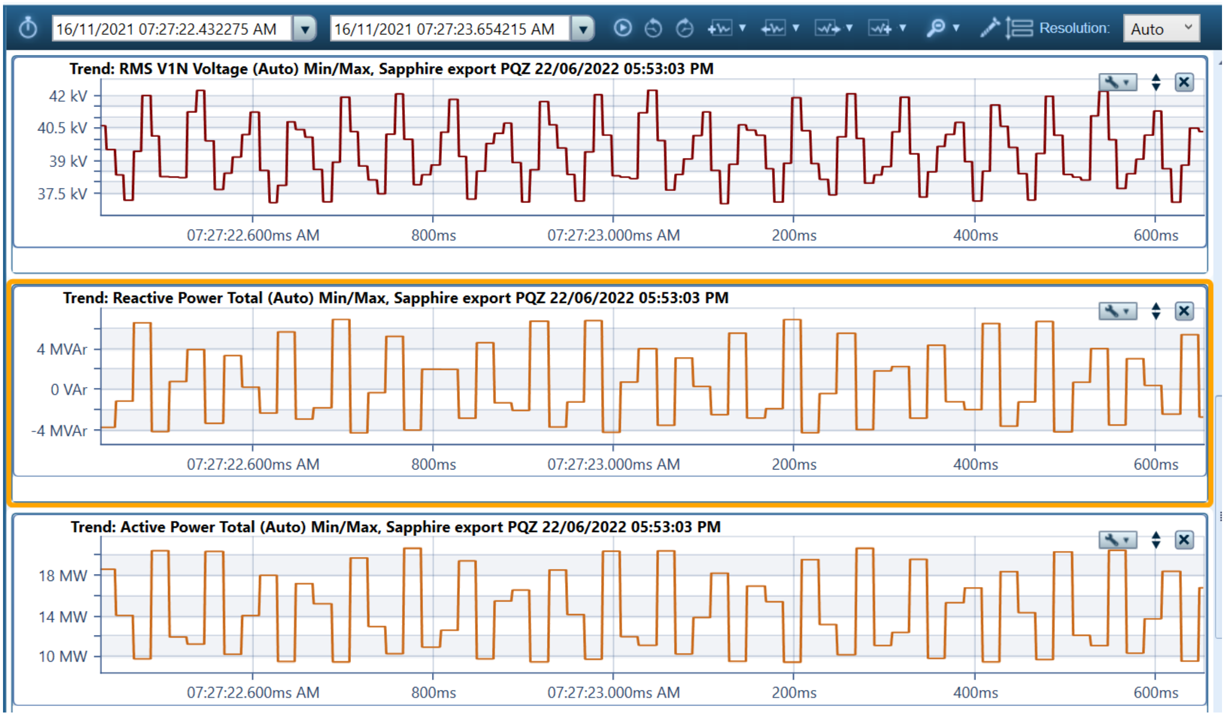


Figure 22 Bannerton Solar Farm, 0627 hrs on 16 November 2021, Q and V (both in-phase and out-of-phase)



5.1 Key takeaways

Key observations are:

- Voltage oscillations with a frequency of around 18 Hz and magnitude up to 1.94% were observed at RCTS 220 kV for around 37 minutes during the event on 16 November 2021. The oscillations continued despite a substantial number of inverters tripping at Wemen SF.
- The Bannerton SF and Yatpool SF MW output (Figure 18) shows active power varying between 20 MW and 40 MW, however, the nearby solar plants like Karadoc SF and Kiamal SF presented a smooth ramp in the active power output.
- The Q and V response of Bannerton SF was in-phase at around 0610 hrs. However, the Q and V response of both Bannerton SF and Wemen SF was not consistent at 0627 hrs snapshot, sometimes being in-phase and sometime being out-of-phase. (Q and V data for other solar farms during this and other events is included in Section 8).
- During the oscillations observed on 16 November 2021, the WETS 220/66 kV transformer B2TR was out of service for maintenance, resulting in lower system strength around the 66 kV PoC for Wemen SF and Bannerton SF. However, from the evening of 17 November 2021, AEMO applied a constraint of 38% of inverters online (around 15 inverters) for Wemen SF and Bannerton SF, while one of the WETS 220/66 kV transformers was out of service for maintenance. During this period, after applying the constraint, no significant oscillations were observed. Both transformers were restored in-service on 25 November 2021.

6 Impact of solar farm inverters

There were a few instances during the above-described events when a substantial number of inverters at Wemen SF were either disconnected or tripped; however, oscillations were still observed at RCTS 220 kV:

- During the oscillations observed around 1235 hrs on 20 August 2020, Wemen SF had completely tripped, however Bannerton SF was online and generating close to 60 MW. The oscillations lasted for about 30 seconds. Karadoc SF was also online and generating around 35 MW, while Yatpool SF and Kiamal SF were not online during this event.
- During the event around 0613 hrs on 16 November 2021, about 35 inverters at Wemen SF were confirmed as tripped, however the oscillations observed at RCTS 220 kV continued for another 30 minutes as Wemen SF was still being restored to service. The active power output of Bannerton SF and Yatpool SF was varying between 20 MW and 40 MW as shown in Figure 18. In comparison, Kiamal SF and Karadoc SF were ramping up smoothly, as seen in Figure 18.
- Around 0645 hrs on 28 December 2021, oscillations were observed at RCTS 220 kV and lasted for about 2.5 minutes. Wemen SF was not generating (as the active power output seen using PI data was held at zero) between 0630 hrs and 0730 hrs. However, Bannerton SF, Yatpool SF and Kiamal SF were online and generating, whereas Karadoc SF was not generating active power during this event.

In addition, the following observations were made in the active power response of Bannerton SF, coincident with the oscillations observed at RCTS 220 kV:

- During the 25 May 2021 event, the oscillations at RCTS 220 kV started around 1518 hrs and lasted for approximately 12 minutes. Figure 23 shows the variation in the active power MW output of solar plants during this time period. Bannerton SF active power output was varying from 35 MW to 0.5 MW during these 12 minutes. While Wemen SF was also oscillating around this time (although with smaller magnitude), Wemen SF stabilised at around 1530 hrs with an active power output of around 12 MW. The output of Kiamal SF was also varying between 20 MW and 60 MW during the period of the oscillations; however, the active power response was not as oscillatory compared to Bannerton SF during this time period.
- During the 29 July 2021 event (highlighted in Section 2.4 and Figure 8), the oscillations at RCTS 220 kV started around 1629 hrs and lasted for about 85 seconds. Figure 24 shows the variation in active power MW output of solar plants in the region. Just prior to the event it can be noted that there was a sudden step change in the Bannerton SF output at around 1616 hrs from 40 MW to almost 0.5 MW, and then a sudden ramp up from 0.5 MW to 36 MW at around 1629 hrs.

With regard to the reactive power response of Bannerton SF and Wemen SF, it was observed that Wemen SF was absorbing around 11 megavolt amperes reactive (MVAR) on most occasions before the onset of oscillations, whereas Bannerton SF was held at 0 MVAR. During the oscillations, the MVAR output of both Bannerton SF and Wemen SF was seen to be varying, with Bannerton SF presenting higher sensitivity (compared to Wemen SF), as shown in Figure 25.

For the 25 May 2021 event, the reactive power output of Karadoc SF was also seen oscillating similar to Bannerton SF, and Yatpool SF changed its reactive power output from around 27 MVAR generating to around -2.5 MVAR absorption at around 1506 hrs prior to the event, as seen in Figure 25.

While there has been some mention in literature[8] of sub-synchronous instability when the reactive components of the IBR and grid impedances are equal and opposite (such as inductive and capacitive) resulting in oscillations, no clear correlation or pattern could be established based on the analysed data for the oscillations in WMZ region.

Figure 23 Solar plant MW output, around 1500 hrs to 1600 hrs on 25 May 2021

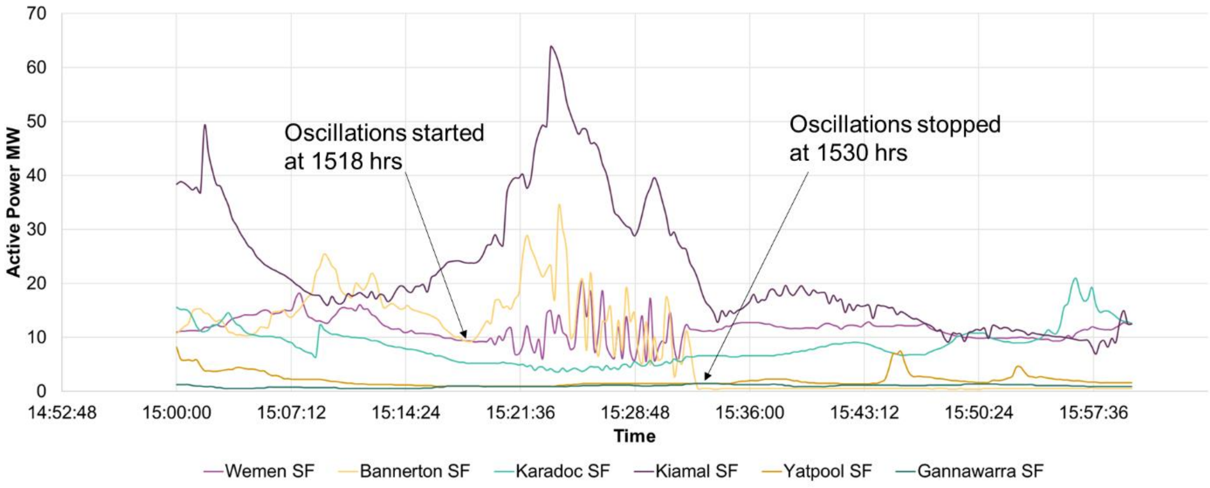
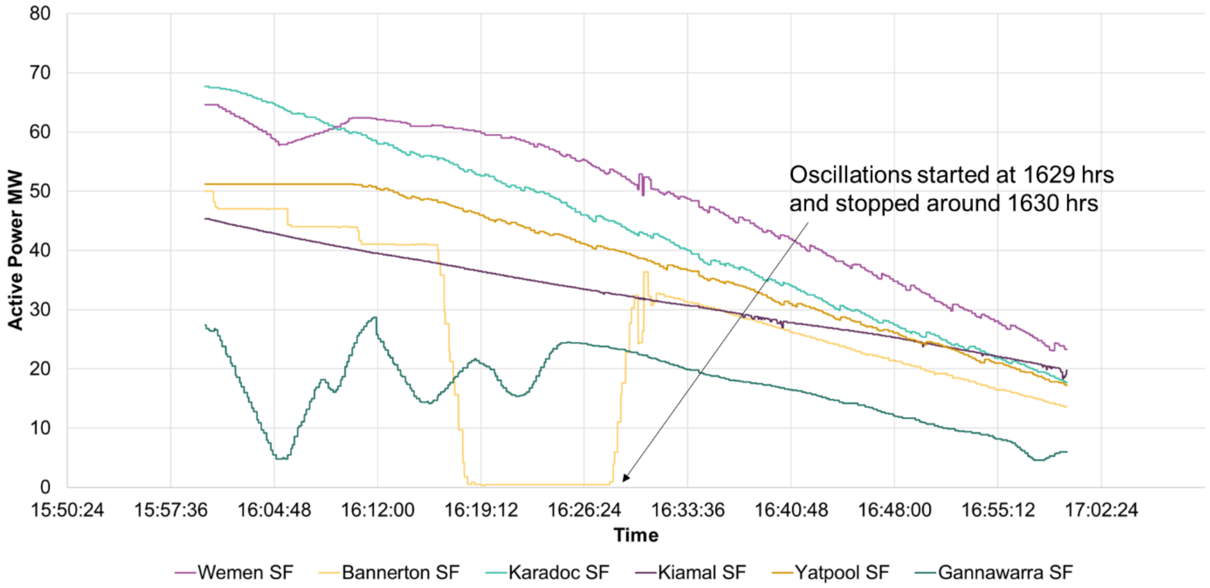
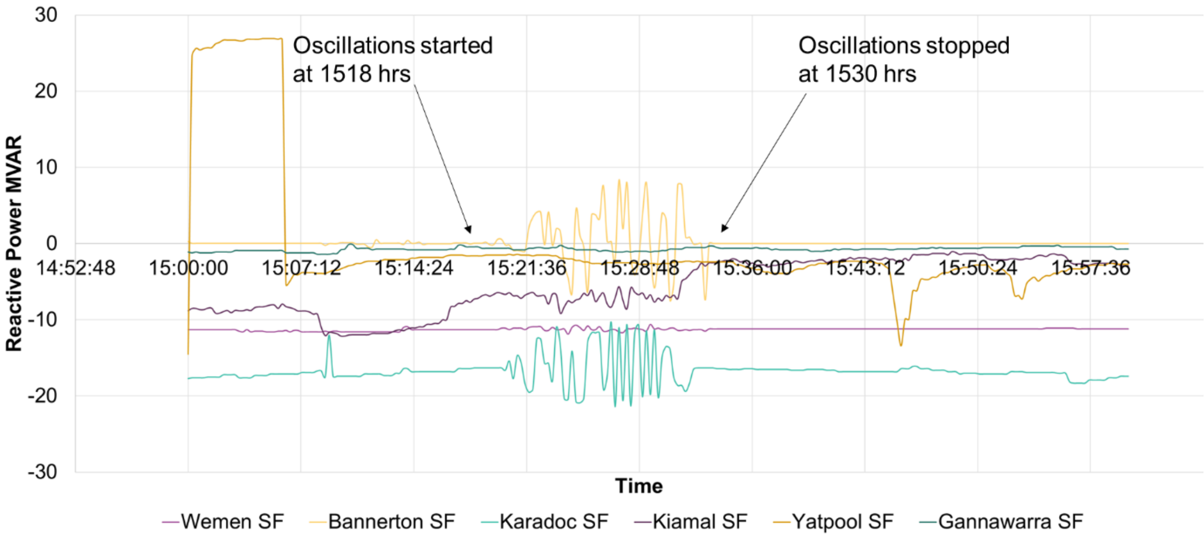


Figure 24 Solar plant MW output, around 1600 hrs to 1700 hrs on 29 July 2021



[8] Based on IEEE P2800 (for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems), page 136 of 180.

Figure 25 Solar plant MVAR output, around 1500 hrs to 1600 hrs on 25 May 2021



6.1 Key takeaways

Key observations are:

- There were at least three instances (on 20 August 2020, 16 November 2021 and 28 December 2021), where Wemen SF was either disconnected or tripped or not generating any active power, and yet oscillations were observed at RCTS 220 kV.
- An oscillatory response in the active power output of Bannerton SF was observed around the time of occurrence of some of these oscillations (for example, in the 16 November 2021 and 25 May 2021 events), as shown in Figure 18 and Figure 23.
- Wemen SF was absorbing around 11 MVAR on most occasions when online before the onset of oscillations, whereas Bannerton SF was held at 0 MVAR, as seen in Figure 25, however, no clear relationship could be established between the onset of oscillations and the reactive power absorption or generation pattern of these plants.
- Karadoc SF was absorbing around 19 MVAR on most occasions before onset of oscillations and, as seen in Figure 25, was also oscillating similar to Bannerton SF; however, the reactive power response of Yatpool SF was not consistent, presenting a wide range of operating points. Nevertheless, no conclusions could be drawn regarding the reactive power setpoints of these plants and occurrence of oscillations.

7 Impact of local loads

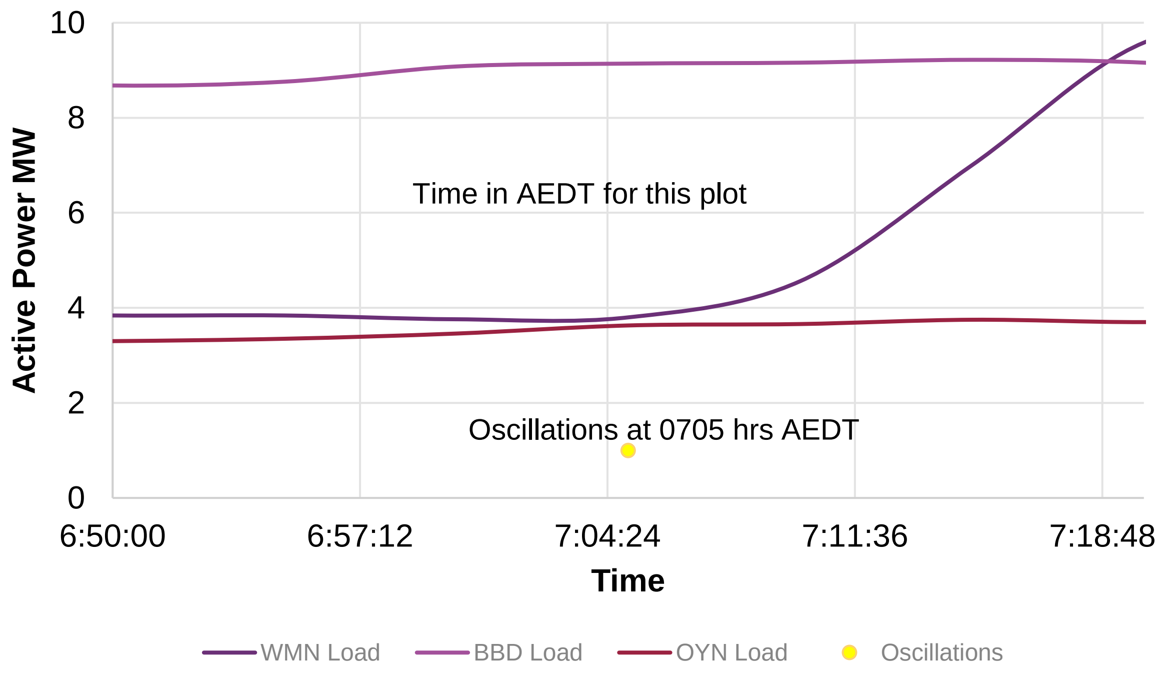
More recently, AEMO and Powercor started looking at the change of load around the Wemen and Bannerton area and any potential correlation with the presence or onset of oscillations. In at least two incidents in WMZ, it was observed that some loads at distribution stations around WETS ramped up almost at the same time that the oscillations were noticed[9]. This raised the question of whether there is a correlation between load ramp in the region and the voltage oscillations seen at RCTS 220 kV.

This section provides observations during the two incidents where load change was simultaneous with the start of oscillations. However, there were several instances (as shown in Table 2) when the onset of oscillations did not have any correlation with the active power ramping of load in the region.

7.1 16 November 2021 event

During the 16 November 2021 event, voltage oscillations were observed at RCTS 220 kV, starting at 0605 hrs (0705 hrs Australian Eastern Daylight Time [AEDT]), and lasted for 37 minutes. Based on 5-minute average load data provided by Powercor for the loads around WETS, there was a load ramp around the same time at Wemen (WMN) zone substation, as shown in Figure 26. However, the loads at Boundary Bend (BBD) and Ouyen (OYN) zone substations did not show any sudden change at the time of oscillations during this event.

Figure 26 Local loads active power ramp, 0605 hrs on 16 November 2021

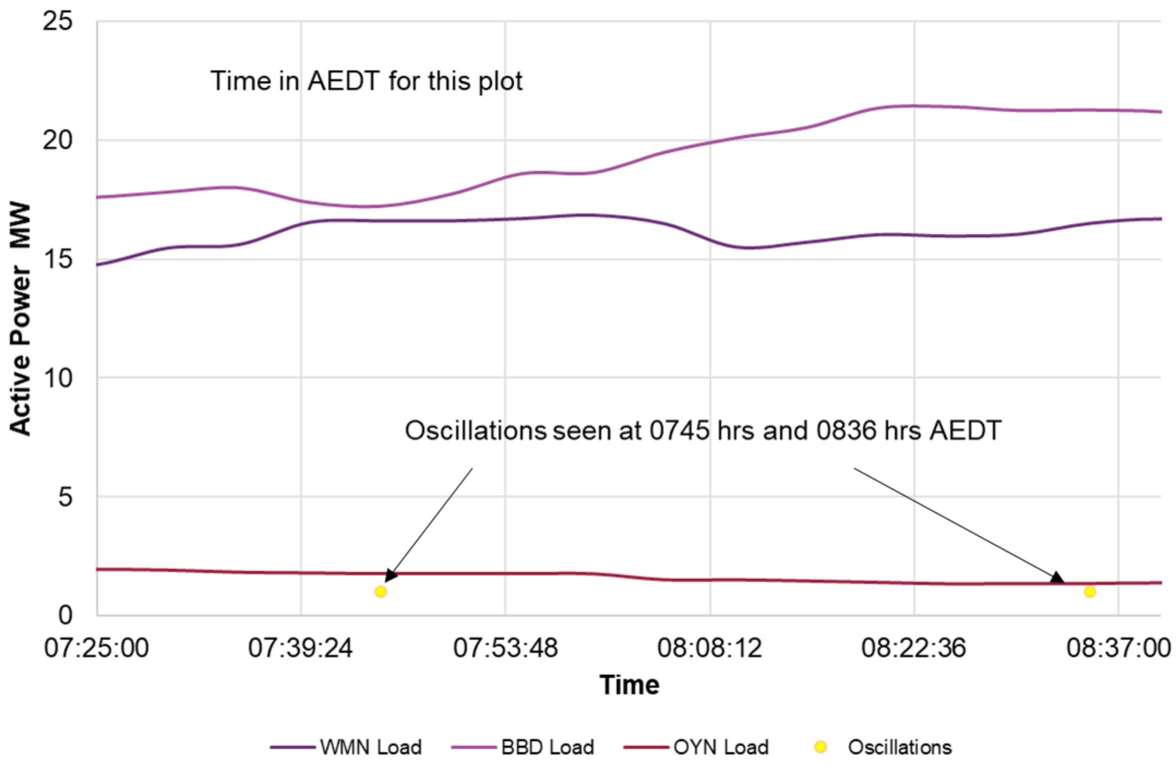


9 On the few instances where there was correlation observed between load ramp and onset of oscillations, an attempt was made to identify which solar farm started oscillating first, however, as all solar farm data was not synchronized to the same GPS clock, it proved to be challenging.

7.2 28 December 2021 event

On 28 December 2021, voltage oscillations were observed at RCTS 220 kV starting at 0645 hrs market time (0745 hrs AEDT) and lasted for 2.5 minutes. Based on 5-minute data provided by Powercor for the loads around WETS, there was a load ramp around the same time at BBD zone substation, as shown in Figure 27. The loads at WMN and OYN zone substations did not show any sudden change at the time of oscillations during this event. Another instance of oscillations was also noted around 0736 hrs market time (0836 hrs AEDT) and lasted for close to 1 minute, however there was no load ramp that was noticed around this instance.

Figure 27 Local loads active power ramp, 0645 hrs on 28 December 2021



The 5-minute average load data for reactive power of the loads around WETS was also analysed and no sudden changes could be identified, before the onset of oscillations. Therefore, this did not suggest any change in inductive versus capacitive impedance such as to result in a resonance condition.

Table 2 Summary of active power load ramps noticed during oscillation events in WMZ

Date and Time (AEST or Market Time)	Frequency of oscillations [Hz]	% Peak-to-peak voltage magnitude (max) RCTS 220 kV	Duration [s]	Noticeable load ramp around WMN or BBD*
17/10/2021 1730 hrs	19	0.78	67	NO
24/10/2021 1710, 1714 hrs	19,18	0.74, 0.82	21, 45	NO
25/10/2021 1735 hrs	19	0.78	47	NO
28/10/2021 1357 hrs	19	0.62	360	NO
08/11/2021 1512, 1626,1745 hrs	20,19,19	0.87,0.82.0.86	37,75,84	YES 1455 to 1525 hrs
10/11/2021 14:41, 1623, 1637, 1646 hrs	20,19,19,19	0.6,0.61,0.58,0.84	29,44,72,234	YES 1325 to 1700 hrs
15/11/2021 1700 hrs	NA	NA	NA	NO
16/11/2021 0605 hrs	18	1.94	2215	YES 0555 to 0625 hrs
18/12/2021 1811 hrs	19	0.56	75	NO
20/12/2021 1730, 1825 hrs	19,20	0.43, 0.47	45,45	YES 1812 to 1827 hrs
21/12/2021 1725, 1810 hrs	20,20	0.43,0.4	26,45	NO
25/12/2021 1755, 1840 hrs	20, 18	0.49, 0.47	70, 81	NO
27/12/2021 1755 hrs	19	0.4	81	NO
28/12/2021 0644, 0736, 1825 hrs	20, 20, 19	1.95, 0.27, 0.26	137, 57, 60	YES 0630 to 0730 hrs
02/01/2022	NA	NA	NA	YES 1000 to 1030 hrs
14/01/2022 1758 hrs	NA	NA	NA	NO

* Any load ramp below 1 MW was considered as not significant for the purpose of this table.

7.3 Key takeaways

Key observations are:

- The load ramps analysed in the region were mostly around a few megawatts and not significant, however, no specific and consistent correlation could be established between active power load ramps in the region and the onset or presence of oscillations on various instances.
- The reactive power of the loads did not have any correlation during load ramp up with the onset or presence of oscillations observed at RCTS 220 kV.

8 Reactive power and voltage relationship

As the reactive power and voltage response of IBR control loops are closely coupled, it is expected that when the Q and V oscillations are in-phase, there is a strong indication that an IBR plant could be contributing or participating in the oscillations. Therefore, this section presents some additional ELSPEC data, relevant to the events analysed in the earlier sections of this report.

The summary of Q and V relationship analysed for various solar farms around RCTS is presented in Table 3 below, along with individual plots in Figure 28 through Figure 42. It may be noted that Yatpool SF presented consistent in-phase behaviour between Q and V during a few instances analysed during these oscillation events. However, Yatpool SF was not online during the initial event on 20 August 2020. For the purpose of this table, a close to 0-degree alignment between RMS voltage (V) and total reactive power (Q) was considered an in-phase relationship. The magnitude of voltage oscillations was seen to be highest at Bannerton SF 66 kV, followed by Wemen SF 66 kV during the below events analysed.

Table 3 Summary of Q-V phase relationship at SF PoC and voltage oscillation magnitude

Date and time (AEST or Market Time)	Relation	Bannerton SF	Karadoc SF	Kiamal SF	Wemen SF	Yatpool SF
20/8/2020 1235 hrs	Q & V along with voltage oscillation magnitude%*	In-phase Figure 28 1%	Inconsistent Figure 29 0.9%	Not online	Tripped	Not online
25/5/2021 1525 hrs	Q & V along with voltage oscillation magnitude%	Inconsistent Figure 30 5.25%	Inconsistent Figure 31 See note[10]	No data	Inconsistent Figure 32 2.62%	In-phase Figure 33 1.57%
11/8/2021 1905 hrs	Q & V along with voltage oscillation magnitude%	Inconsistent Figure 34 4.2%	In-phase Figure 35 0.92%	In-phase Figure 36 0.14%	In-phase Figure 37 4.7%	In-phase Figure 38 0.42%
16/11/2021 0627 hrs	Q & V along with voltage oscillation magnitude%	Inconsistent Figure 39 11.8%	No data	In-phase Figure 40 0.63%	Inconsistent Figure 41 6.6%	In-phase Figure 42 0.78%

*The voltage oscillation magnitude noted above refers to the variation in RMS voltage typically within a span of 1 second noted at the PoC of respective solar farms, based on ELSPEC data shown in the figures below.

In addition to the ELSPEC data described in this section, some measurements based on monitoring available at WETS 66 kV, is also included in Appendix A2, as part of this report to highlight the frequency and phase relation of the oscillations, during a more recent oscillation event.

[10] Only inverter level data was available, therefore the magnitude of oscillation is not comparable with rest of the entries in the table, which is based on oscillations noticed at PoC.

Figure 28 Bannerton SF – 20 August 2020, Q and V relation

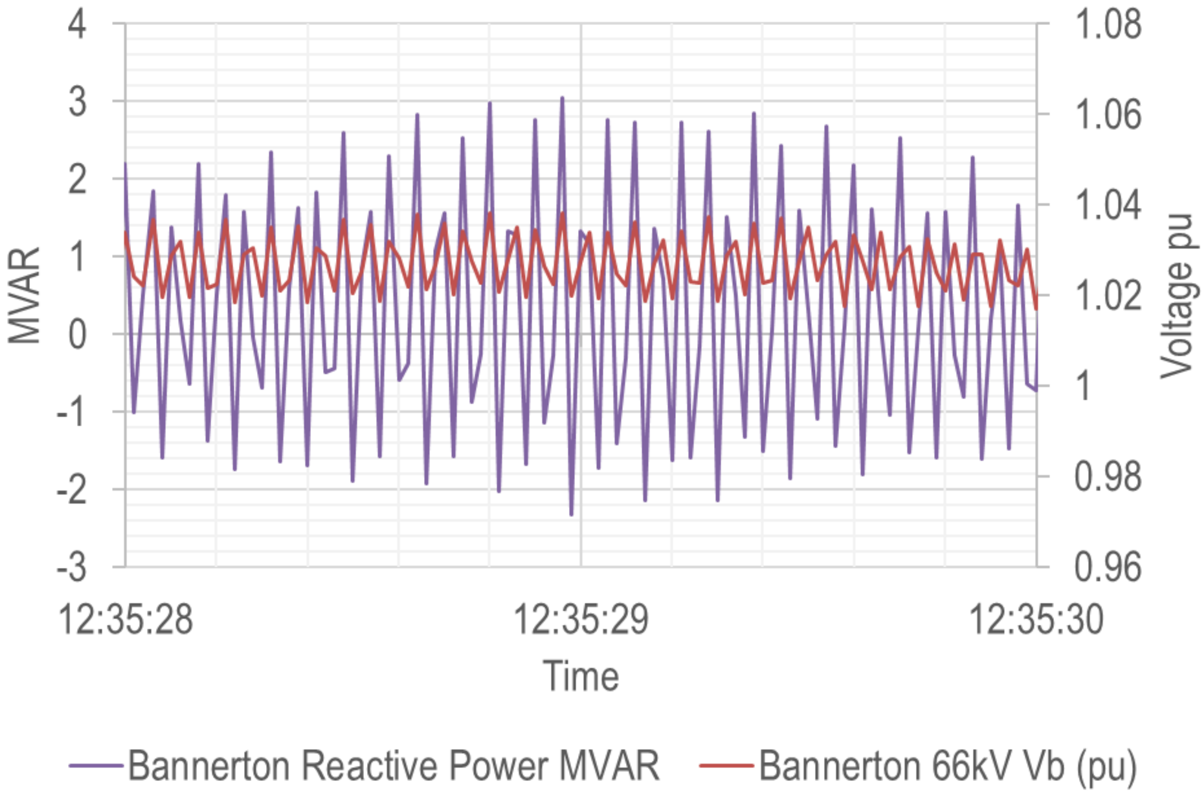


Figure 29 Karadoc SF – 20 August 2020, Q and V relation

Note – data is not time synchronized for Figure 29.

Figure 30 Bannerton SF – 25 May 2021, Q and V relation

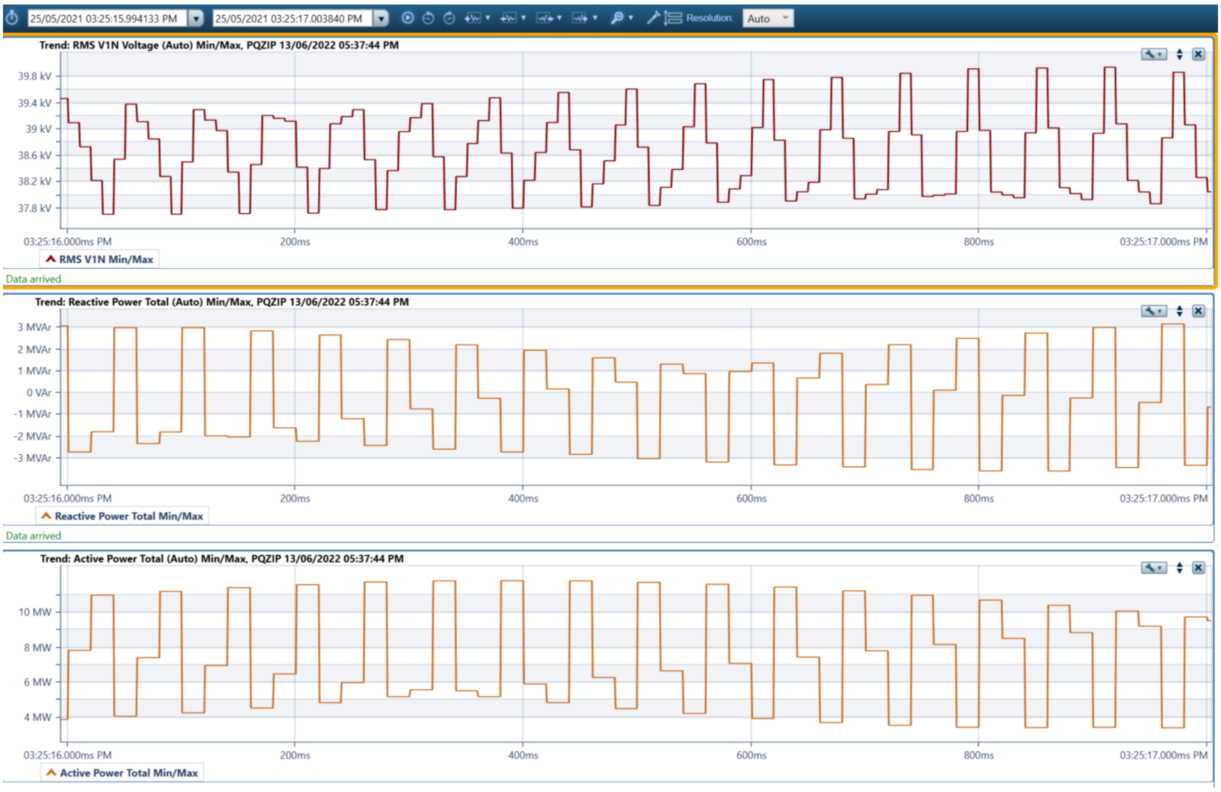


Figure 31 Karadoc SF – 25 May 2021, Q and V relation

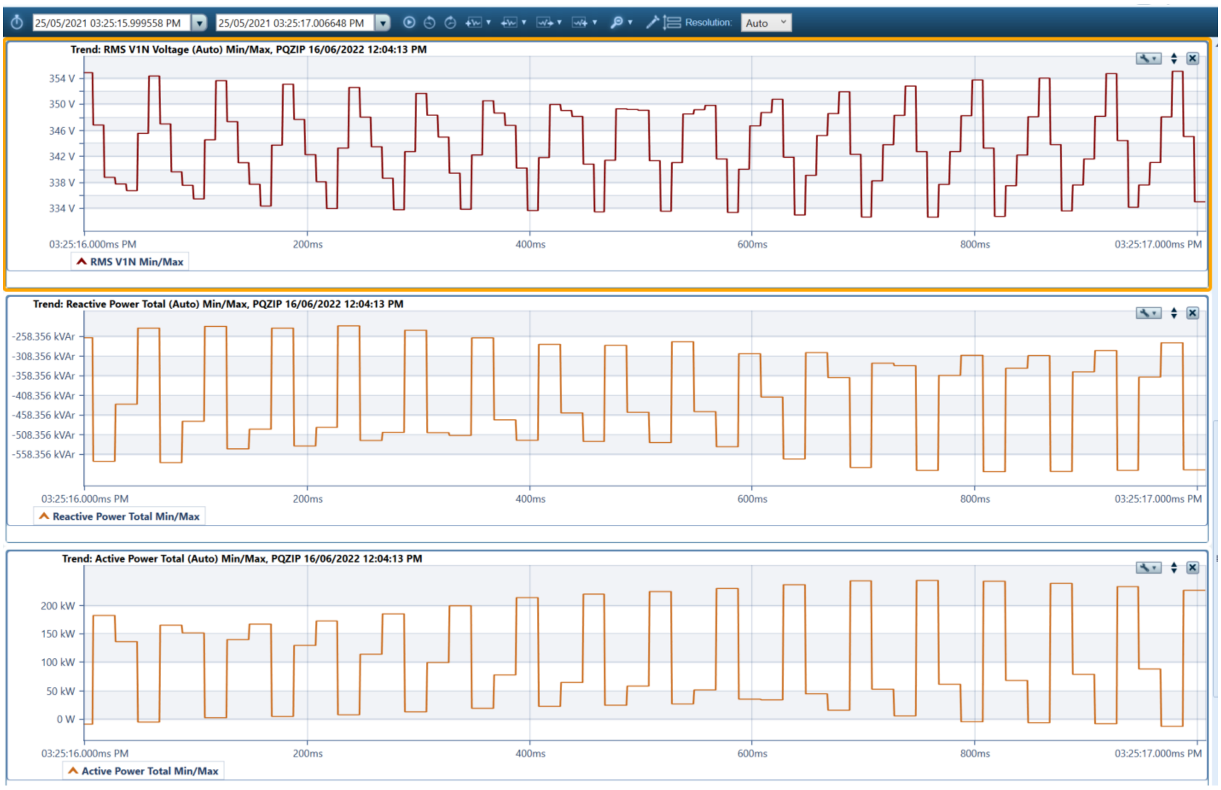


Figure 32 Wemen SF – 25 May 2021, Q and V relation

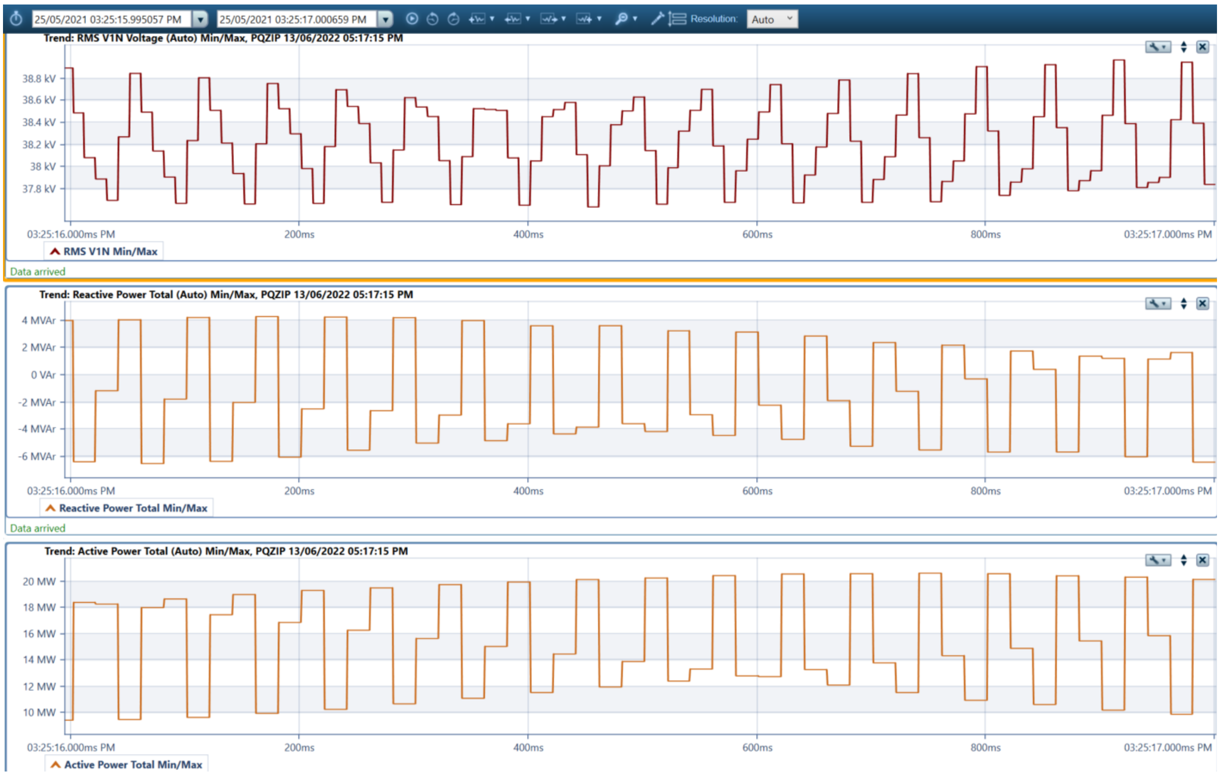


Figure 33 Yatpool SF – 25 May 2021, Q and V relation

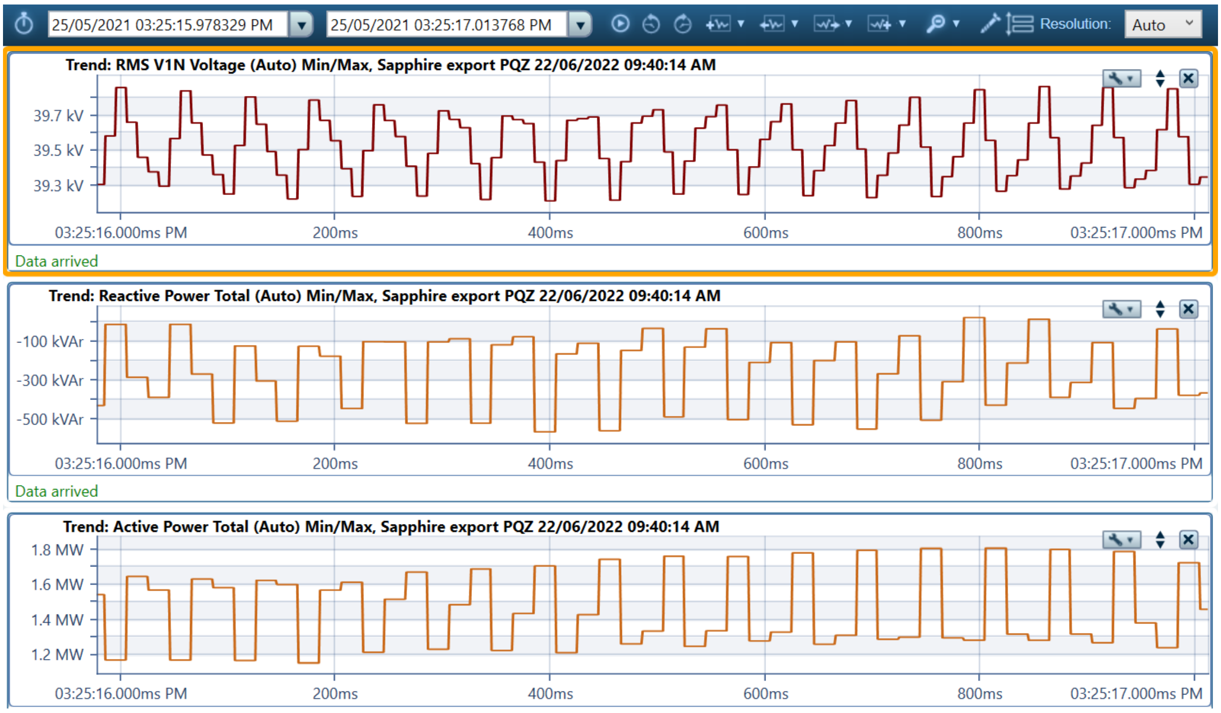


Figure 34 Bannerton SF – 11 August 2021, Q and V relation

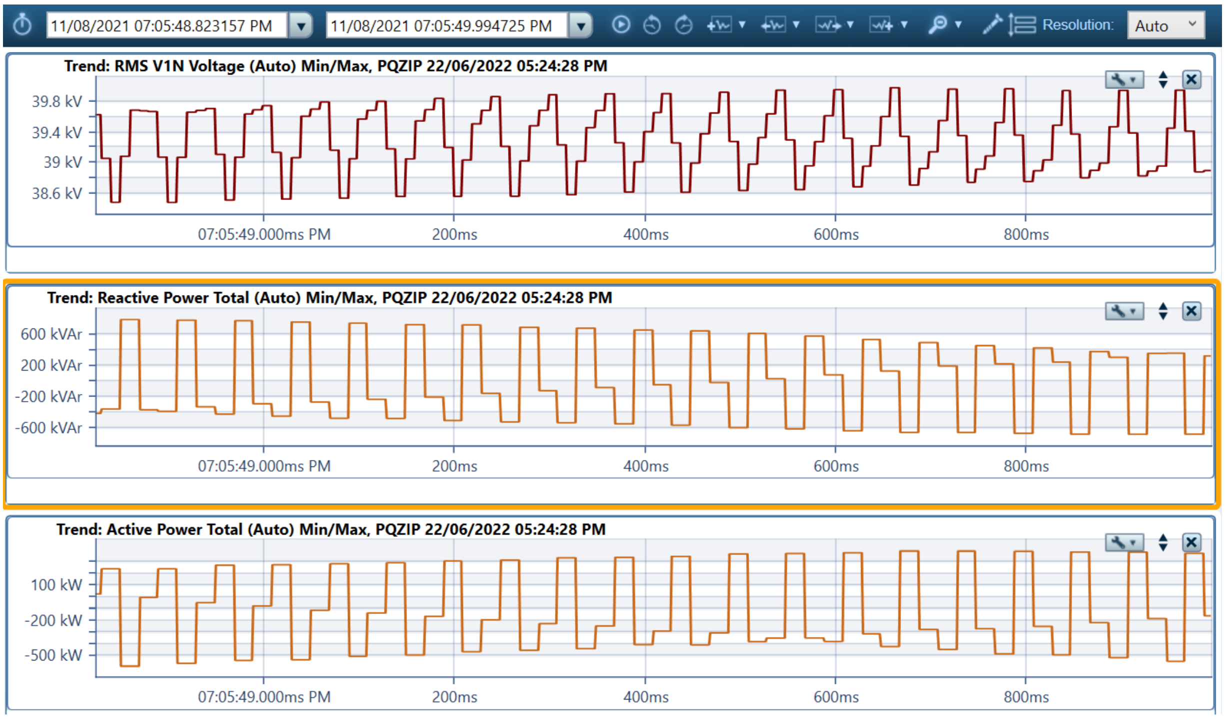


Figure 35 Karadoc SF – 11 August 2021, Q and V relation

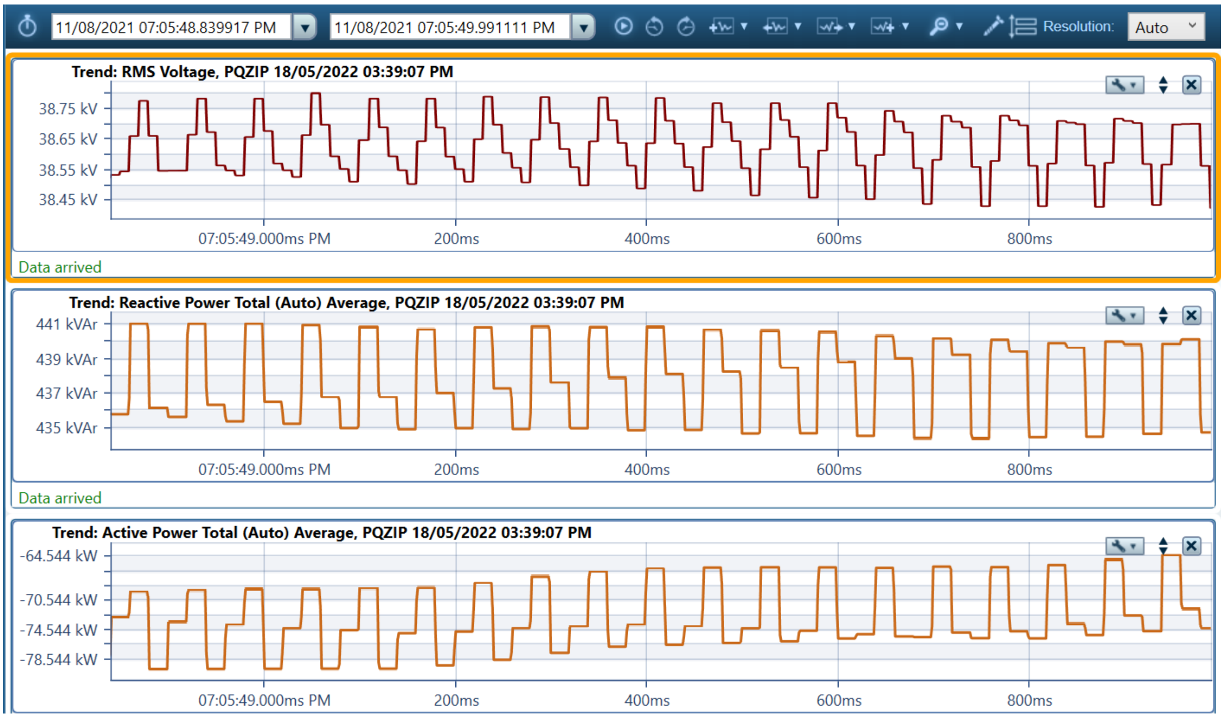


Figure 36 Kiamal SF – 11 August 2021, Q and V relation around 1905 hrs

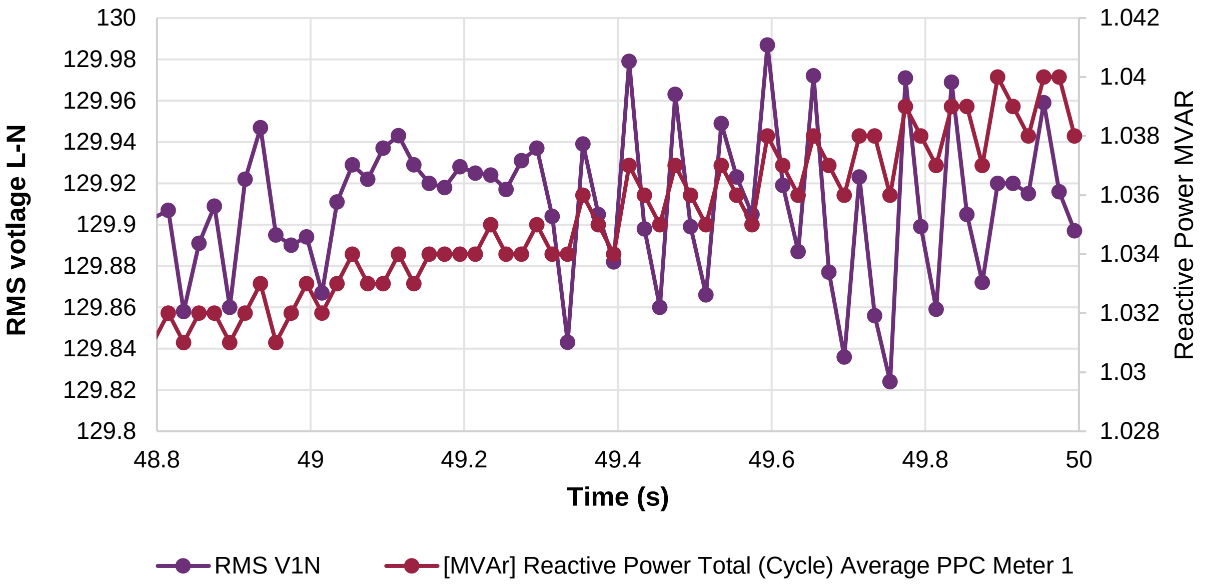


Figure 37 Wemen SF – 11 August 2021, Q and V relation

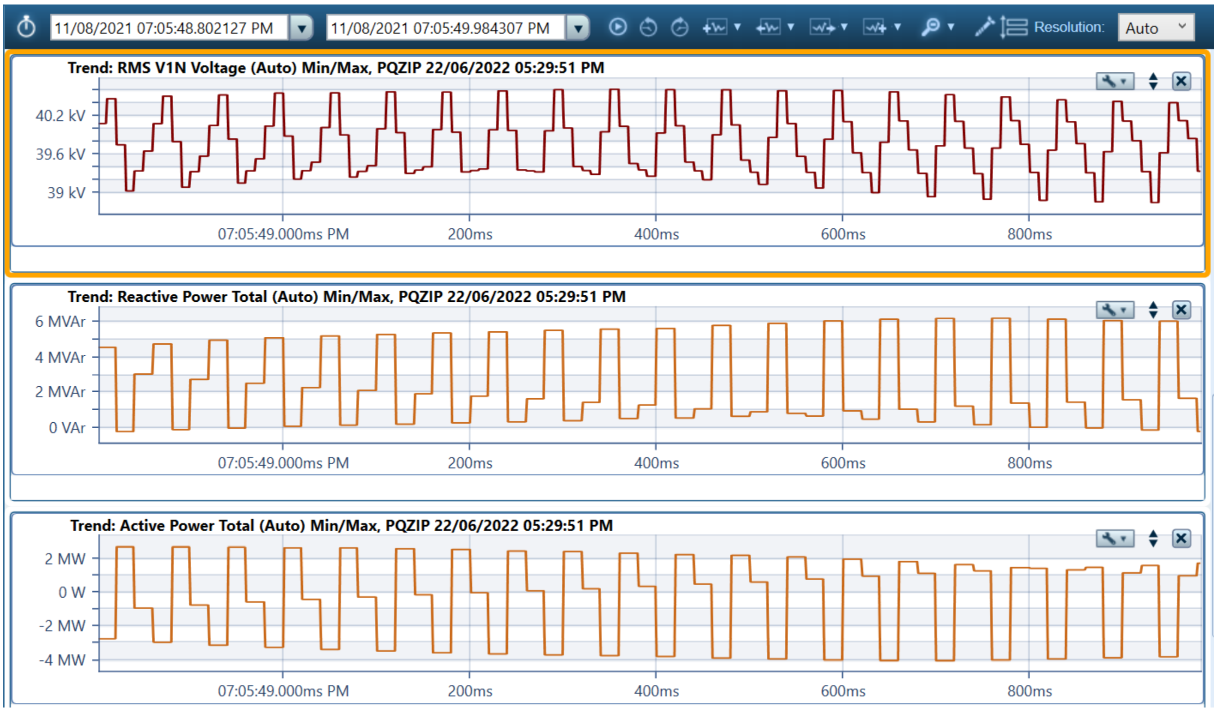


Figure 38 Yatpool SF – 11 August 2021, Q and V relation

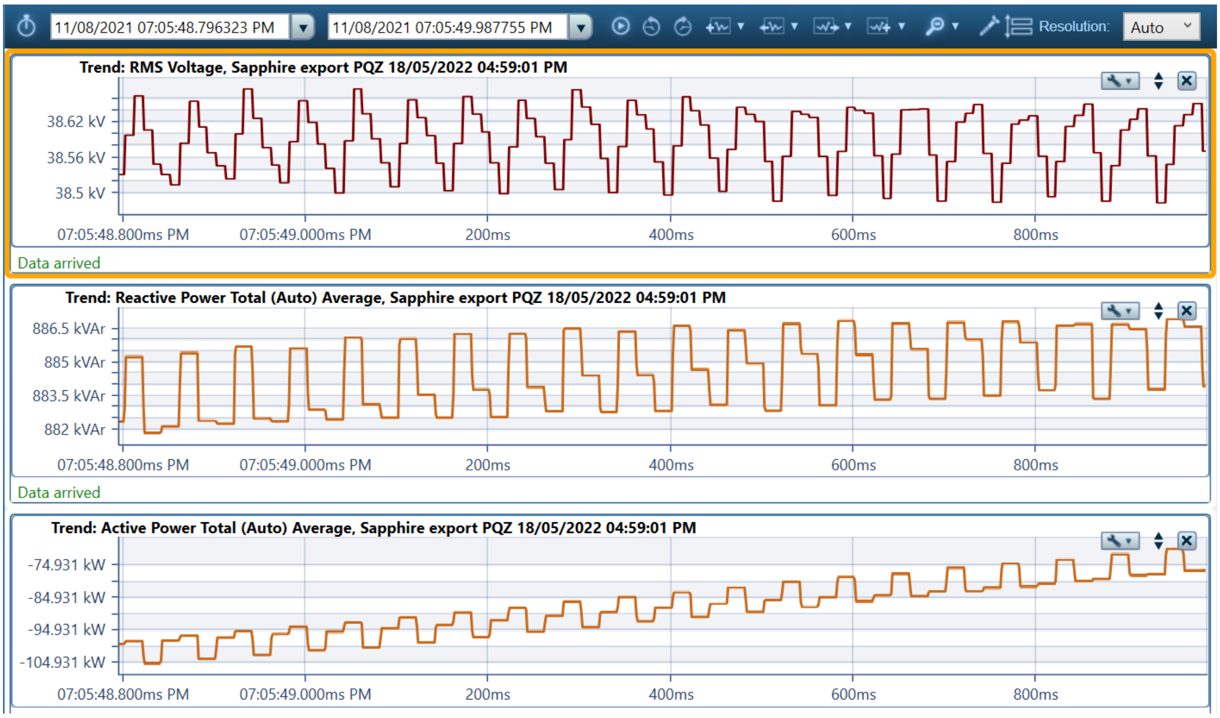


Figure 39 Bannerton SF – 16 November 2021, Q and V relation

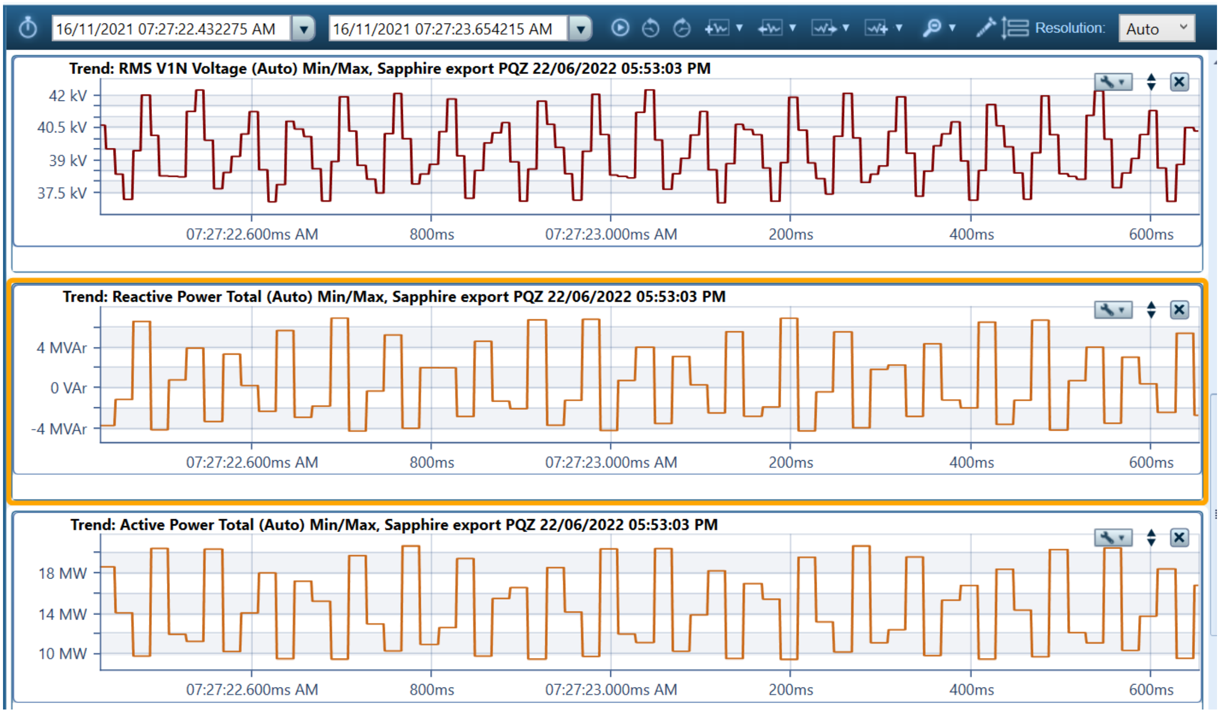


Figure 40 Kiamal SF – 16 November 2021, Q and V relation around 0627 hrs

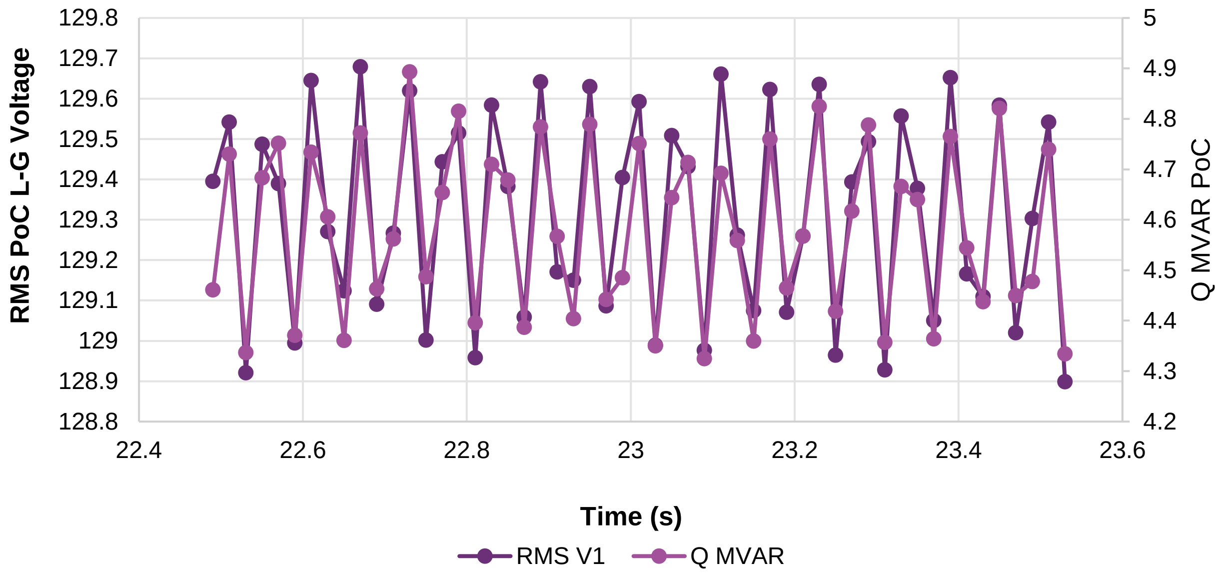


Figure 41 Wemen SF – 16 November 2021, Q and V relation

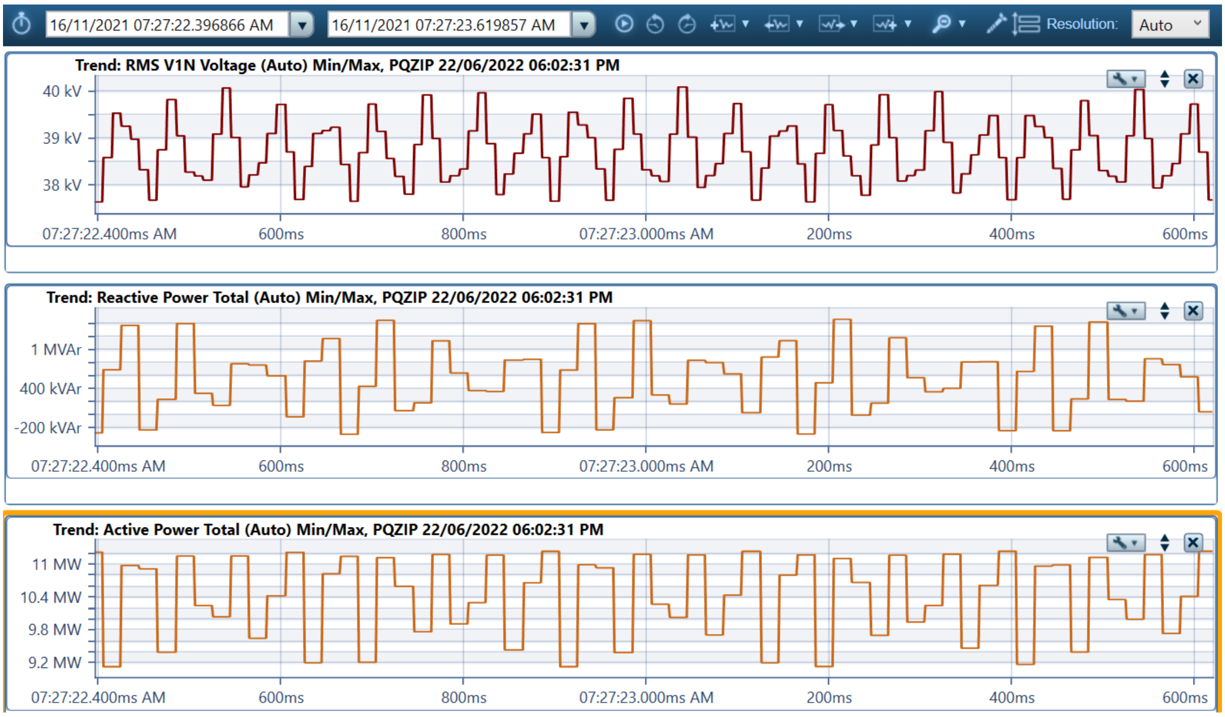
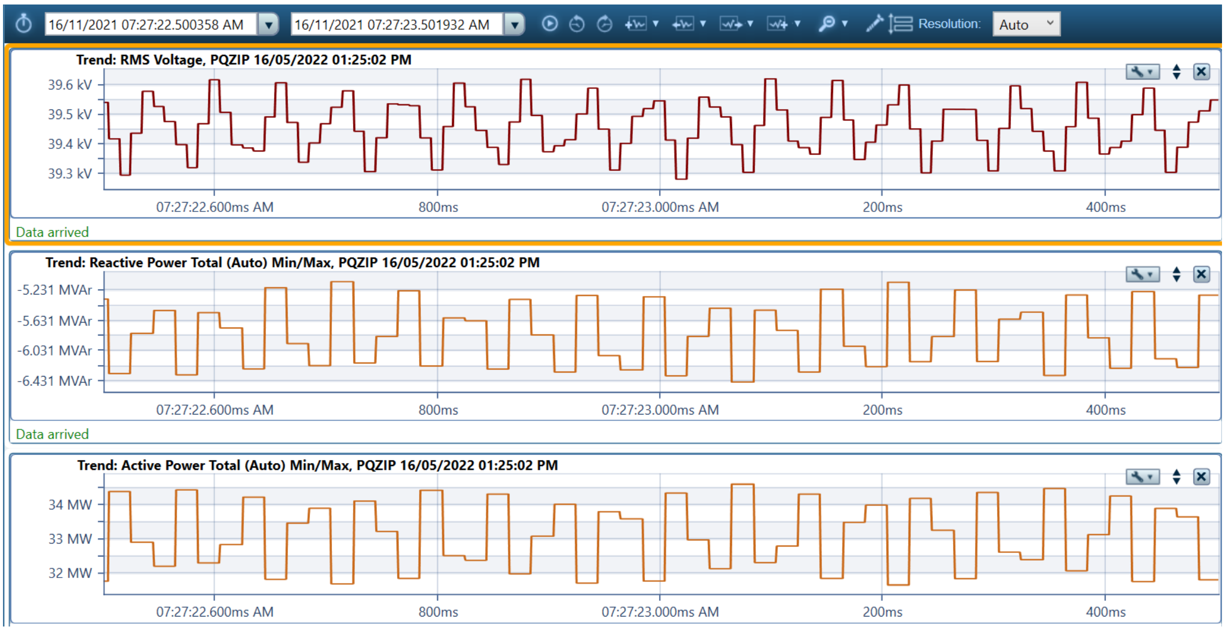


Figure 42 Yatpool SF – 16 November 2021, Q and V relation



9 Conclusions

The following conclusions are made based on this investigation:

- The sub-synchronous oscillations seem to be intermittent and occurring both with and without any apparent disturbance in the WMZ or surrounding region. The magnitude of oscillations, as measured at RCTS 220 kV, is mostly small and usually does not exceed 1% peak-to-peak RMS, although they have been observed up to 2.2%. The frequency of oscillations is mostly around 17 – 19 Hz (RMS), but with some events also measuring oscillations in the slightly lower range between 15 – 17 Hz (RMS).
- For three distinct events, where a large magnitude of oscillation was observed in WMZ, the magnitude of oscillations seems to be highest at Bannerton SF 66 kV PoC, followed by Wemen SF 66 kV PoC.
- The SVCs in the region (Horsham, Kerang SVCs) and MLDC link were unlikely to contribute in initiating or exacerbating these oscillations. As the oscillations occur even during instances when MLDC station circuit breaker was monitored as open (and transferring 0 MW). Similarly, on 11 August 2021, the oscillations continued despite the trip of RCTS – WETS – KGTS 220 kV line, and on 4 September 2020, the oscillations were observed even with Horsham SVC placed in manual mode operation.
- The role of IBRs in New South Wales has also been ruled out, as the oscillations seem to occur even when the Buronga to Red Cliffs 220 kV transmission line is out of service.
- The role of loads ramping on the 66 kV network around WETS was also analysed, but based on SCADA data, no correlation could be established between ramping of loads and occurrence of oscillations.
- The oscillations have therefore been identified as contained to be in the north west of Victoria and specifically around the Red Cliffs and Wemen area, with the following solar plants likely participating, Wemen SF, Bannerton SF, Karadoc SF, Yatpool SF and Kiamal SF.
- Based on instances when the response of these solar plants was analysed, the Q and V response from the solar plants were sometimes in-phase and sometimes out-of-phase. However, during the 20 August 2020 event, Yatpool SF was not commissioned and yet oscillations were observed.
- The role (if any) of nearby Gannawarra SF and BESS on the ongoing oscillations was also unlikely, as the oscillation event on 11 August 2021 resulted in oscillations continuing despite the trip of RCTS – WETS – KGTS 220 kV line.
- There were three incidents when Wemen SF was either tripped or disconnected or not in service, yet oscillations were observed.

10 Recommendations

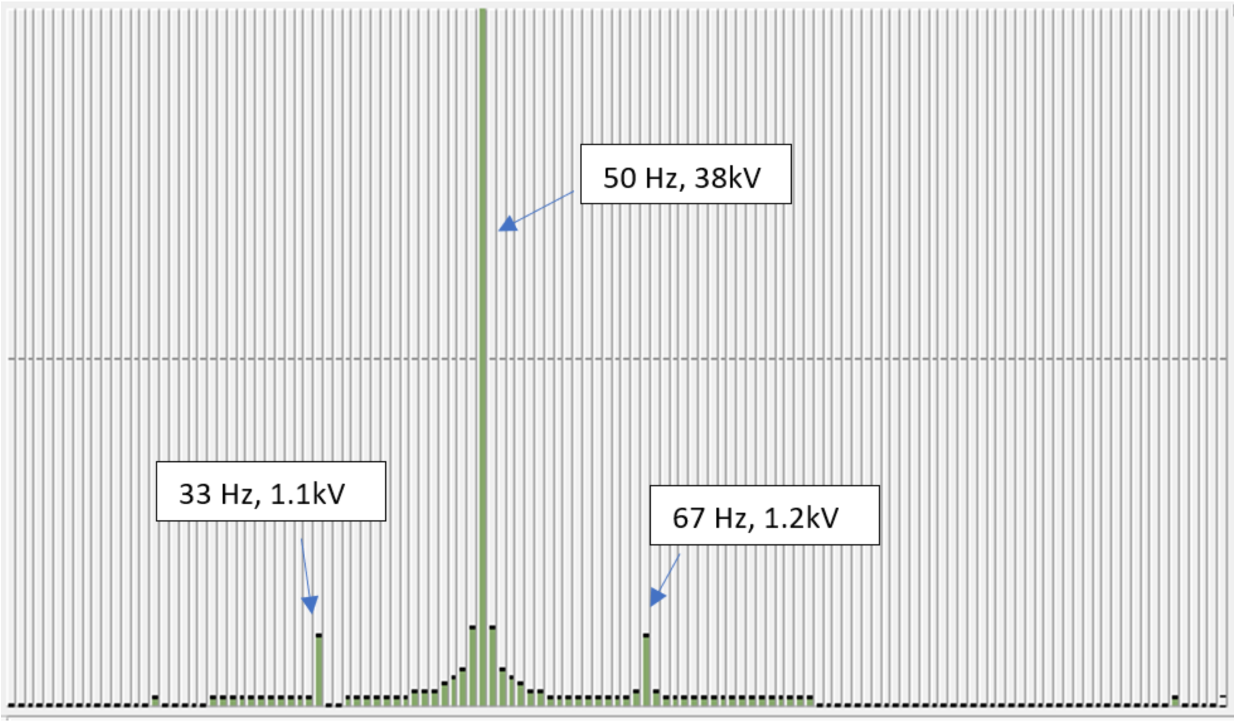
As the cause or causes of the oscillations remain unclear at the time of publication of this document, AEMO proposes following actions for further investigation:

- AEMO will work in collaboration with AusNet and Powercor on further monitoring, particularly in the distribution network around Wemen and Bannerton. This would also include additional review of all major industrial loads in the area to verify the impact of load operations (and any changes in the past two years) on the performance of IBR and oscillations observed.
- AEMO, in collaboration with Powercor, is pursuing the possibility of installing additional high speed monitoring equipment on the 66 kV network, around Yatpool, Karadoc, Robinvale zone substations and other loads connected in that portion of the 66 kV network to gain better visibility.
- The voltage controller bandwidth and Q-V performance of the plants around Red Cliffs and Wemen area, should be investigated, as their controllers seem to present higher gain/magnitude to the oscillations observed.
- A long-term solution could involve evolving the use of impedance analysis and monitoring techniques to identify the grid conditions for these oscillations and taking preventive measures.

A1. Note on RMS alias frequency

Most of the oscillation frequency data mentioned in this report, such as 17 Hz or 19 Hz oscillations, refer to the RMS aliased frequency as measured in the phasor variables, primarily voltage at RCTS 220 kV bus. However, the Fast Fourier Transform (FFT) of the instantaneous three-phase voltages and currents would indicate the actual frequency components to be modulated as 50 ± (the RMS frequency of 17 Hz or 19 Hz). Below is an example showing the actual frequency components (33 Hz and 67 Hz) in addition the 50 Hz fundamental, revealed by FFT analysis, for an RMS oscillation frequency of 17 Hz.

Figure 43 FFT analysis of instantaneous phase voltage at SF 66 kV PoC



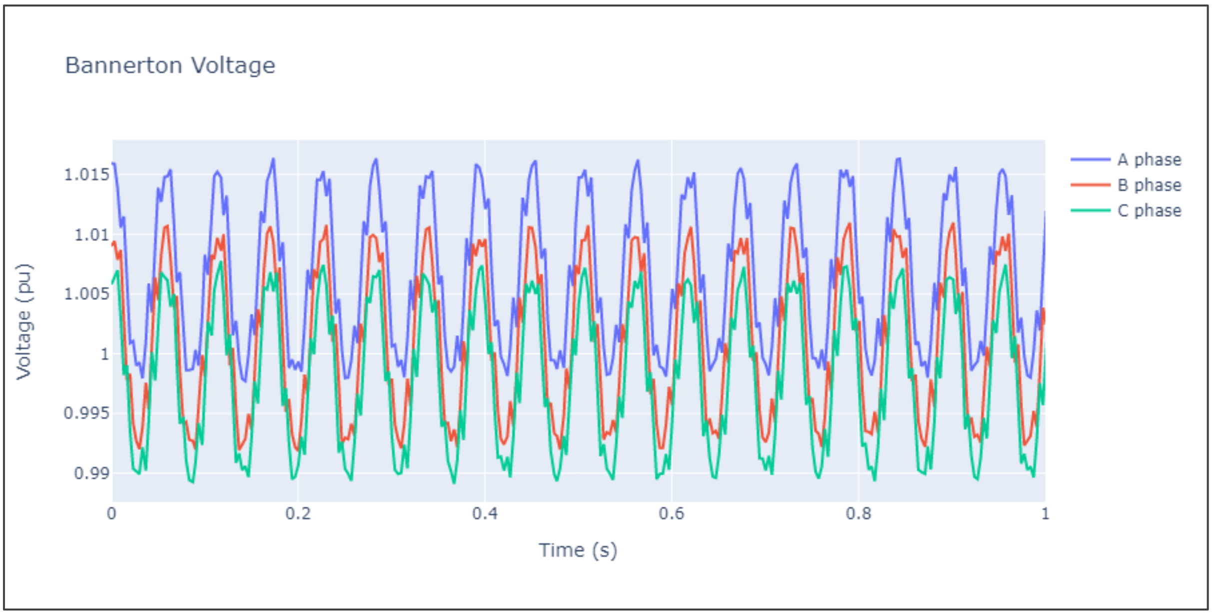
A2. Additional Measurements

AEMO has access to two power quality meters located at Wemen substation:

- One monitoring the Bannerton SF and Boundary Bend load
- One monitoring the Wemen SF and Wemen Township load

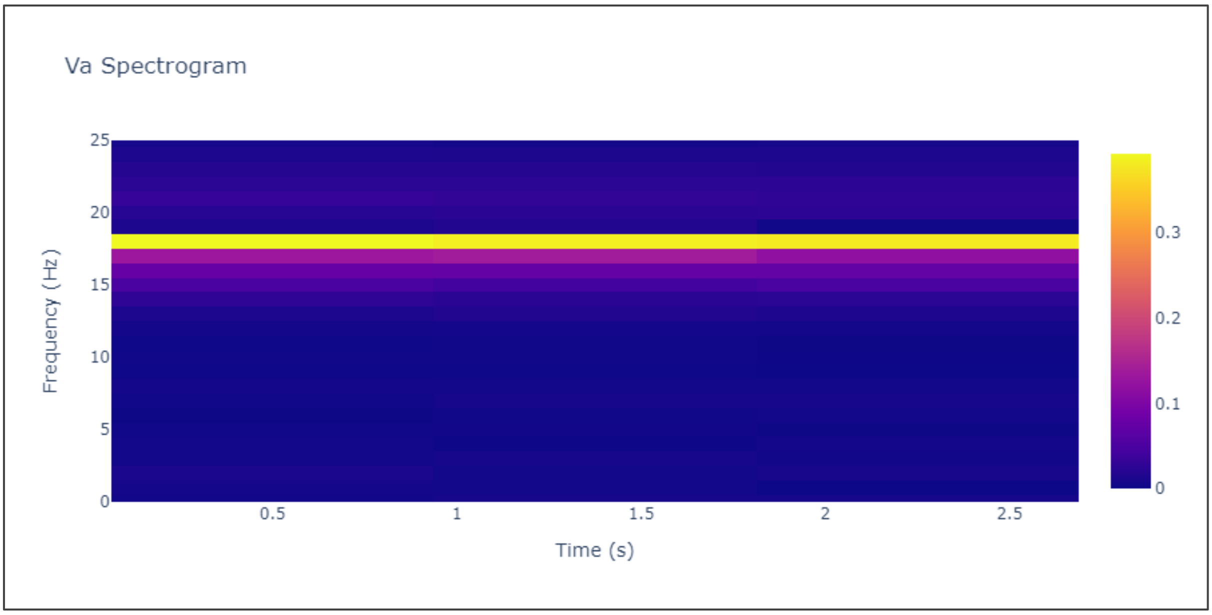
For the event on 23 June 2022 at 10:28:41 am, the following oscillations in voltage were observed:

Figure 44 Three-phase RMS 66 kV voltage measurements on 23 June 2022 at 1028 hrs



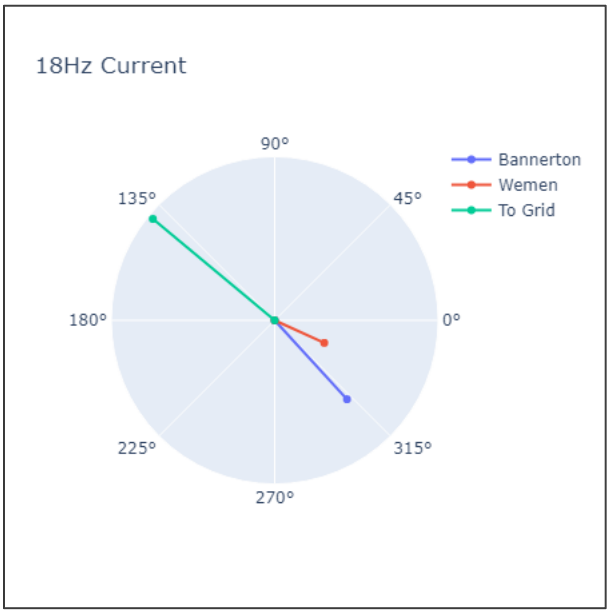
Running the signal for phase A voltage through a moving window FFT provided the following spectrogram:

Figure 45 Phase A voltage spectrogram of oscillations on 23 June 2022 at 1028 hrs



The major component is a persistent 18Hz oscillation of approximately 1% peak-to-peak in the RMS voltage measurements. Performing a FFT of the A phase RMS current injections from Wemen and Bannerton and extracting the magnitude and angle of the 18Hz component gives the following polar plot:

Figure 46 Phase A current phasor plot of Bannerton and Wemen SF on 23 June 2022 at 1028 hrs



From this polar chart, we can see that the oscillations in current from both Bannerton and Wemen are approximately in-phase. As the 18Hz current vectors for Bannerton and Wemen lie in the right-hand plane (with angles relative to A phase voltage), both are generating oscillating energy at 18Hz, which is being sent into the grid (by Kirchhoff's current law). This means that both Bannerton and Wemen are oscillating together against the grid, instead of against one-another.