# Solar Analytics – Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances

# Project results and lessons learnt

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# Table of Contents

# Executive Summary

The Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances project was initiated with the aim of helping the Australian Energy Market Operator (AEMO) to manage the transition to an energy system with a high proportion of distributed energy resources (DER).

## Disturbance analysis

Data from distributed photovoltaic (DPV) systems connected to the National Electricity Market (NEM) around voltage and frequency disturbances was provided to AEMO for analysis so that a better understanding of fielded DPV response to various grid conditions could be achieved, enabling AEMO to update system models and make appropriate adjustments to system management to maintain system reliability through the rapid growth in DPV capacity.

The findings from this analysis include evidence of extensive disconnection of DPV in response to voltage disturbances. This can increase contingency sizes, and necessitate market intervention such as enablement of increased frequency reserves, or implementation of more stringent network constraints. Evidence was also found of failure of significant proportions DPV systems to correctly reduce output in response to over-frequency conditions.

Several outcomes of significant system relevance have been made as a result of these findings together with other complementary research. These include:

- A new voltage ride-through test which has been incorporated into the new Distributed Energy Resource (DER) technical standards
- A change in constraints on the South-Australia – Victoria Heywood Interconnector.
- A new recommendation for managing minimum operational demand in South Australia, which led to the South Australian Smarter Homes regulations
- Engagement with inverter manufacturers to review settings in fielded systems
- Updates to system models, including more accurate contingency calculations based on more accurate understanding of DPV response
- Initiation of a similar program of analysis in the South-West Interconnected System

## Firmware/software improvements for existing devices

In order to make continued the provision of disturbance data sustainable, changes to firmware and software have been completed by hardware partner Wattwatchers and Solar Analytics respectively. These changes make highest resolution data available when it is most needed – around grid disturbances, while minimising data costs at other times. The changes include:

- Setting the default data interval to 60s, with only the most critical attributes {time, active energy} in order to reduce data cost
- Introduce a firmware change to store a buffer of 5s data containing the full suite of attributes {time, active energy, reactive energy, voltage, current, frequency}, which can be extracted after a grid disturbance, even when the device is normally reporting at 60s intervals

- Introduce an algorithm to detect frequency and voltage disturbances, to request the buffered 5s interval data from before the disturbance and to set monitoring to 5s with full data attributes for several minutes following the disturbance
- Introduce a firmware change to calculate and report min, max and mean voltage, based on 250ms samples (rather than 5s samples) such that voltage disturbances are more likely to be detected.

These changes have been implemented on the existing fleet of fielded monitoring devices via over-the-air firmware updates.

## Feasibility of greater capabilities for future devices

Finally, a feasibility study has been conducted by Wattwatchers on a next generation monitoring device, which could include the following additional capabilities for even more valuable disturbance analysis.

- 250ms reporting of energy (real and reactive), frequency and voltage.
- Ability to detect voltage spikes or sags of <=50ms duration
- On-board detection of disturbances and automatic triggering of high-resolution data
- More powerful processing through a real-time operating system and more reliable IoT communications

# Project Overview

## Project summary

As the amount of distributed photovoltaic (DPV) energy systems connected to the grid increases, it becomes more important to understand how these systems respond to different grid conditions. A reliable energy system must be able to withstand disturbances such as the loss of generation or load or the interruption of transmission infrastructure, which allows power to flow where it's needed. Such events can manifest as rapid changes to the grid frequency (nominally balanced at 50Hz over the entire synchronised system) or to voltage (which changes depending on the location, but is nominally 230 V when delivered to residential consumers).

A number of features are in place in the energy markets and in regulatory processes to ensure that energy systems can react appropriately to such disturbances. With the combined DPV capacity in the National Electricity Market (NEM) already over 11GW[1] - greater than the capacity of the Loy Yang, Eraring, Bayswater and Liddell coal power stations combined – it is vital that these PV generators also play their part in keeping the system working. Mechanisms to ensure this include the AS/NZS 4777.2:2015 standard for grid connection of energy systems via inverters, which covers DPV. However, until now, the performance of DPV in the field has not been thoroughly analysed to verify the operation in line with these standards or to identify opportunities to improve the standards.

The project *Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances* is aimed at helping the Australian Energy Market Operator manage the clean-energy transition. The two project outcomes were defined as

1. Enable market operators to manage the power system with a high share of Distributed Energy Resources (DER) while maintaining reliability and system security.
2. Increase the visibility, predictability or control of DER for AEMO, network service providers or other relevant entities to optimise power system operation within secure technical limits.

## Project scope

The project has endeavoured to meet these outcomes through three activity streams:

1. Sharing Solar Analytics datasets around grid disturbances for AEMO to analyse and use in improving system models.
2. Implementing firmware and software improvements by Wattwatchers and Solar Analytics respectively to add further data monitoring capabilities, providing greater opportunities for AEMO analysis and lower cost of data provision.
3. Investigating hardware improvements to add more sophisticated monitoring capabilities, including sub-second time-series.

[1] https://pv-map.apvi.org.au/historical

# Outcomes

Several outcomes of significant system relevance have been made as a result of analysis of AEMO's analysis of data collected by Solar Analytics using Wattwatchers monitoring devices. These include:

- A new voltage ride-through test[2] which has been incorporated into the new Distributed Energy Resource (DER) technical standards[3]
- A change in constraints[4] on the South-Australia – Victoria Heywood Interconnector.
- A new recommendation for managing minimum operational demand in South Australia[5], which led to the South Australian Smarter Homes regulations[6]
- Engagement with inverter manufacturers to review settings in fielded systems
- Updates to system models, including more accurate contingency calculations based on more accurate understanding of DPV response
- Initiation of a similar program of analysis in the South-West Interconnected System

Further to this, new software and firmware capabilities have been developed, making it feasible to continue cost-effective provision of data around grid disturbances. The development of further hardware capabilities, targeting sub-second data reporting have also been assessed as feasible through a next-generation hardware design process.

# Transferability

While the focus of this project has been on the impact of voltage and frequency disturbances on distributed PV within the National Electricity Market, the outcomes are also relevant to other networks, including the South-West Interconnected System in Western Australia. Investigations have begun regarding disturbance events in that network.

The voltage disturbances that have been detected and demonstrated in this report have been shared with the relevant network service providers. Discussions have been initiated in order to understand whether these data may be of benefit to operational management.

Finally, Australia is leading the world in experiencing and solving issues regarding integration of high levels of distributed energy into electricity networks. It is likely that the findings outlined here will be of value to others around the world in developing policy, standards and operational procedures to help ensure a successful clean energy transition.

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[2] https://aemo.com.au/-/media/files/electricity/der/2021/vdrt-test-procedure.pdf?la=en
[3] https://www.aemc.gov.au/news-centre/media-releases/new-standards-will-help-power-system-handle-more-home-solar?utm_medium=email&utm_campaign=New%20AEMC%20Update%20-%20%2025%20February%202021&utm_content=aemc.gov.au/news-centre/media-releases/new-standards-home-solar-will-help-protect-power-stability&utm_source=www.vision6.com.au
[4] https://www.aemo.com.au/-/media/files/initiatives/der/2020/heywood-ufls-constraints-fact-sheet.pdf?la=en
[5] https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/SA_Advisory/2020/Minimum-Operational-Demand-Thresholds-in-South-Australia-Review
[6] https://www.energymining.sa.gov.au/energy_and_technical_regulation/energy_resources_and_supply/regulatory_changes_for_smarter_homes

# Conclusion and next steps

The planned project outcomes have been met as evidenced by the significant changes that have been made based on project findings as presented in the Outcomes section above and in the Lessons learnt reports. The changes made by AEMO as a result of this project and complementary research programs will help AEMO manage the system without requiring severe limits on DER hosting capacity. It is quite likely that the probability of a major system outage due to unexpected impacts of DPV has been reduced through the changes made as a result of this project and associated research.

The findings made by AEMO based on data shared within this project have been significant enough to encourage further collaboration. A follow-on collaborative project is being formed to continue to help AEMO manage the transition to a high DER grid.

The trigger settings and software capabilities at Solar Analytics will be optimised based on feedback such that the ideal balance between data value and cost can be achieved.

Engagement with Wattwatchers will continue through the existing commercial arrangements between it and Solar Analytics. Where new features are cost effective in terms of the base hardware and royalty costs compared with the potential revenue of data sales, these features may be integrated into the new hardware.

# Lessons Learnt

## Lessons Learnt Report 1: Response of distributed photovoltaics to grid disturbances

***Project Name: Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances***

| | |
|---|---|
| **Knowledge Category:** | Technical |
| **Knowledge Type:** | Other (please specify): Network/market management; compliance |
| **Technology Type:** | Solar PV |
| **State/Territory:** | Qld, NSW, Vic, SA, Tas |

## Key learning

The project revealed evidence of extensive disconnection of distributed photovoltaics (DPV) in response to voltage disturbances and evidence of significant numbers of DPV systems failing to deliver the expected over-frequency droop response.

## Implications for future projects

The value of evidence obtained exceeded expectations and suggest that the right approach was taken within this project. The implications of the findings on system reliability are significant and warrant further investigation. Future projects would benefit from larger datasets, resulting in greater statistical confidence and allowing greater coverage and diversity in manufacturers, models, geographic location and date of installation.

## Knowledge gap

The project was limited to the NEM region. Similar analysis in the South-West Interconnected System in Western Australia is needed to confirm if similar results are found there. Data availability was also limited in Tasmania. Since Tasmania is not synchronised to the NEM and therefore has less frequency stability, more data is needed to monitor and manage DPV response there.

## Background

### Objectives or project requirements

The project *Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances* is aimed at helping the Australian Energy Market Operator manage the clean-energy transition. The two project outcomes were defined as

1. Enable market operators to manage the power system with a high share of Distributed Energy Resources (DER) while maintaining reliability and system security.
2. Increase the visibility, predictability or control of DER for AEMO, network service providers or other relevant entities to optimise power system operation within secure technical limits.

## Process undertaken

For this aspect of the project, we endeavoured to meet these outcomes by sharing Solar Analytics datasets around grid disturbances for AEMO to analyse and use in improving system models.

Many datasets around grid disturbances have been shared with AEMO during the course of the project, including PV production, site load, voltage and frequency at either 5s, 30s or 60s time resolution for hundreds or thousands of sites, together with standing data such as inverter manufacturer and model, year of installation and postcode.

The data from these sites are measured at the main supply board by Wattwatchers Auditor monitoring devices and communicated to Solar Analytics servers via 4G mobile networks. The maximum data resolution at the start of the project was 5s, but due to the cost of mobile communications, most devices were configured to communicate at 30s or 60s intervals. In order to assess the relative benefit of 5s data, 1000 devices were configured to communicate at 5s intervals from ~September 2020 to ~March 2021.

Shared datasets include those listed in Table 1.

*Table 1: List of datasets shared with AEMO. Where data analysis is included in an AEMO incident report, these are listed with links.*

| Event date | Region | Incident report |
|---|---|---|
| 2017-03-03 | SA | |
| 2018-01-18 | VIC | |
| 2018-01-24 | SA, VIC | |
| 2018-08-25 | NSW, QLD, SA, VIC | Queensland and South Australia system separation |
| 2019-01-24 | SA, VIC | |
| 2019-04-11 | NEM | |
| 2019-04-15 | NSW, QLD, SA, VIC | |
| 2019-06-07 | NEM | |
| 2019-09-22 | TAS | |
| 2019-10-09 | NSW, QLD | |
| 2019-10-09 | SA, VIC | |
| 2019-10-09 | NEM | |
| 2019-11-16 | NEM | South Australia and Victoria Separation Event |
| 2019-11-26 | NSW, QLD | Trip of South Pine 275 kV No. 1 Busbar and 275/110 kV No. 5 Transformer |
| 2020-01-04 | NEM | New South Wales and Victoria Separation Event |
| 2020-01-23 | TAS | |
| 2020-01-31 | NEM | Victoria and South Australia Separation Event |
| 2020-03-02 | NEM | |
| 2020-08-30 | TAS | |
| 2020-10-27 | QLD | |
| 2020-10-28 | QLD | |
| 2020-12-03 | TAS | |
| 2020-12-07 | SA | |

The data from the South Pine event on 2019-11-26 has also been shared with a number of research institutes to allow for further analysis. These include:

- Murdoch university
- University of Sydney
- University of Queensland
- University of Technology, Sydney
- Queensland University of Technology

## Supporting information

Findings from this project have been incorporated in several AEMO reports, including incident reports[7] for a number of disturbances, the Renewable Integration Study[8] (RIS), the 2020 Integrated System Plan[9] (ISP) and the 2020 Electricity Statement of Opportunities[10] (ESOO).

AEMO is in the process of drafting a further report – "Behaviour of distributed photovoltaics during power system disturbances" - covering the findings specifically from this project and a related ARENA-funded project "Addressing Barriers to Efficiency Renewable Integration", focusing on laboratory bench testing of DER behaviour.

The findings include evidence of extensive disconnection of DPV in response to voltage disturbances. This can increase contingency sizes, and necessitate market intervention such as enablement of increased frequency reserves, or implementation of more stringent network constraints. The trend across multiple events is shown in Figure 1.

[7] https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-events-and-reports/power-system-operating-incident-reports
[8] https://aemo.com.au/en/energy-systems/major-publications/renewable-integration-study-ris
[9] https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp
[10] https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2020/2020-electricity-statement-of-opportunities.pdf?la=en&hash=85DC43733822F2B03B23518229C6F1B2

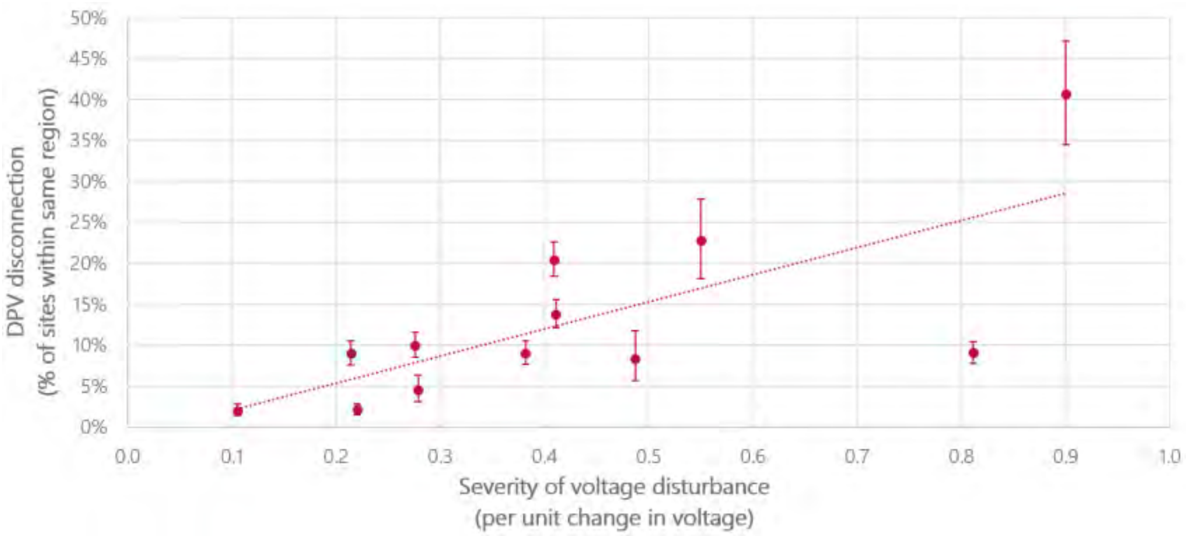



*Figure 1: Percentage of distributed PV sites in a region observed to disconnect following voltage disturbances. From Fig. 14 of AEMO's Renewable Integration Study, Appendix A[11], section A4.1, pg. 31.*

Undesirable behaviour was also identified during frequency disturbances. AEMO's incident report - Victoria and South Australia Separation Event on 31 January 2020[12] – identified that *"About 35% of* distributed PV systems on the 2015 standard did not deliver the over-frequency droop response specified in the standard, instead remaining in continuous operation at pre-disturbance output." as shown in Figure 2.

[11] https://aemo.com.au/-/media/files/major-publications/ris/2020/ris-stage-1-appendix-a.pdf?la=en
[12] https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/final-report-vic-sa-separation-31-jan--2020.pdf?la=en

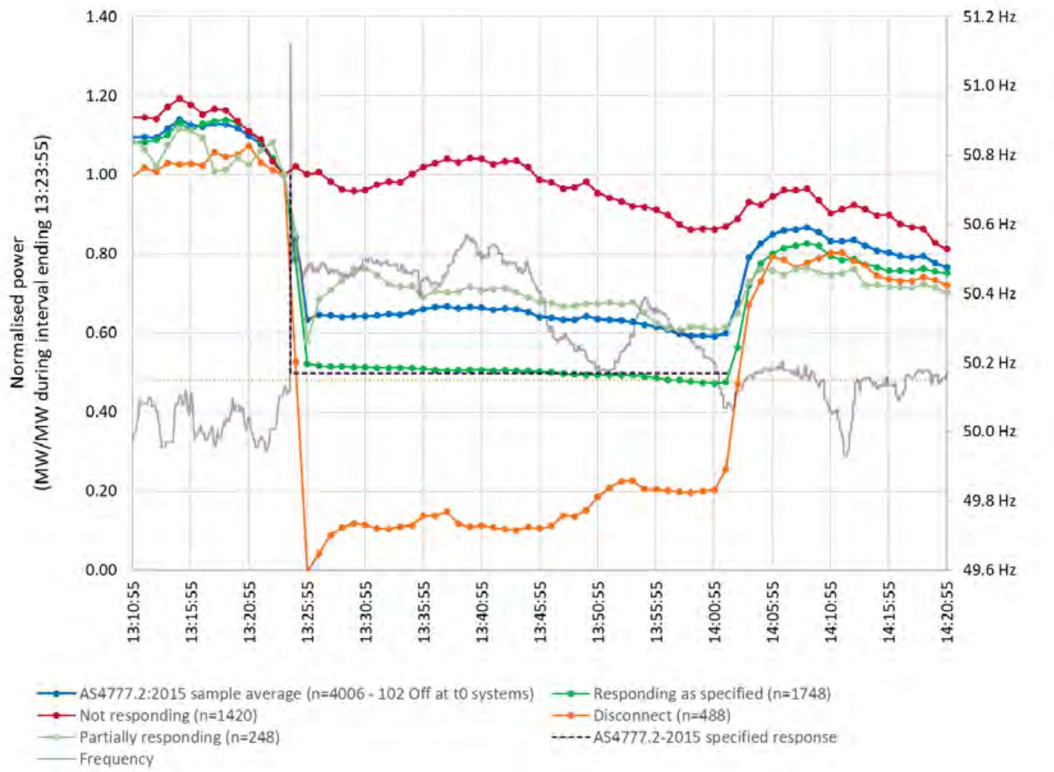



*Figure 2: Normalised response of DPV systems under the 2015 standard in South Australia during 31 January grid separation event. From Fig 14 of AEMO incident report, Victoria and South Australia Separation Event on 31 January 2020[13], Appendix 1, pg. 34.*

[13] https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/final-report-vic-sa-separation-31-jan--2020.pdf?la=en

# Lessons Learnt Report 2: Value of different data intervals

***Project Name: Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances***

| | |
|---|---|
| **Knowledge Category:** | Technical |
| **Knowledge Type:** | Other (please specify): Network/market management; compliance |
| **Technology Type:** | Solar PV |
| **State/Territory:** | Qld, NSW, Vic, SA, Tas |

## Key learning

Data with shorter time intervals is more valuable for analysis of DPV response.

## Implications for future projects

New data capabilities have been deployed to allow provision of 5s data around disturbances at manageable cost (see Lessons learnt report 3). This capability should be utilised in future projects, enabling deeper analysis of events and better understanding of response.

## Knowledge gap

Analysis of response at even shorter time intervals (<1s) would potentially add greater value in identifying the disconnection response of DPV with regard to Australian Standard 4777.2

## Background

### Objectives or project requirements

The project *Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances* is aimed at helping the Australian Energy Market Operator manage the clean-energy transition. The two project outcomes were defined as

1. Enable market operators to manage the power system with a high share of Distributed Energy Resources (DER) while maintaining reliability and system security.
2. Increase the visibility, predictability or control of DER for AEMO, network service providers or other relevant entities to optimise power system operation within secure technical limits.

### Process undertaken

For this aspect of the project, we reviewed the findings from AEMO analysis of datasets with different time resolutions and compared available data resolutions to the requirements in AS4777.2

# Supporting information

While many valuable conclusions were able to be made by AEMO based on 60s samples. It is clear than when the energy system is changing quickly, higher data resolution is better for analysing events.

### *Voltage sags*

Comparisons shown in Figure 1 were made between PV disconnection rates and minimum voltage following a disturbance, where the voltage was measured via high speed monitoring in the transmission network. These voltage sags have typical durations of 100-300ms, and are therefore unlikely to be captured by Wattwatchers devices measuring at 5s intervals. This means that it is not possible to measure the minimum voltage experienced by the solar inverter in the distribution network (for comparison with high speed measurements in the transmission network). Voltages measured at 250ms intervals will be more likely to capture an accurate representation of the voltage sag.

### *Reconnection profiles*

AS/NZS 4777.2:2015 requires systems to disconnect within 0.2 – 2 seconds of a voltage or frequency disturbance, depending on severity, as shown in **Error! Reference source not found.**. It further requires systems to reconnect after no less than 60s and to ramp back to rated power over no less than 6 minutes.

While the ramp up can be observed in measurements over 60s intervals, the duration of the disconnection can only be confirmed using 5s intervals. The trip delay and disconnection time would be verifiable with 250ms intervals for most cases. For Overvoltage 2 and for over-frequency, a disconnection time of 0.2s is required. While the precise verification of this time could not be achieved with 250ms intervals, they would at least give a very good indication of conformance.

*Table 2: Passive anti-islanding set-point values. From AS/NZS 4777.2:2015, section 7.4:*

| Protective function | Protective function limit | Trip delay time | Maximum disconnection time |
|---|---|---|---|
| Undervoltage (V<) | 180 V | 1 s | 2 s |
| Overvoltage 1 (V>) | 260 V | 1 s | 2 s |
| Overvoltage 2 (V>>) | 265 V | - | 0.2 s |
| Under-frequency (F<) | 47 Hz (Australia)<br>45 Hz (New Zealand) | 1 s | 2 s |
| Over-frequency (F>) | 52 Hz | - | 0.2 s |

When frequency disturbances last for many minutes, which is the case for example in grid separation events, 60s intervals are sufficient to assess the output of DPV, as is evident in Figure 2. However, accurately estimating the pre-event power output is essential for assessing conformance with the over-frequency droop requirements in the 2015 standard.

Figure 3 shows the average response of DPV to a Voltage disturbance associated with the South Pine busbar and transformer trip on 26 November 2019. The data are in 5s intervals and demonstrate sufficient resolution to identify the pre-disturbance power and duration of disconnection, which was not reliably possible with larger data intervals.


*Figure 3: Response of DPV systems installed under different standards to the voltage disturbance associated with a voltage disturbance. Inset shows the response of inverters installed under the 2015 standard against the expected response. From Fig 6 of AEMO incident report Trip of South Pine 275 kV No. 1 Busbar and 275/110 kV No. 5 Transformer on 26 November 2019[14], Appendix 2, pg. 16.*

[14] https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2019/incident-report-south-pine-incident-on-26-nov-19.pdf?la=en&hash=0DF7B519D37BF3CCA1FCF9CF4A4C0CE7

# Lessons Learnt Report 3: New firmware/software capabilities

***Project Name: Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances***

| | |
|---|---|
| **Knowledge Category:** | Technical |
| **Knowledge Type:** | Technology |
| **Technology Type:** | Solar PV |
| **State/Territory:** | Qld, NSW, Vic, SA, Tas |

## Key learning

We are able to extract the most valuable data specifically around grid disturbances, while keeping data costs low at other times.

## Implications for future projects

This makes it financially viable to continue analysing data around grid disturbances. Allowing future projects to follow on from this work.

## Knowledge gap

More work is needed to find the ideal trigger settings to identify significant disturbances, balancing sufficient data availability with low cost.

## Background

### Objectives or project requirements

The project *Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances* is aimed at helping the Australian Energy Market Operator manage the clean-energy transition. The two project outcomes were defined as

1. Enable market operators to manage the power system with a high share of Distributed Energy Resources (DER) while maintaining reliability and system security.
2. Increase the visibility, predictability or control of DER for AEMO, network service providers or other relevant entities to optimise power system operation within secure technical limits.

### Process undertaken

For this aspect of the project, we implemented firmware and software improvements by Wattwatchers and Solar Analytics respectively to add further data monitoring capabilities, providing greater opportunities for AEMO analysis and lower cost of data provision.

# Supporting information

## Planned improvements

In order to increase data capabilities while reducing costs, a number of firmware and software changes were targeted:

1. Set default data interval to 60s (reduce cost compared with 5s)
2. Set default 60s data attributes to {time, active energy} (reduce cost compared to the full suite of {time, active energy, reactive energy, voltage, current, frequency})
3. Introduce a firmware change to calculate and report min, max and mean voltage over the 60s or 5s period, based on 250ms samples.
4. Introduce a firmware change to calculate and report min, max and mean voltage over a 5min period, based on 250ms samples.
5. Introduce a firmware change to store a buffer of 5s data containing the full suite of attributes, which can be extracted after a grid disturbance, even when the device is normally reporting at 60s intervals
6. Introduce an algorithm to detect frequency and voltage disturbances, to request the buffered 5s interval data from before the disturbance and to set monitoring to 5s with full data attributes for several minutes following the disturbance

The expected benefit of this was to make 5s interval data available when it's most valuable, i.e. around disturbances and otherwise keep data communication costs to a minimum at other times. Further, the voltage statistics based on 250ms samples allow for more accurate measurement of voltage conditions, which influence PV response, as well as better detection of disturbances.

Each of these is discussed in the following sections

## Demonstrated Improvements

### *Default 60 second interval*

Wattwatchers Auditor devices can be configured to report data in multiples of 5s. When Solar Analytics first began monitoring DPV with Wattwatchers devices in 2014, communication was via WiFi, which kept costs low, allowing 5s reporting. When devices were moved to 3G in 2015 to increase reliability, reporting was changed to 30s to manage mobile communications costs. A further increase to 60s intervals was made in 2018, along with software functionality to automatically switch to 5s intervals when a PV system owner logged on to their Solar Analytics dashboard.

In August 2019, 1000 devices, about half of which were in Qld, were set to always report at 5s intervals in order to allow AEMO to perform deeper analysis while new capabilities were being developed. These were set back to 60s in March 2021.

The cost difference between permanent reporting in 60s data intervals and 5s intervals was estimated to be about $1/device/month, which is significant for a full fleet of over 20,000 devices.

### *Fewer attributes*

A further cost saving was made in April 2020, in which the number of attributes reported at 60s (or 5s) was reduced to the most essential for core monitoring services, i.e. energy and timestamp. Prior to that, each interval contained additional attributes, including voltage, frequency, reactive power.

### *250ms voltage sampling*

The voltage reported in the 5s or 60s data was previously measured as a single instantaneous value at the end of the period. This means that important short-duration voltage events during that period would go undetected. Voltage summary information - voltage_min and voltage_max reported in 5 minute intervals were based on the minimum and maximum of the 5s voltage samples.

In order to increase the accuracy of reported voltage information, a firmware upgrade was completed by Wattwatchers to measure and report min, max and mean voltage based on 250ms samples within the 5s or 60s reporting intervals and in the 5-minute summary data.

### *Buffered 5 second data*

Wattwatchers introduced a firmware upgrade in 2020, first as a prototype and then as a production-grade version, which enabled the storage of a buffer of 5s data containing the full suite of attributes, which can be extracted after a grid disturbance, even when the device is normally reporting at 60s intervals.

The buffer stores approximately 10 minutes of 5s interval data, which can be extracted via multiple API calls to the device.

### *Automatic extraction of 5s data*

Software development at Solar Analytics allowed for the automatic extraction of 5s data when a disturbance is detected. When this occurs, a series of API calls are sent to the relevant devices to extract the data and then store it on the Solar Analytics cloud servers. Further, the device is then configured to keep reporting at 5s intervals for the following 7 minutes, providing the full suite of attributes. This means that an uninterrupted 17 minutes' worth of 5s data can be provided around a disturbance.

An email notification is sent to defined addresses, allowing the preparation and sharing of datasets around the disturbances.

Although this capability has been functional from October 2020, there have been no significant disturbances involving PV since then for AEMO to analyse. However, the buffers have been triggered many times by minor disturbances, which are discussed below as demonstration.

### *Voltage disturbances*

The algorithm has been configured to monitor the 5-minute values of voltage_min and voltage_max. For any enabled monitoring device, when the difference between voltage_min and voltage_max is greater than 30V, the additional data is captured.

Figure 4 shows 5-minute voltage data for one device on October 23, revealing a dip at 5:45am local time.

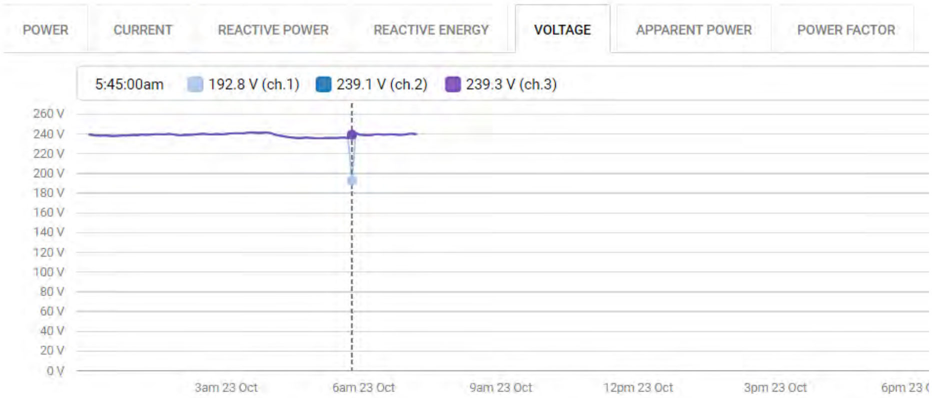



*Figure 4: 5 minute voltage data for a single device. This plot shows the mid-range between voltage_min and voltage_max.*

Figure 5 then shows the change in data captured from 60s intervals to 5s intervals, occurring several minutes prior to 5:45am and lasting until several minutes after. Additional spikes in the measured power can be identified in the 5s measurements, which were not visible in the 60s measurements.

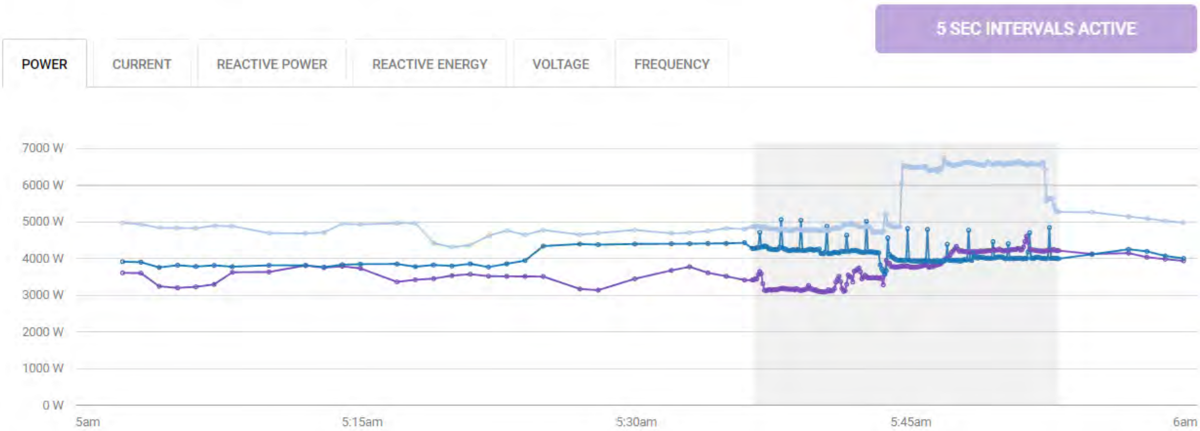



*Figure 5: Grid consumption data for a single device showing the change from 60s intervals to 5s intervals*

Figure 6 shows the capture of additional voltage data. No voltage data is provided until the period surrounding the disturbance. This is also true for frequency and other ancillary parameters.

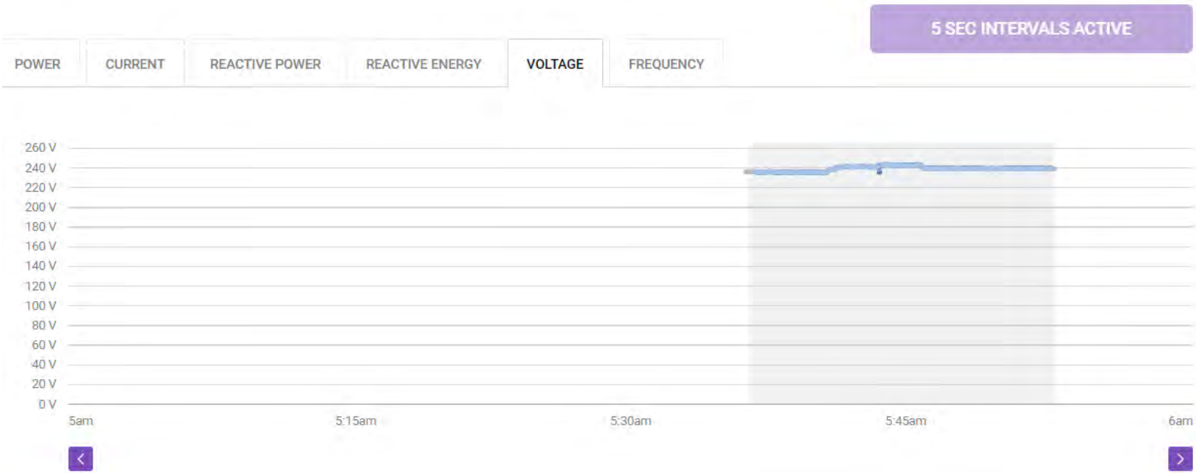



*Figure 6: 5s voltage data for the device on which the disturbance was detected*

Table 1 shows further detail on the extracted data, with a minimum voltage of 140.3V recorded at 5:43:30am. These min, max and mean values were calculated based on 250ms samples discussed above

*Table 3: Selected 5s voltage data for the device on which the disturbance was detected*

| timestamp | energy (J) | freq (Hz) | vmin (V) | vmax (V) | vmean (V) |
|---|---|---|---|---|---|
| 2020-10-23 05:43:15 | 17351 | 49.95 | 240.6 | 241.4 | 241.1 |
| 2020-10-23 05:43:20 | 17279 | 49.93 | 240.8 | 241.3 | 241.1 |
| 2020-10-23 05:43:25 | 17422 | 49.95 | 240.8 | 241.3 | 241 |
| 2020-10-23 05:43:30 | 16425 | 49.94 | 140.3 | 245.2 | 235 |
| 2020-10-23 05:43:35 | 17853 | 49.97 | 231.1 | 242.5 | 241.5 |
| 2020-10-23 05:43:40 | 19760 | 50 | 237.7 | 243.5 | 242.6 |
| 2020-10-23 05:43:45 | 19328 | 49.94 | 242.7 | 243.9 | 243.5 |

At present, the buffered data is captured only for the devices on which a disturbance is detected. An email alert is sent when 100 or more devices within a single state experience these conditions in the same 5 minute interval. To date, such events appear to be related to localised network issues rather than disturbances of significant relevance to AEMO.

Figure 7 to Figure 9 show the voltage disturbances mapped to location for three such separate events. In each case, the maximum voltages recorded were similar to those in surrounding timestamps, but the minimum voltages were significantly lower, in some cases below 20V, i.e. a delta of more than 0.9.pu. Such measurements were beyond the specified voltage measurement range of the Wattwatchers devices (rated down to 50V), however the exact value in this range is not deemed to be important (as it is well beyond the values relevant for inverter standards), but is simply sufficient to show that some locally significant disturbance occurred. Such events were not associated with a power outage at the measured location (which would cause a loss of data). Discussions have begun with the relevant network operators on whether such disturbance information is valuable to them.

In the meantime, these events demonstrate the ability to detect widespread voltage disturbances. AEMO has indicated that for significant disturbances, it would be valuable to extract the buffered 5s data for *all* devices in a region, including those which don't experience the disturbance. Further work is anticipated to optimise the definition of a significant disturbance, such that these additional data can be captured without incurring excessive data costs.

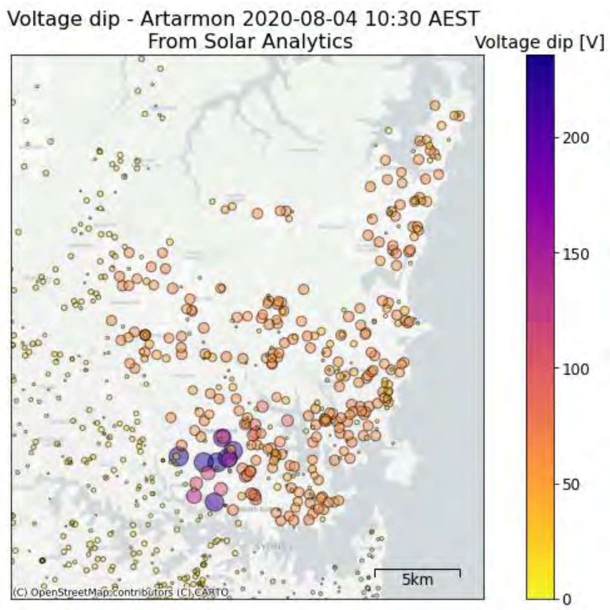



*Figure 7: Voltage disturbance centred at Artarmon, in the Ausgrid network in NSW. Colour and size both represent the size of the voltage dip between the maximum and minimum voltages recorded in the five minutes to 10:30 AEST*

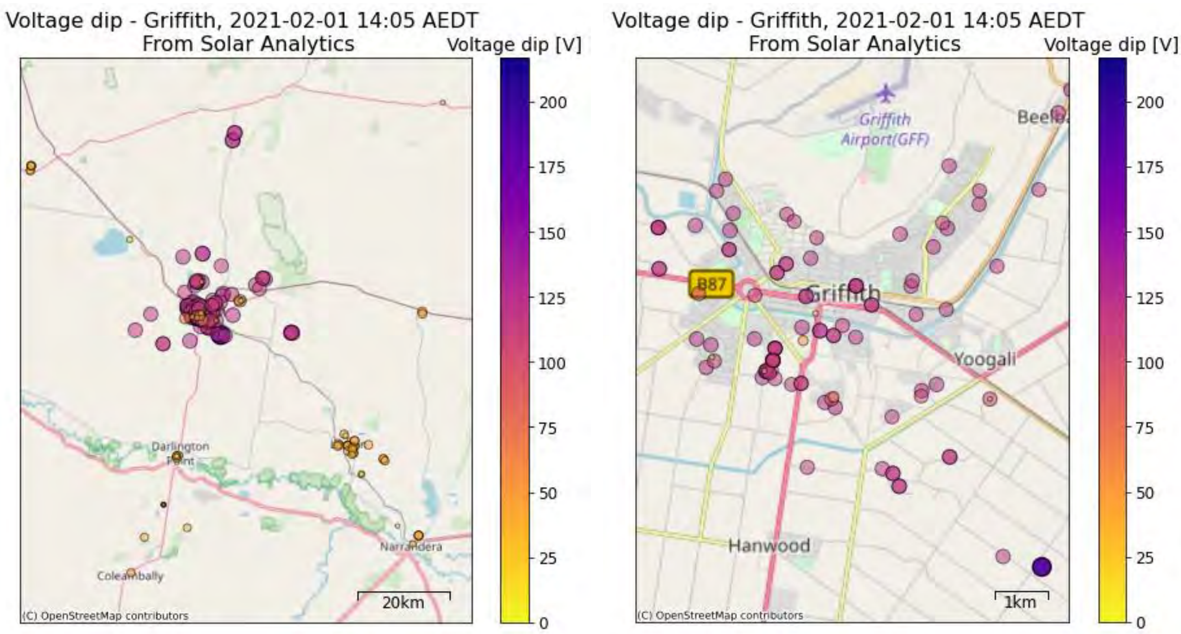



*Figure 8: Voltage disturbance centred around Griffith, in the Essential Energy network in NSW showing (left) regional scale and (right) central scale. Colour and size both represent the size of the voltage dip between the maximum and minimum voltages recorded*

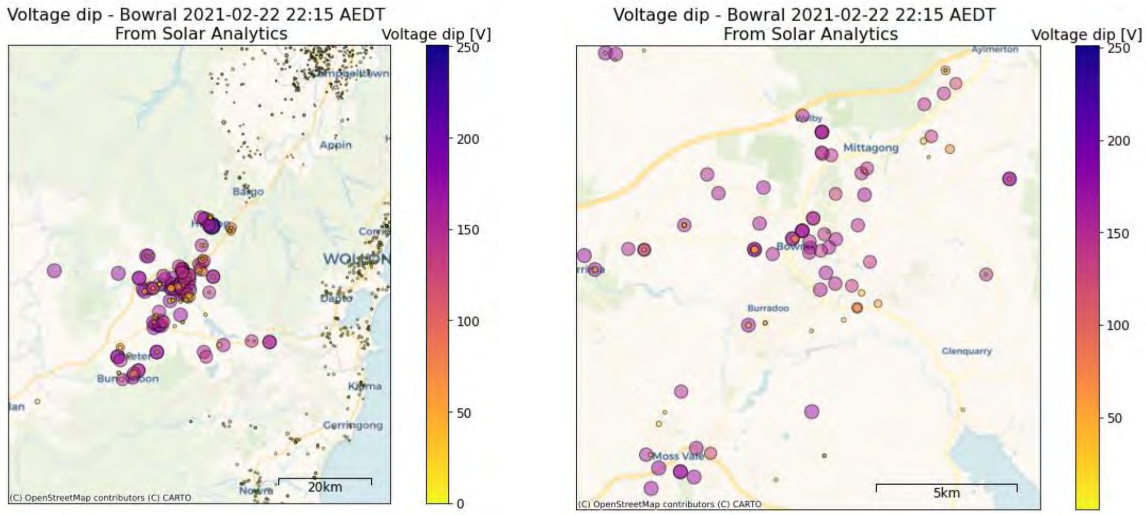



*Figure 9: Voltage disturbance centred around Bowral, in the Endeavour Energy network in NSW showing (left) regional scale and (right) central scale. Colour and size both represent the size of the voltage dip between the maximum and minimum voltages recorded in t*

### *Frequency disturbances*

Since frequency is nearly identical everywhere on a synchronised grid, it is not necessary to monitor every device separately, but it is necessary to capture data for all devices when a disturbance is detected.

In each NEM region (Qld, NSW, Vic, SA, Tas), five devices have been set to always report frequency in 5s intervals. These data are constantly monitored and when a deviation beyond a set boundary is detected in a region, the buffer of 5s data is extracted from up to a set maximum number of devices in that region and those devices are set to continue to report 5s data with all attributes for the following 7 minutes.

If, as is usually the case, a disturbance causes frequency to move beyond the set boundaries simultaneously in *all* synchronised regions, the data is extracted from devices in all of those regions.

This can put great strain on the Solar Analytics servers and an increase in the number of workers was required to extract data all the data. Limitations on numbers were made in order to test operation in small volumes before increasing. The limitation is currently set to 2000 devices per region.

The frequency deviation thresholds are currently set to 51.0 Hz and 49.0 Hz in Tasmania and to 50.15 Hz and 49.85 Hz in all other NEM regions. The boundaries were set wider in Tasmania as it is not synchronised to the main grid and incurs greater frequency fluctuations than the rest of the NEM.

One minor disturbance was detected at around 21:21 AEST on the 2$^{nd}$ of February 2021 and is presented below for demonstration.

An email alert was received at 21:21 AEST reporting frequency above 50.15Hz. 5s data were automatically captured for devices in Qld, NSW, Vic and SA.

Figure 10 shows the frequency measurements for one device in Qld around the time of the disturbance.

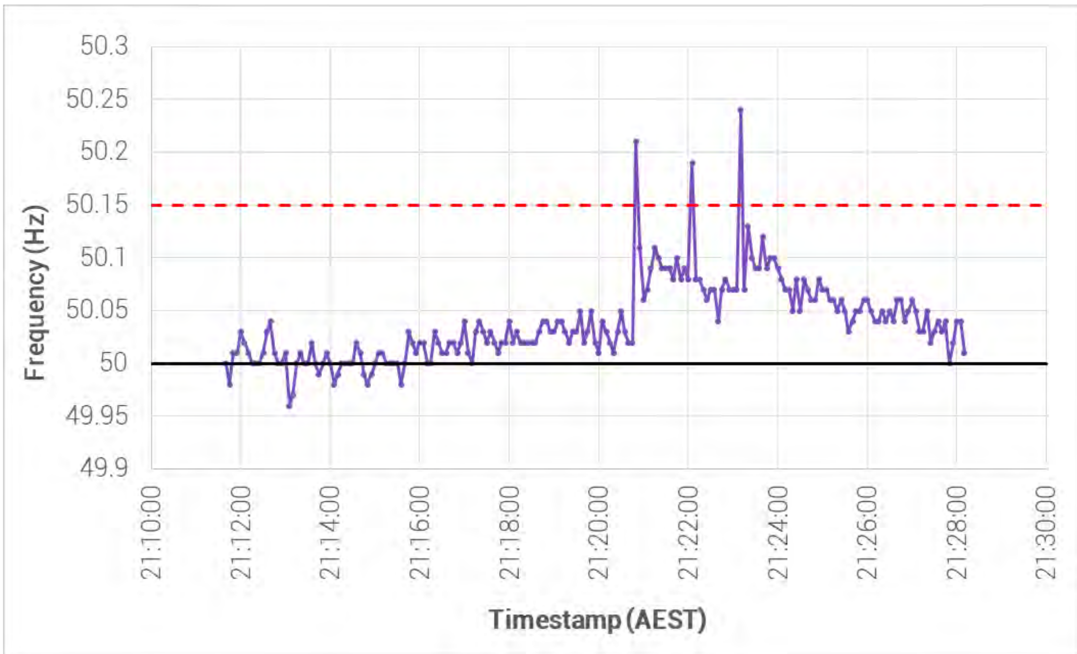
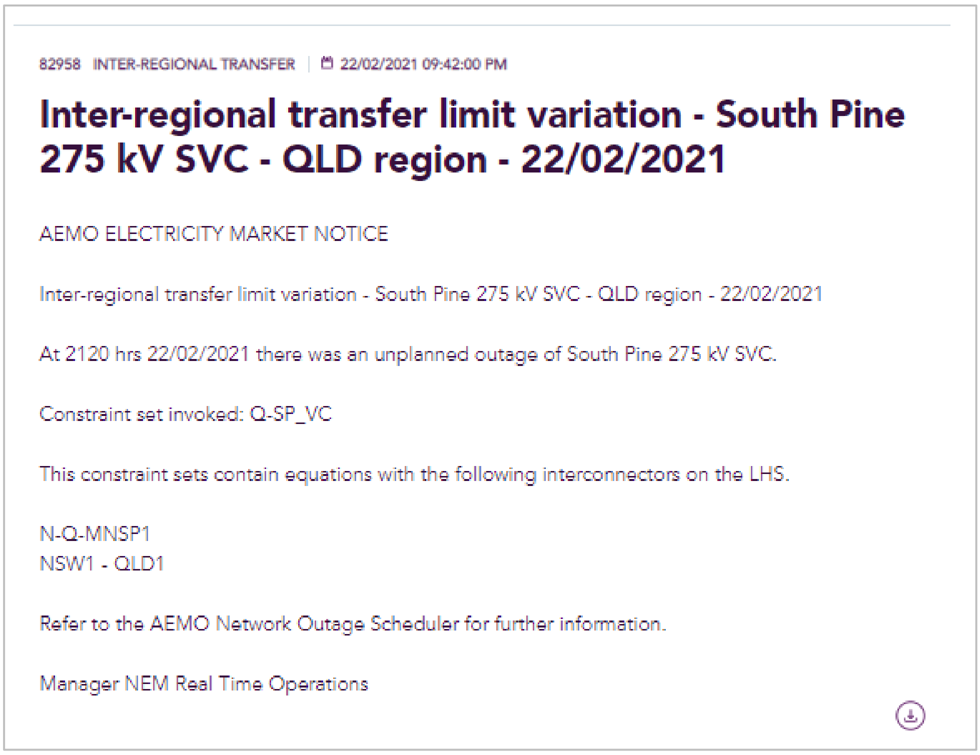



*Figure 10: Frequency measured in 5 second intervals by a Solar Analytics monitor in Qld, 2021-02-22, during a network fault. The red dashed line represents the upper edge of the Normal Operating Frequency Band (NOFB) at 50.15 Hz.*

Soon after, at 21:42, an AEMO market notice[15] alerted to an unplanned outage at the South Pine static VAr compensator (SVC) corresponding to the time of the detected disturbance.



82958 INTER-REGIONAL TRANSFER | 22/02/2021 09:42:00 PM

**Inter-regional transfer limit variation - South Pine 275 kV SVC - QLD region - 22/02/2021**

AEMO ELECTRICITY MARKET NOTICE

Inter-regional transfer limit variation - South Pine 275 kV SVC - QLD region - 22/02/2021

At 2120 hrs 22/02/2021 there was an unplanned outage of South Pine 275 kV SVC.

Constraint set invoked: Q-SP_VC

This constraint sets contain equations with the following interconnectors on the LHS.

N-Q-MNSP1
NSW1 - QLD1

Refer to the AEMO Network Outage Scheduler for further information.

Manager NEM Real Time Operations

*Figure 11: AEMO market notice regarding an outage at the South Pine SVC.*

[15] https://aemo.com.au/en/market-notices?marketNoticeQuery=South+Pine+275+kV+SVC&marketNoticeFacets=INTER-REGIONAL+TRANSFER#mnsr

Analysis of the times surrounding the event determined the proportion of devices in each region for which the additional data were captured before and after the event. Figure 12 shows almost no 5s data was available at exactly 10 minutes before the disturbance (normal monitoring conditions), but significant proportions were able to be extracted from the buffer, from -8 to 0 minutes to the disturbance, and these continued to 6 minutes after the disturbance.

NSW is the only region in which response was significantly lower than expected, at around 40-60% of devices prior to and during the disturbance. Two reasons are hypothesised for this:

1. The Bowral voltage event shown in Figure 9 was just six minutes prior to this frequency disturbance. It is possible that the continued processing of those earlier requests prevented full processing of the latter event.
2. NSW may simply have been last in the queue for processing and the number of workers is still insufficient for the amount of data requested.


*Figure 12: Percentage of devices responding with additional 5 second interval data, both prior to and during the disturbance, as extracted from the buffered data, and after the disturbance after switching to ongoing 5s reporting*

Table 4 shows the maximum number of monitoring devices which were online and available for 5s data extraction around the time of the disturbance. The percentages shown in Figure 12 are normalised to these maxima. These numbers are lower than the 2000 per region limit due to some being offline or no longer active.

Work will continue to ensure 100% reporting of available data and then the 2000 per region limit will be lifted to further increase the data availability.

*Table 4: Maximum number of monitoring channels online and available around the time of the disturbance and median frequency by state at the time of the first peak.*

| | Median frequency at 2021-02-22 21:20:50 | Number of devices reporting |
|---|---|---|
| Qld | 50.21 | 1308 |
| NSW | 50.17 | 1517 |
| SA | 50.16 | 1495 |
| Vic | 50.16 | 1621 |

Table 4 also shows the median frequency at timestamp 21:20:50 – the time the first disturbance above the NOFB was recorded. The median is taken to avoid influence of occasional erroneous measurements. This shows a slightly higher value in Qld, the region of the outage, compared to the other states. At all other times, the median frequency was within 0.01 Hz across all regions.

Although there was no record of a complete separation between Qld and the other regions at this time, the immediately reduced transmission capacity between NSW and Qld, which was a likely result of this event, probably prevented the resulting supply/demand imbalance to be evenly spread across the whole grid, resulting in a difference in the measured frequency.

The event also caused a momentary voltage dip across the Qld region as shown in Figure 13.

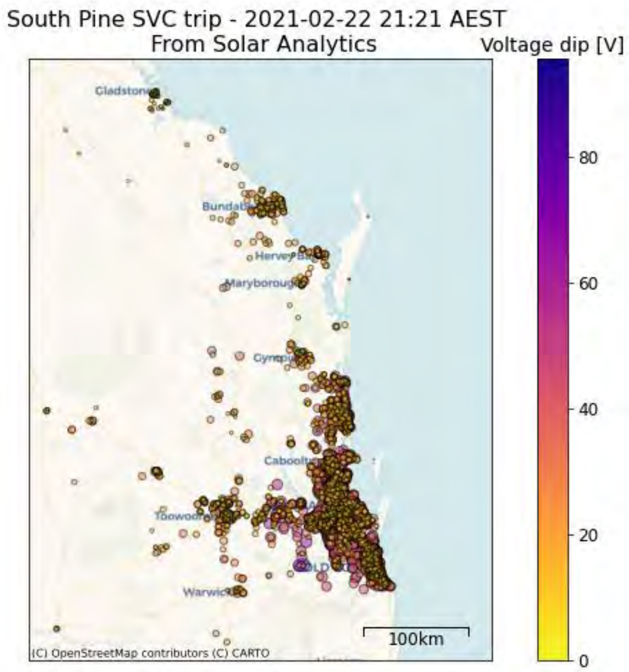



*Figure 13: Voltage disturbance throughout Queensland. Colour and size both represent the size of the voltage dip between the maximum and minimum voltages recorded in the five minutes to 21:25 AEST*

Of the 6070 sites monitored in Qld, 1880 had voltage dips of greater than 30V, reaching up to 70V ($\Delta V$ = 0.125 – 0.375pu). The dips were recorded in the same timestamp as the first frequency spike at 21:20:50. They were immediately followed by an increase in voltage to around 10V above the pre-disturbance values, which then abated over the following few minutes. Similar voltage conditions were observed in northern NSW, just south of the Qld border.

# Lessons Learnt Report 4: Feasibility of hardware improvements

***Project Name: Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances***

| | |
|---|---|
| **Knowledge Category:** | Technical |
| **Knowledge Type:** | Technology |
| **Technology Type:** | Solar PV |
| **State/Territory:** | Qld, NSW, Vic, SA, Tas |

# Key learning

New monitoring hardware design suggests it is feasible to report energy and voltage data at sub-second intervals around grid disturbances.

# Implications for future projects

The value of sub-second data may be more directly investigated in future projects to warrant the inclusion of such capabilities in future hardware iterations.

# Knowledge gap

Prototyping is required to verify that the features deemed feasible in design can be manufactured at the reasonable cost and are successful as anticipated.

# Background

## Objectives or project requirements

The project *Enhanced Reliability through Short Term Resolution Data around Voltage Disturbances* is aimed at helping the Australian Energy Market Operator manage the clean-energy transition. The two project outcomes were defined as

1. Enable market operators to manage the power system with a high share of Distributed Energy Resources (DER) while maintaining reliability and system security.
2. Increase the visibility, predictability or control of DER for AEMO, network service providers or other relevant entities to optimise power system operation within secure technical limits.

## Process undertaken

For this aspect of the project, hardware partner Wattwatchers investigated hardware improvements to add more sophisticated monitoring capabilities, including sub-second time-series.

# Supporting information

The potential qualitative value of data reported at 250ms intervals has been shown in this report, primarily with respect to verification of grid protection requirements in fielded systems. The hardware manufacturer Wattwatchers has undertaken an extensive hardware redesign study aimed at assessing the feasibility and cost of monitoring devices which best achieve the balance between the low-cost requirement of DPV monitoring, with the sophisticated feature set targeted and extending AEMO's ability to analyse DPV behaviour around disturbances.

The addition of several disturbance monitoring features has been assessed as feasible in the design assessment.

The features assessed include:

- Extending 250ms summary data across all three phases
- Identifying voltage peaks or sags with < 50ms duration
- Adding frequency summary data (min, max mean) based on 250ms sampling
- Allowing buffered data to be automatically pushed from the device upon certain triggers detected on-board without external intervention
- Allow minimum data reporting interval to be configured down to 250ms (currently 5s)
- Send a 'last-gasp' message alerting to imminent power down, allowing differentiation between power outages and communications outages.

These features have been assessed as feasible by the nature of the hardware design, particularly the improved capabilities of a real time operating system. The next steps to confirm these features and more accurate costs would be device prototyping.

The communications cost associated with constant reporting of 250ms interval data could be quite considerable, considering the 240x data volume increase compared to 60s interval data. However, like the 5s interval data in the present device, it is anticipated that the highest resolution would only be needed on rare occasions. An extension of the buffer feature demonstrated in this report would be required to only report 250ms interval data when it is needed.