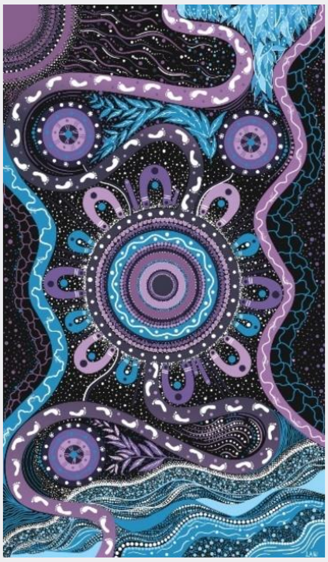
Analysis and modelling of a grid-forming battery energy storage system during a system incident

December 2024

Investigation of Dalrymple battery dynamic performance for 28 December 2023 events



We acknowledge the Traditional Custodians of the land, seas and waters across Australia. We honour the wisdom of Aboriginal and Torres Strait Islander Elders past and present and embrace future generations.

We acknowledge that, wherever we work, we do so on Aboriginal and Torres Strait Islander lands. We pay respect to the world's oldest continuing culture and First Nations peoples' deep and continuing connection to Country; and hope that our work can benefit both people and Country.

'Journey of unity: AEMO's Reconciliation Path' by Lani Balzan

AEMO Group is proud to have launched its first Reconciliation Action Plan in May 2024. 'Journey of unity: AEMO's Reconciliation Path' was created by Wiradjuri artist Lani Balzan to visually narrate our ongoing journey towards reconciliation – a collaborative endeavour that honours First Nations cultures, fosters mutual understanding, and paves the way for a brighter, more inclusive future.

Important notice

Purpose

This report investigates the performance of the Dalrymple Battery Energy Storage System (BESS) following a line trip event. Using simulations and comparison with High-Speed Monitoring (high-resolution) data, it validates the model accuracy and assesses the BESS's ability to support the grid during islanded operation, enhancing overall system resilience and reliability.

This report provides transparency on the emerging capabilities of grid-forming BESS, and the accuracy of AEMO's power system models in replicating the event. The learnings from this work help inform future investigative tasks aimed at optimising the integration and performance of grid-forming BESS. This work forms part of AEMO's Engineering Roadmap efforts to validate desktop study results for new technologies against real world performance.

This report has been prepared by AEMO based on the power system configuration as of 6 March 2024.

Disclaimer

Copyright

Version control

Version	Release date	Changes
1.0	20/12/2024	Initial release

Executive summary

This report presents the results of an investigation into the performance of the Dalrymple Battery Energy Storage System (BESS) when it formed an electrical island with the Wattle Point Wind Farm and local load. AEMO conducted the analysis using high-resolution data available for four events on 28 December 2023. During these power system events, the upstream Ardrossan West – Dalrymple 132 kilovolts (kV) line connecting the battery, wind farm and local load to the South Australia network tripped due to lightning in the area and subsequently re-synchronised several minutes later.

Since the Dalrymple BESS, Wattle Point Wind Farm and local load are connected to the grid via the 132 kV line, tripping the line results in the wind farm and battery becoming disconnected from the grid and forming an island with local load. There is a control scheme which detects opening of the upstream line and disconnects a certain number of wind turbines to facilitate the formation of an island.

AEMO's analysis of high-resolution data showed that the BESS:

- Sustained the islanding operation during all four events and facilitated re-synchronisation afterward, owing to its grid-forming capability.
- Demonstrated smooth transition from the grid-connected operation to the islanding operation, and during the re-synchronisation process.

AEMO also carried out power system model validation for all four events and to validate the BESS model. The simulation results were overlaid with the high-resolution data, demonstrating a reasonable alignment between the power system model response and field measurements. As an important part of the model validation process, it highlighted how the BESS model can be configured to seamlessly transition between the grid-connected operation and island operation modes, depending on the battery's operational state. This finding not only enhances understanding of the Dalrymple BESS performance, but also provides valuable guidance for future investigative tasks aimed at optimising the integration and performance of BESS.

The Dalrymple grid-forming BESS positively contributed to forming a local island and supported re-synchronisation to the main grid.

The investigation of the event not only enhances understanding of the Dalrymple grid-forming BESS performance, but also provides valuable guidance on the capability of grid-forming BESS and accuracy of the AEMO power system model in replicating the event.

The model validation revealed some misalignment between the simulated island frequency and the actual frequency measurement obtained from site. This misalignment could be attributed to a number of factors:

- Certain unknown events or disturbances that occurred within the island.
- The single-phase fault used to separate the island from the main power system in existing modelling practice.
- The difference in the frequency estimation algorithms used by meters on site and the simulation models.

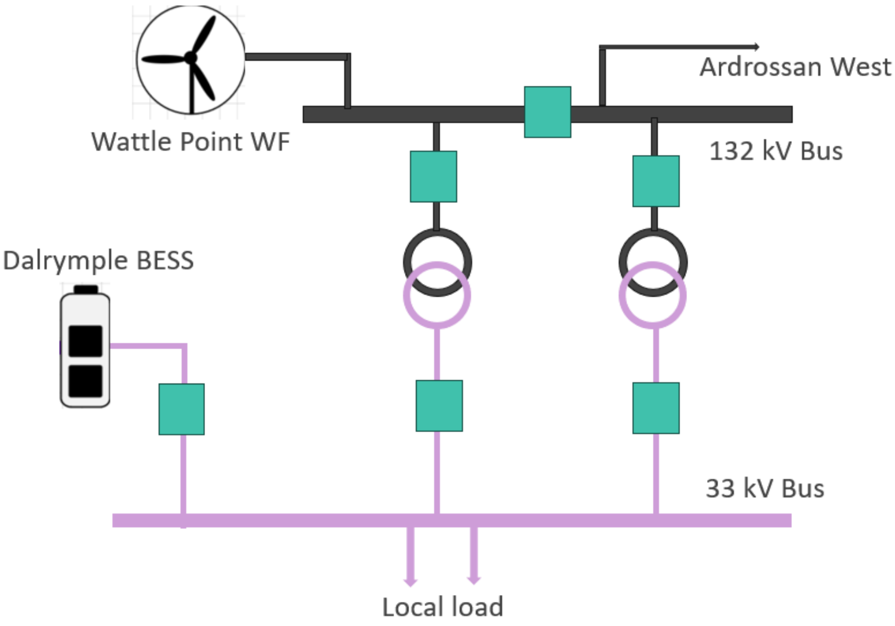
Contents

Figures

1 Introduction

The 30 megawatts (MW) Dalrymple Battery Energy Storage System (BESS) is connected to the remote part of Yorke Peninsula in South Australia. It operates in tandem with the Wattle Point Wind Farm, situated on the Yorke Peninsula, which has 55 turbines and a total capacity of 91 MW. Both assets are connected to the South Australia grid through the Dalrymple – Ardrossan West 132 kilovolts (kV) line, as shown in Figure 1, so a trip of the Dalrymple – Ardrossan West line will island the BESS, the wind farm and local load of approximately 2-3 MW.

Figure 1 Dalrymple BESS and Wattle Point Wind Farm network



The following four incidents occurred on 28 December 2023, involving the Dalrymple BESS and Wattle Point Wind Farm:

- **Event 1:** Line trip and reclose, between 14:52 hrs and 15:02 hrs.
  - Trip and auto reclose of the Ardrossan West – Dalrymple 132 kV line due to lightning in the area.
  - The Dalrymple BESS and Wattle Point Wind Farm successfully islanded and were resynchronised to the South Australia network at 15:02 hrs.
- **Event 2:** Line trip and reclose, between 15:11 hrs and 15:18 hrs.
  - Trip and auto reclose of the Ardrossan West – Dalrymple 132 kV line due to lightning in the area.
  - The Dalrymple Battery successfully islanded and was resynchronised to the South Australia network at 15:18 hrs.
- **Event 3:** Line trip and reclose, between 16:59 hrs and 17:03 hrs.
  - Trip and auto reclose of the Ardrossan West – Dalrymple 132 kV line due to lightning in the area.

  - The Dalrymple BESS successfully islanded and was resynchronised to the South Australia network at 17:03 hrs.
- **Event 4:** Line trip and reclose, between 17:32 hrs and 17:35 hrs.
  - Trip and auto reclose of the Ardrossan West – Dalrymple 132 kV line due to lightning in the area.
  - The Dalrymple BESS successfully islanded and was resynchronised to the South Australia network at 17:35 hrs.

The high-resolution (20 milliseconds [ms]) and low-resolution (4 seconds [s]) data suggested that the wind farm stopped generating power from seven minutes after the line trip in Event 1 until around 13:00 hrs on 29 December 2023, meaning that only Dalrymple BESS was in service in the island for Events 2 to 4.

Details of the analysis carried out using high-resolution data are discussed in the following sections.

2 Event analysis

For each event considered, AEMO conducted analysis by examining the key parameters using high-resolution data provided by the regional transmission network service provider, ElectraNet. The data available were active and reactive power, voltage and frequency at a few locations.

For all four events, the active and reactive power of the wind farm was derived based on other relevant high-resolution data, including the power flowing through the low voltage (LV) side of the two transformers connected between the grid and the BESS, and the power flowing through the 132 kV line. This approach was necessary due to inaccuracies in the wind farm high-resolution data because of inaccurate voltage transformer (VT) measurement after the VT was isolated during the island operation, which exhibited unrealistic oscillations.

2.1 Event 1

During this event, the wind farm was in service before the line trip. The high-resolution data was plotted for active power and reactive power flow for the Dalrymple BESS, Wattle Point Wind Farm and Dalrymple – Ardrossan West 132 kV line, as well as voltage and frequency at the 33 kV LV bus where the BESS is connected (see Figure 1).

Figures 2 to Figure 5 show active power, reactive power, voltage and frequency respectively during the event. In Figures 2 to 5, "1" and "2" indicate the time of island formation and resynchronisation of the island to the main South Australia grid, respectively.

As shown in Figure 2:

- The line tripped around 29 s, corresponding to the actual time stamp of 14:52:29 hrs, which resulted in islanding of the wind farm, BESS and local load. As per the control scheme, some turbine collector feeders of the Wattle Point Wind Farm tripped (as per the design) so that a viable island can be formed.
- The wind farm active power generation reduced from 34 MW before the line trip to around 10 MW after the line trip following the wind turbine collector feeder tripping scheme. The wind farm active power generation was ramping down and eventually reached to zero around 470 s, with zero turbine shown as "Available" on AEMO's SCADA system afterwards.
- The Dalrymple BESS active power generation was around 0 MW before the line trip. After the line trip, the battery absorbed the active power generated by the wind farm until the wind farm generation reached zero. The wind farm remained offline while the battery generated about 3.5 MW power to feed the load in the island between 470 s and 622 s. The island was re-synchronised with the South Australia network at 622 s, corresponding to the actual time stamp of 15:03:09 hrs, when the Dalrymple – Ardrossan West 132 kV line was restored and began to supply the load (3.5 MW). As a result, the BESS returned to 0 MW power generation.

Figure 3 shows that before the line trip, the battery and wind farm were absorbing 2.8 megavolt amperes reactive (Mvar) and 6 MVar reactive power, respectively, which approximate to the 8 MVar reactive power transferred from the upstream system via the 132 kV line. The reactive power of wind farm and BESS became around 0 MVar after the line was tripped.

Figures 4 and 5 demonstrate that immediately after the line trip, the frequency in the island jumped to around 50.6 hertz (Hz). Because of the grid-forming capability, the battery managed to control (within its technical capability) the voltage and frequency and maintain them in acceptable range in the island after the line trip. Referring to the voltage and frequency spikes at 43 s and 323 s in Figures 4 and 5, the island could survive from two other voltage disturbances occurred after the line trip in Event 1.

Figure 2 Active power – Event 1 (MW)

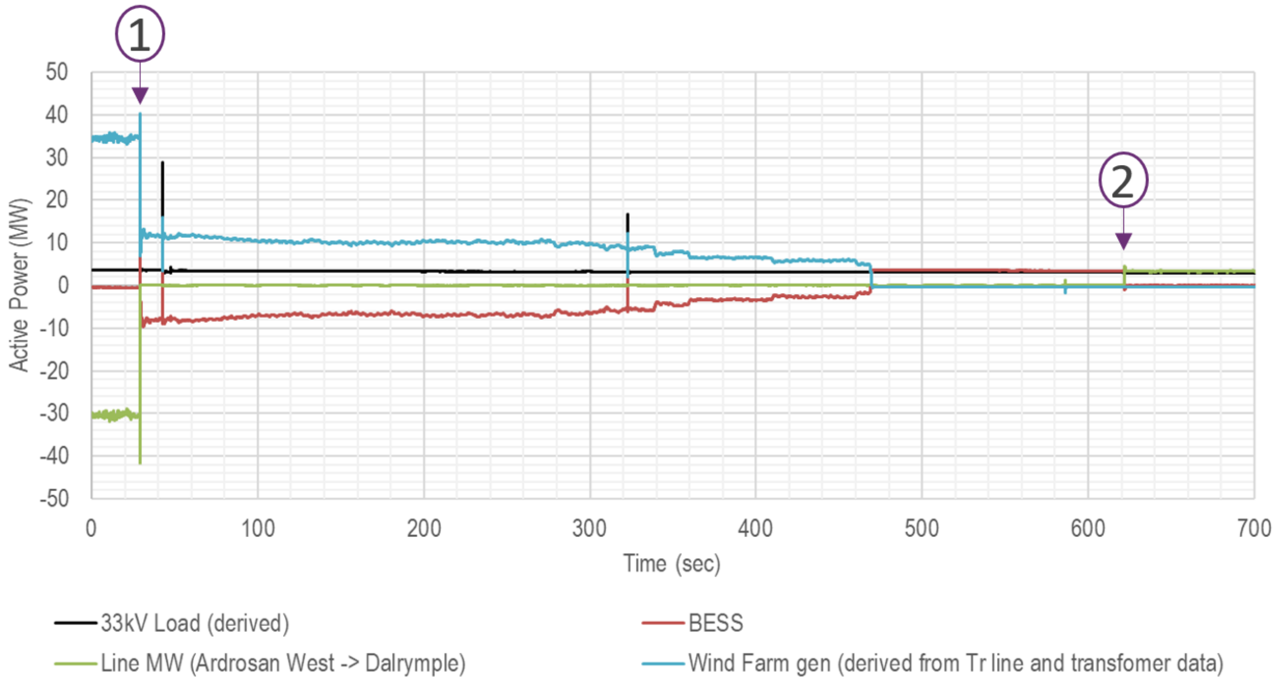


Figure 3 Reactive power – Event 1 (megavolt amperes reactive [MVar])

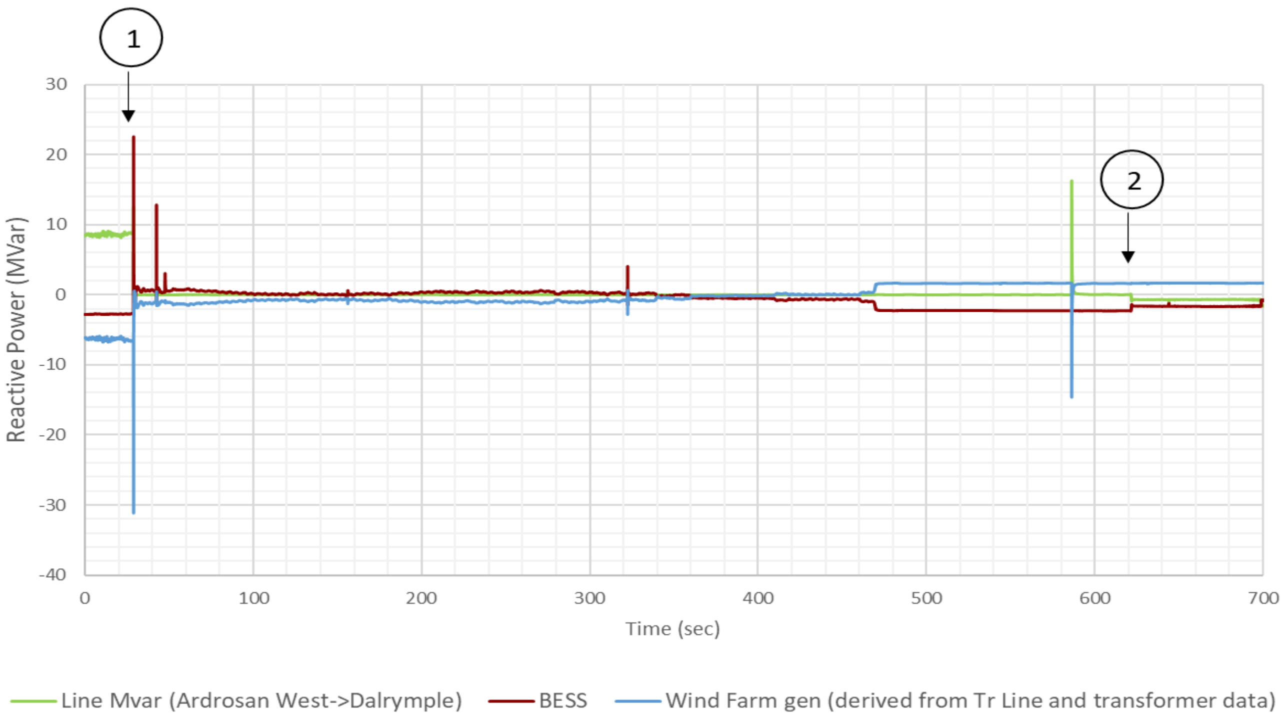


Figure 4 Voltage at the 33 kV bus – Event 1 (per unit [pu])

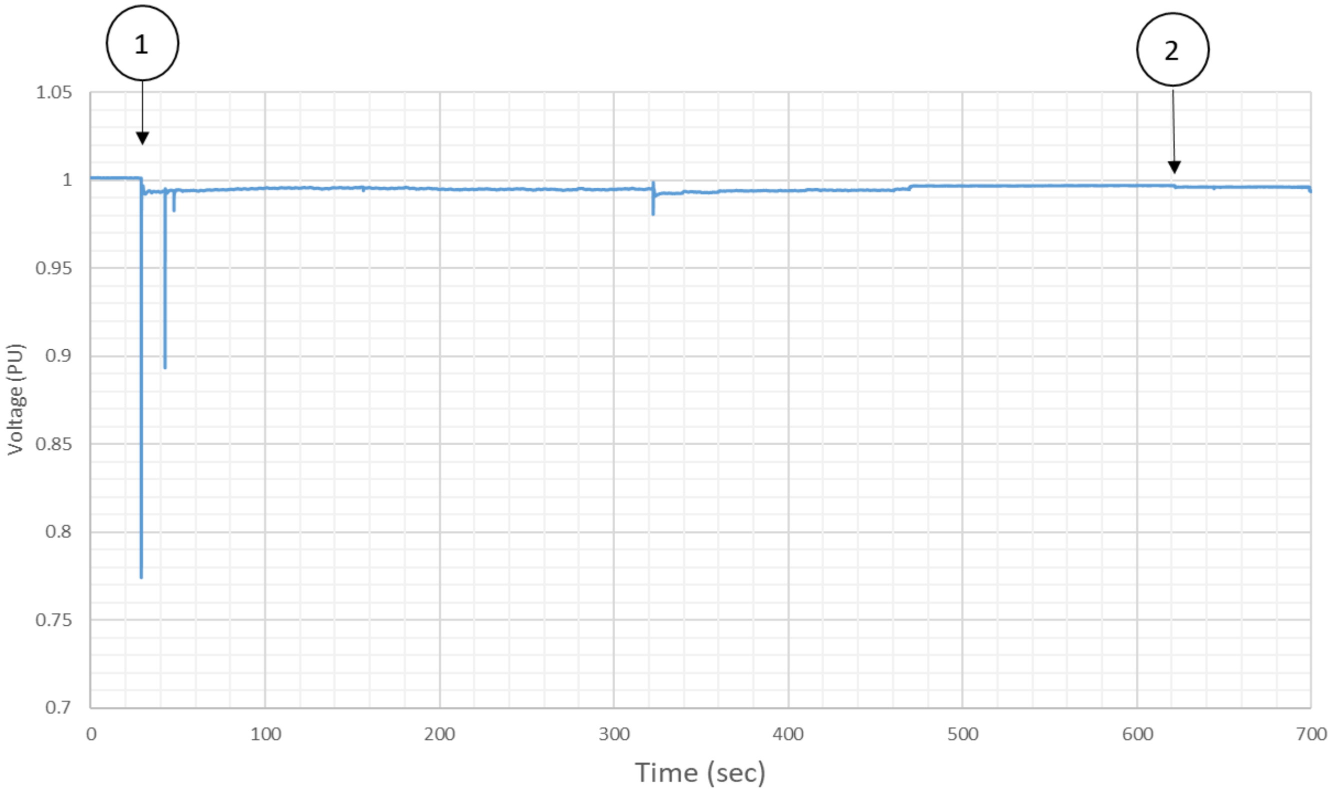
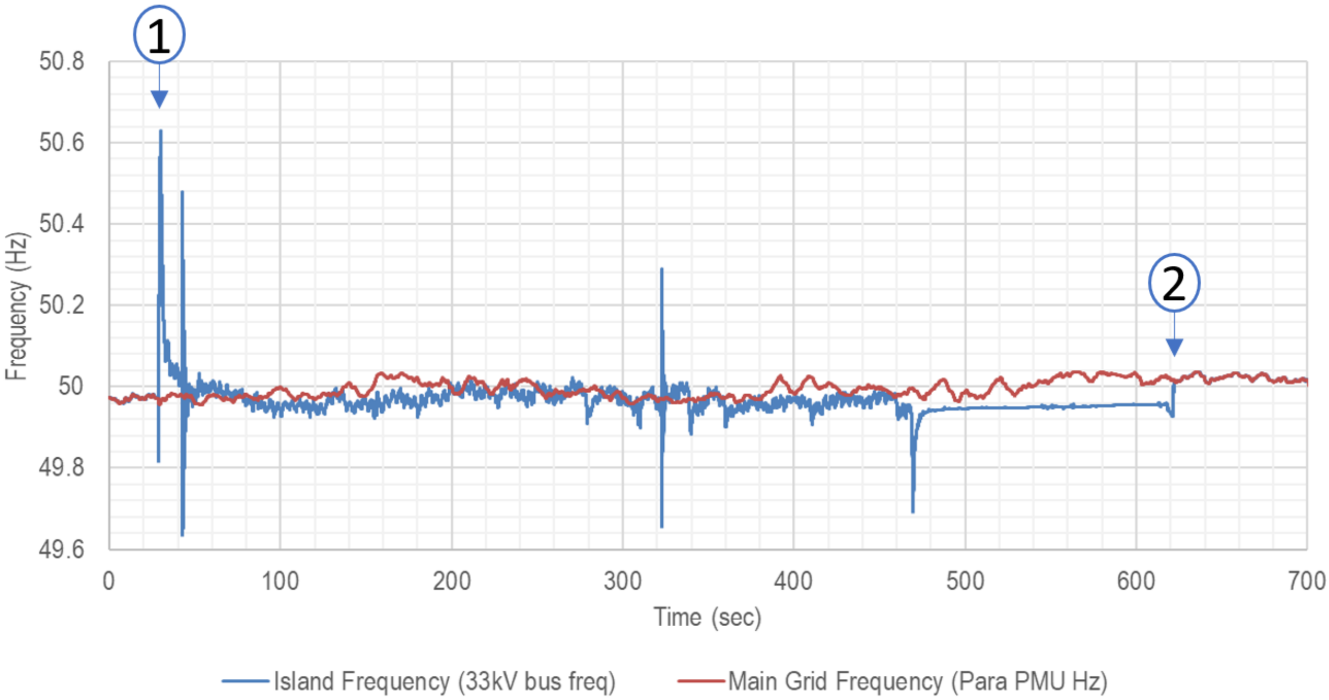


Figure 5 Frequency at the 33 kV bus – Event 1 (hertz [Hz])



2.2 Event 2

Figures 6 to 9 depict the active and reactive power of the Dalrymple BESS, Wattle Point Wind Farm, and Ardrossan West – Dalrymple 132 kV line, alongside voltage and frequency measurements at the 33 kV bus at the BESS connection point. In these figures, "1" and "2" indicate the time of island formation and resynchronisation, respectively.

Analysis of the high-resolution data reveals that the line tripped at 59 s, 15:10:41 hrs in the actual time stamp, and was restored at 486 s, 15:18:09 hrs in the actual time stamp. Before the line trip, the line supplied 3.2 MW of power to the island's load, which was subsequently provided by the battery post-line trip, while the wind farm remained offline throughout the event.

Figure 7 shows that, before the line trip, both the battery and line absorbed reactive power (0.7 MVar and 1.5 MVar, respectively). In addition, the wind farm supplied a small amount of reactive power to the island prior to the occurrence of the event. This can be attributed to two small static Var compensators (SVCs) connected at the wind farm, which remained operational post-trip.

Additionally, Figures 8 and 9 illustrate that the voltage dip and frequency nadir reached approximately 0.8 per unit (pu) and 49.5 Hz respectively, immediately following the line trip. Nonetheless, the battery successfully restored the voltage and frequency to an acceptable range.

Figure 6 Active power – Event 2 (MW)

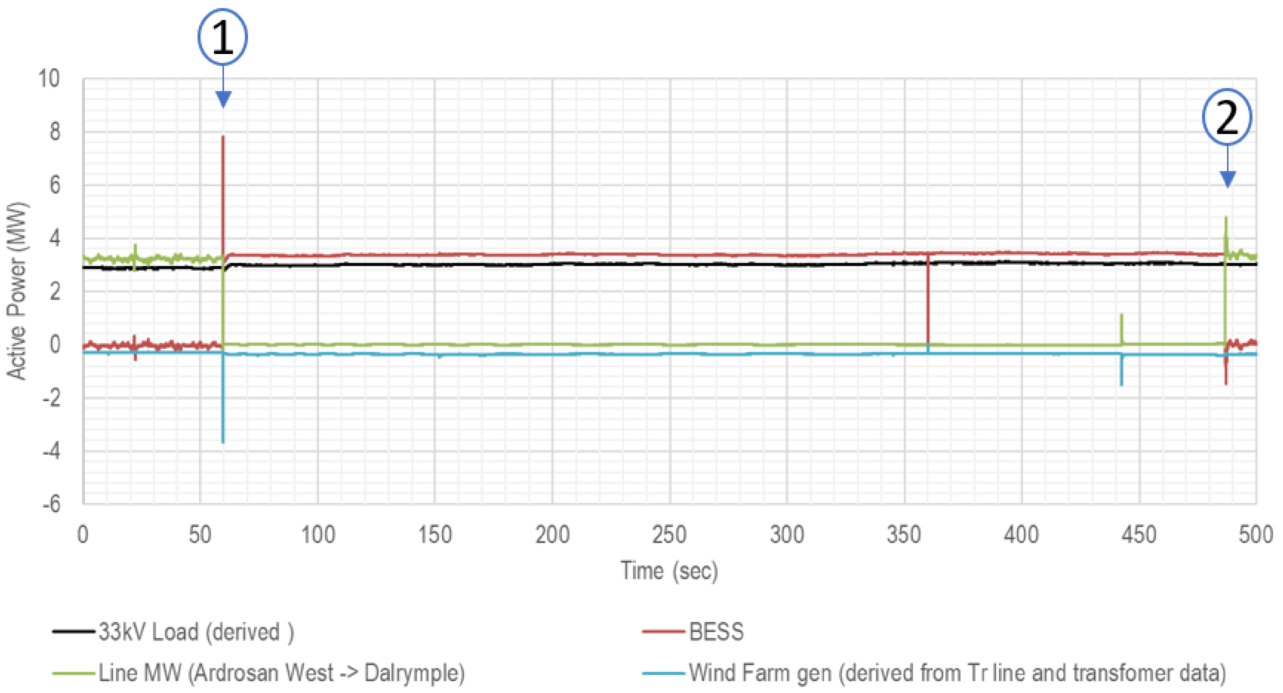


Figure 7 Reactive power – Event 2 (MVAr)

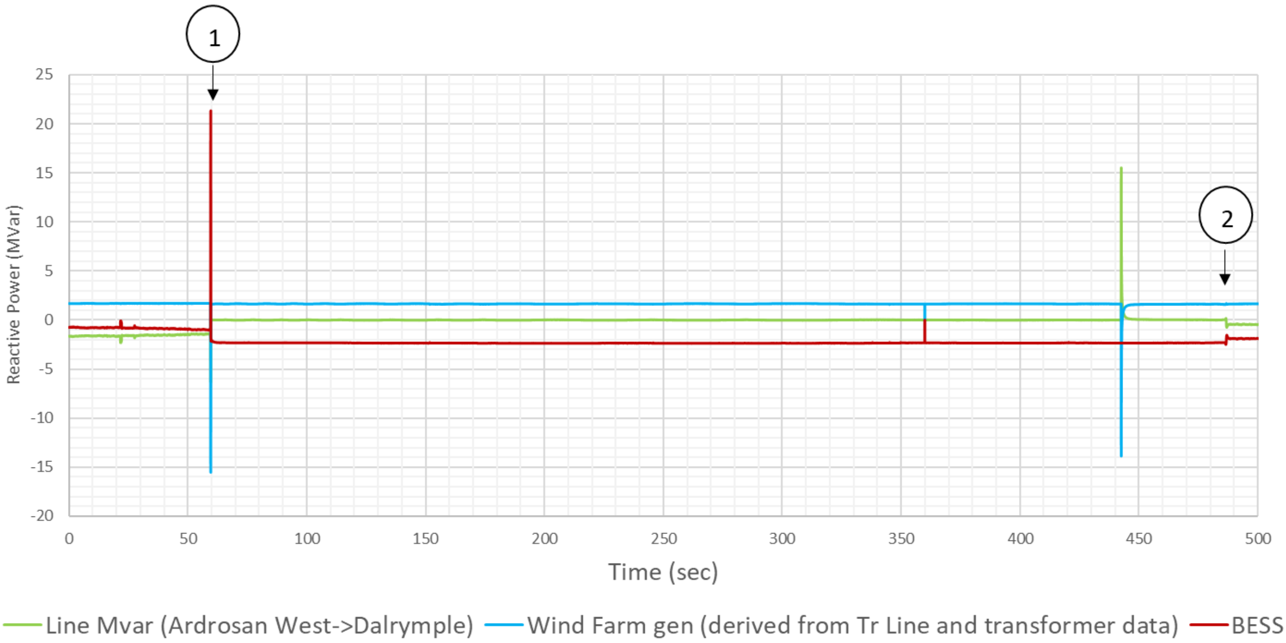


Figure 8 Voltage at the 33 kV bus – Event 2 (pu)

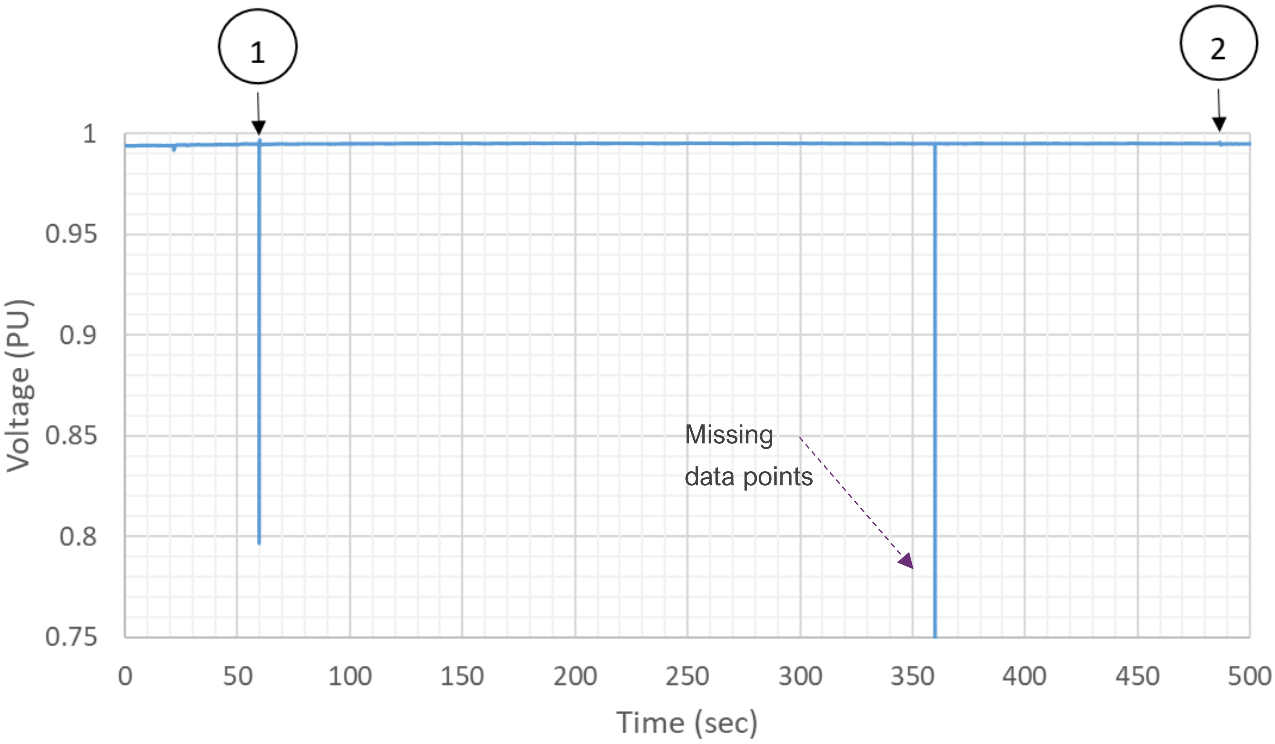
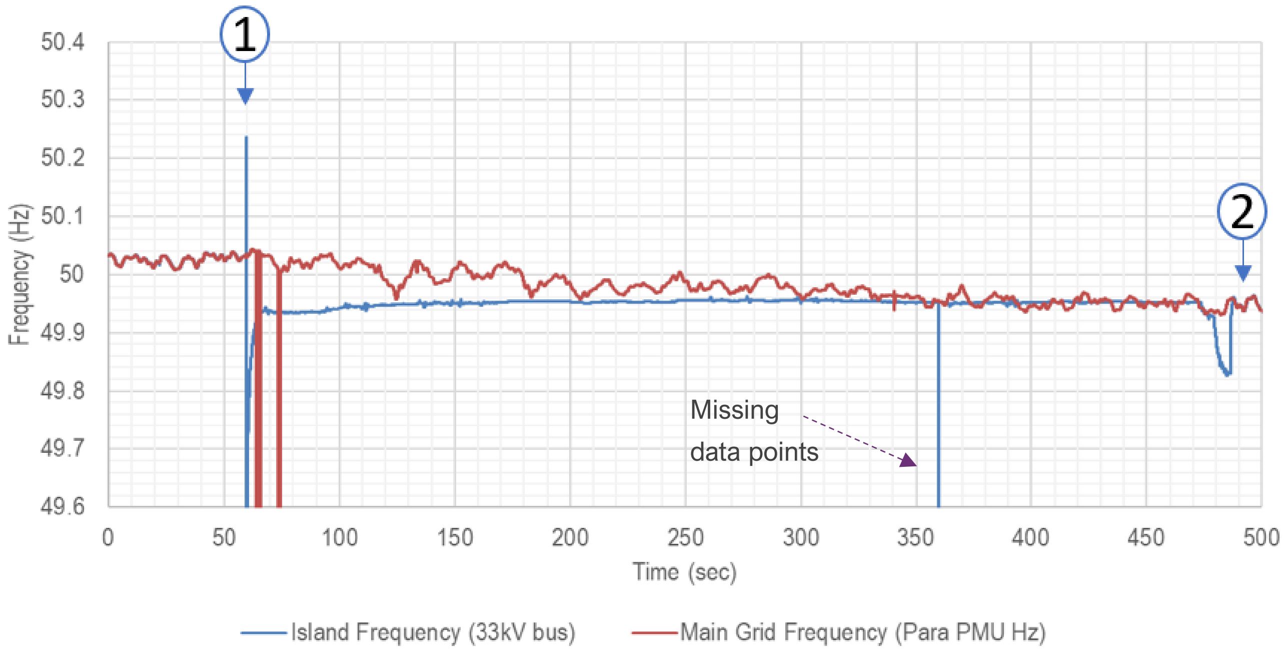


Figure 9 Frequency at the 33 kV bus – Event 2 (Hz)



2.3 Events 3 and 4

AEMO also performed analysis using high-resolution data for Events 3 and 4, with results presented in Figures 10 to 17. Events 3 and 4 were similar to Event 2, in terms of the island formation mechanism (lightning strike causing upstream line trip) and the components present during the island operation, and the discussion above for Event 2 is also applicable to Events 3 and 4.

Figure 10 Active power – Event 3 (MW)

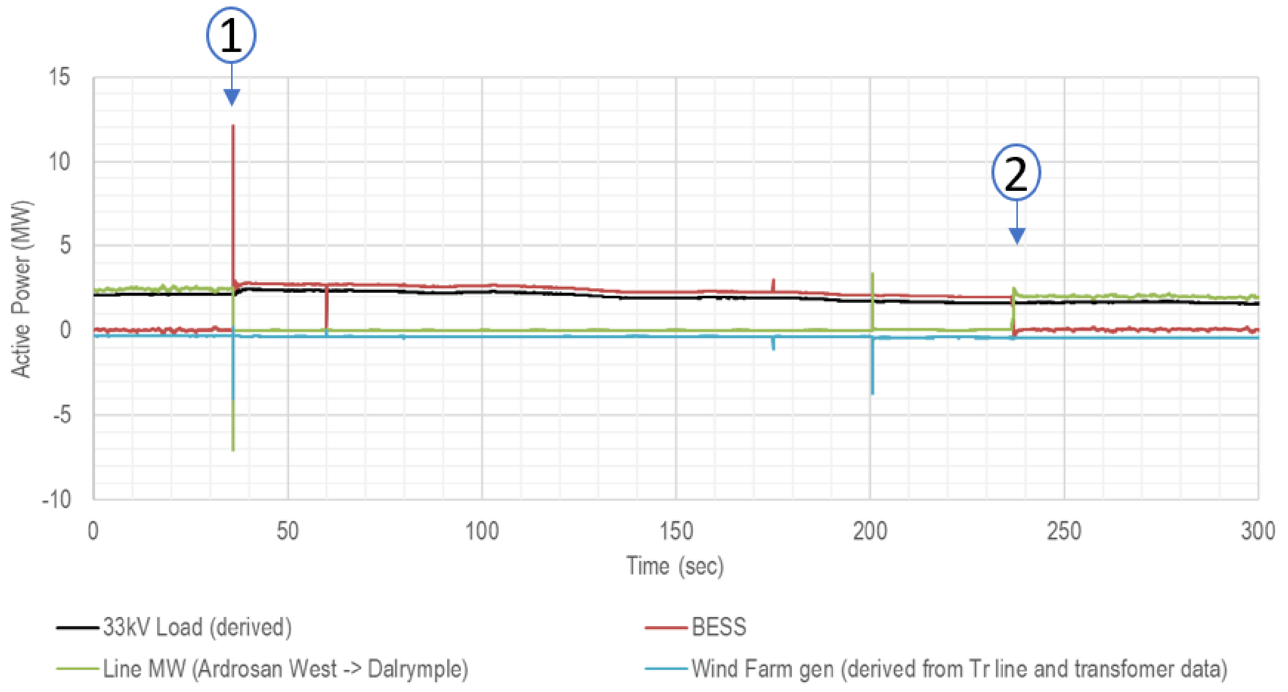


Figure 11 Reactive power – Event 3 (MVAr)

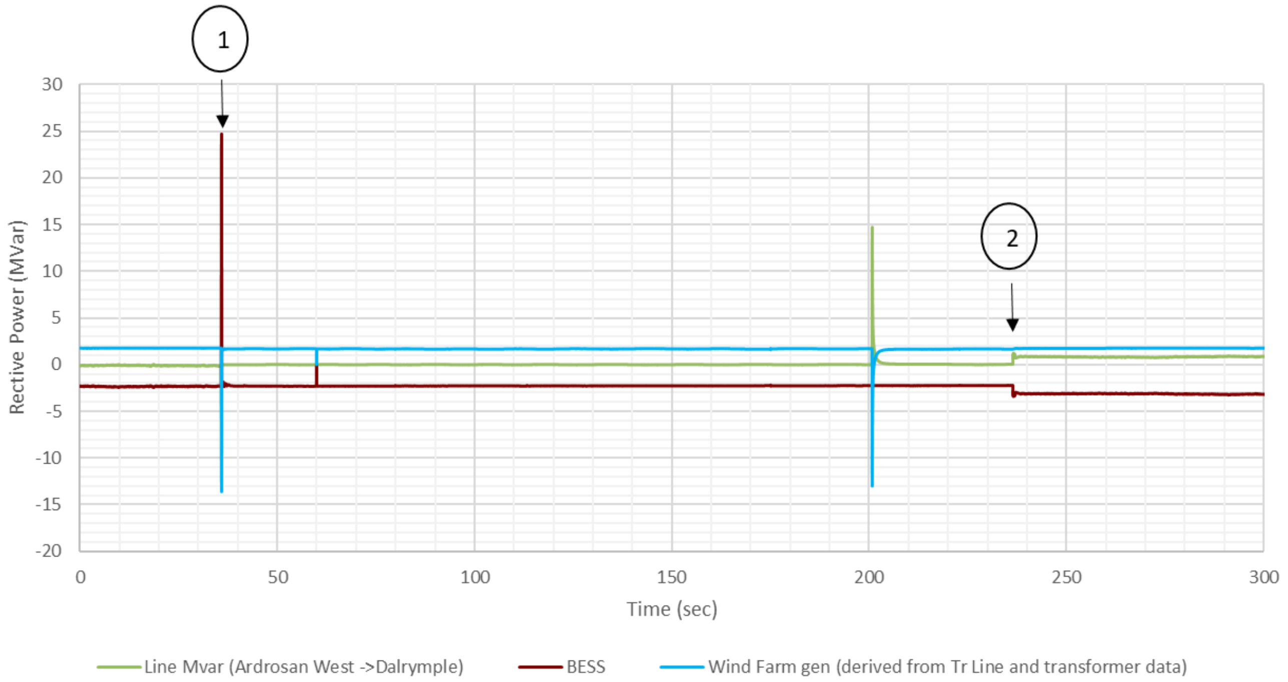


Figure 12 Voltage at the 33 kV bus – Event 3 (pu)

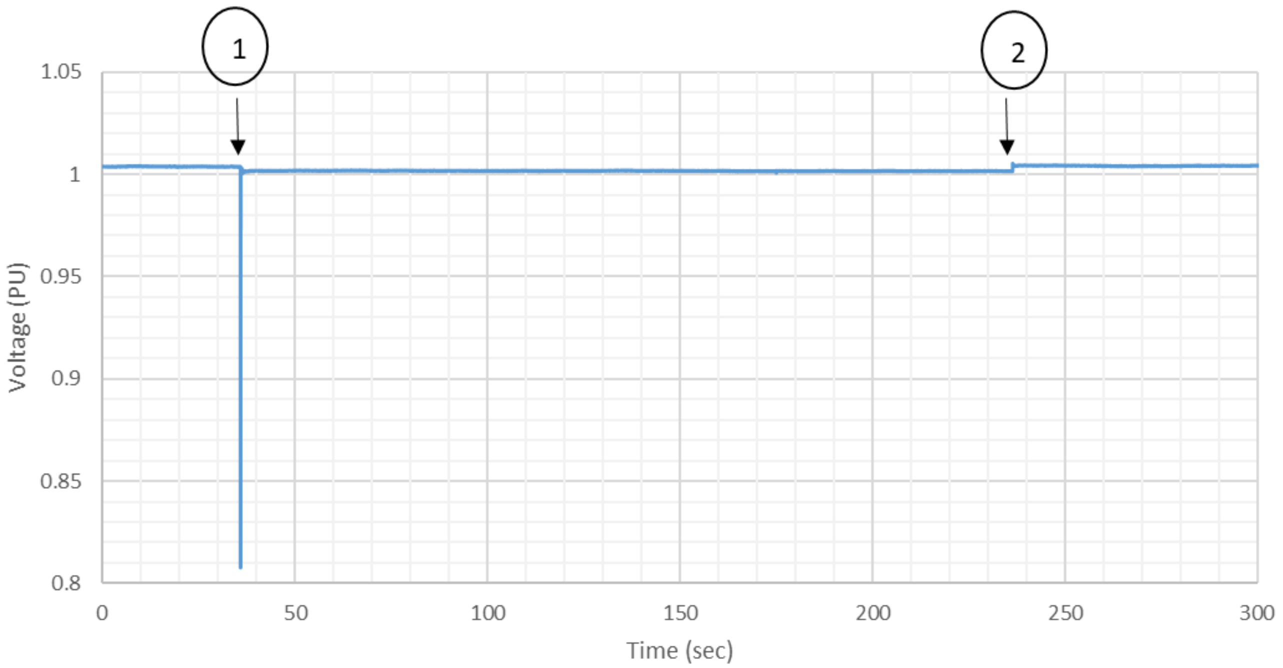


Figure 13 Frequency at the 33 kV bus – Event 3 (Hz)

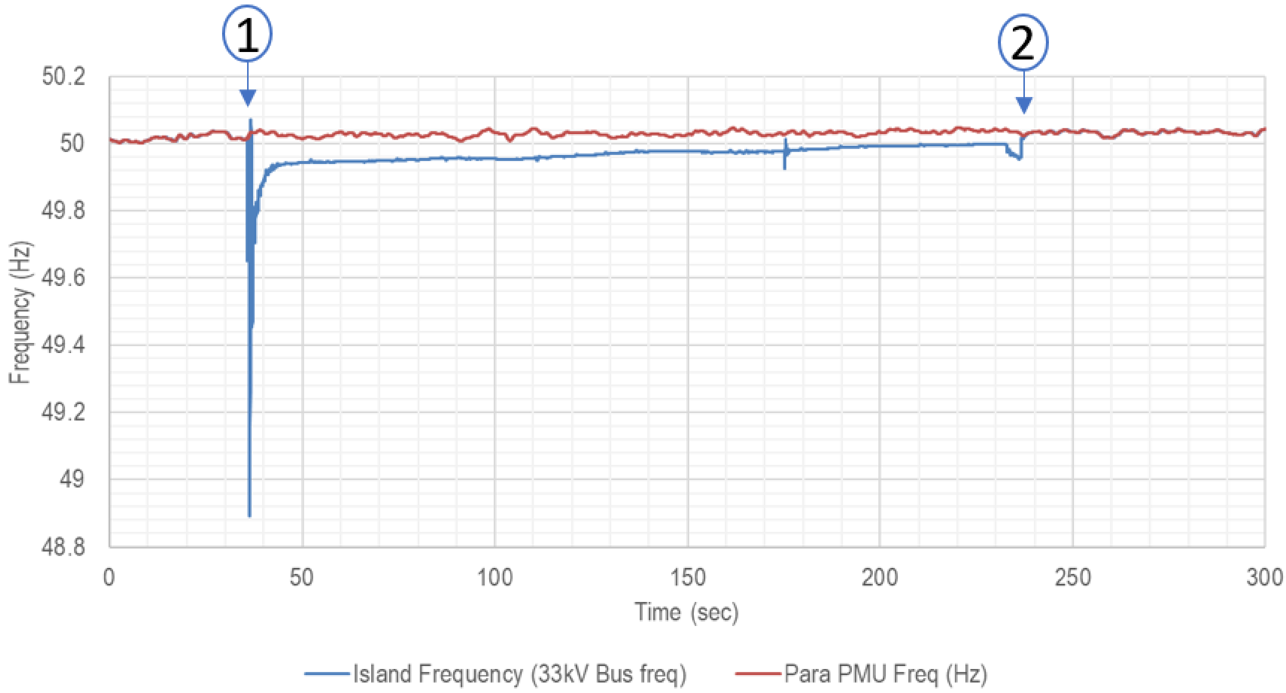


Figure 14 Active power – Event 4 (MW)

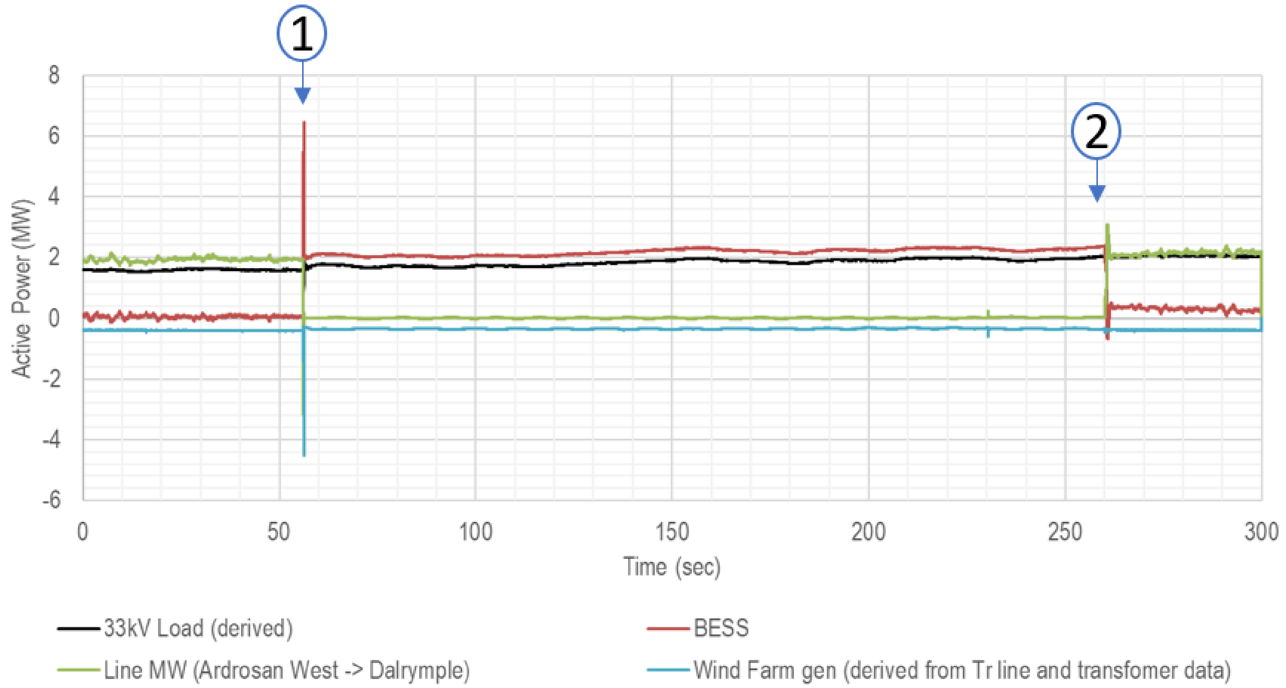


Figure 15 Reactive power – Event 4 (MVAr)

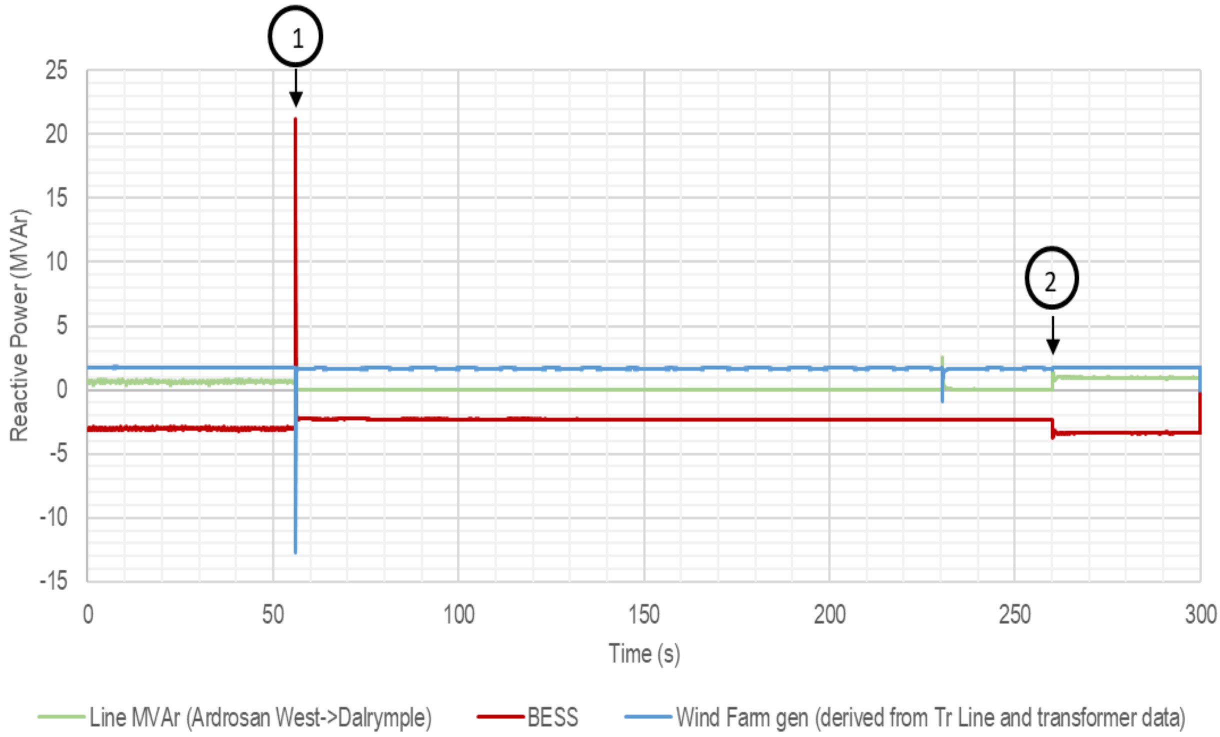


Figure 16 Voltage at the 33 kV bus – Event 4 (pu)

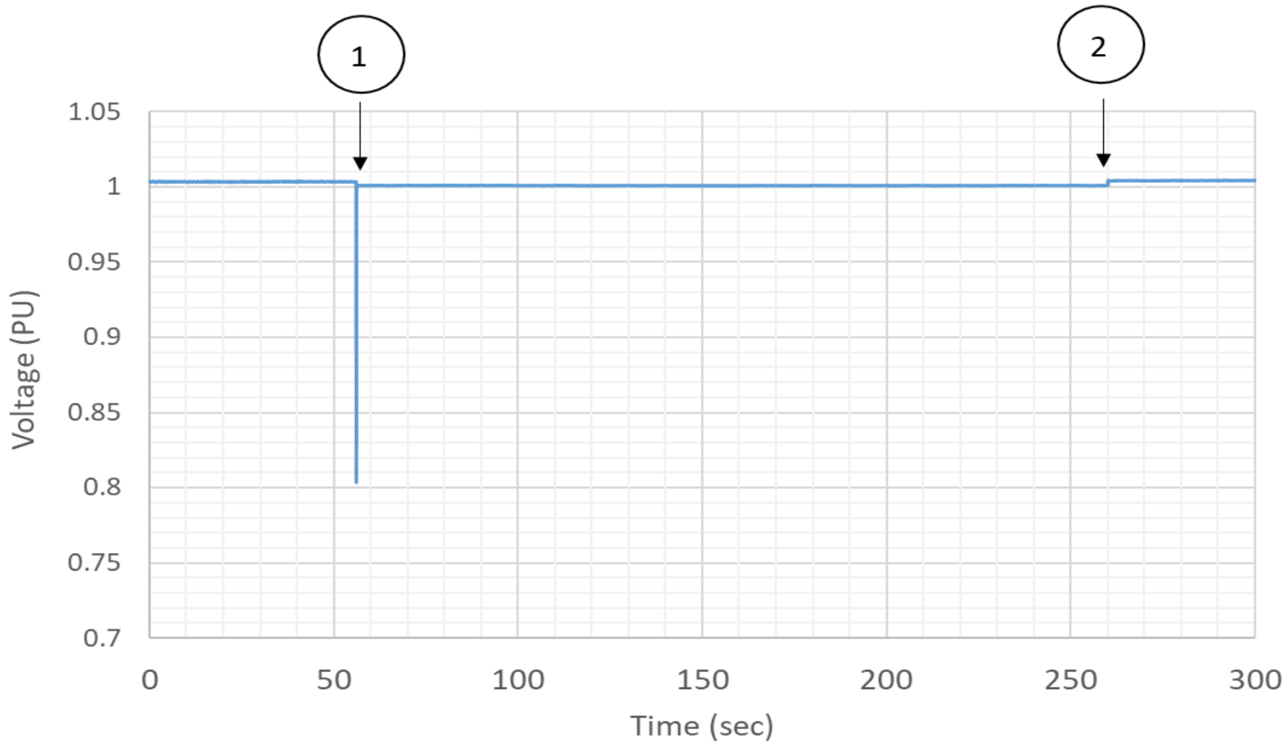
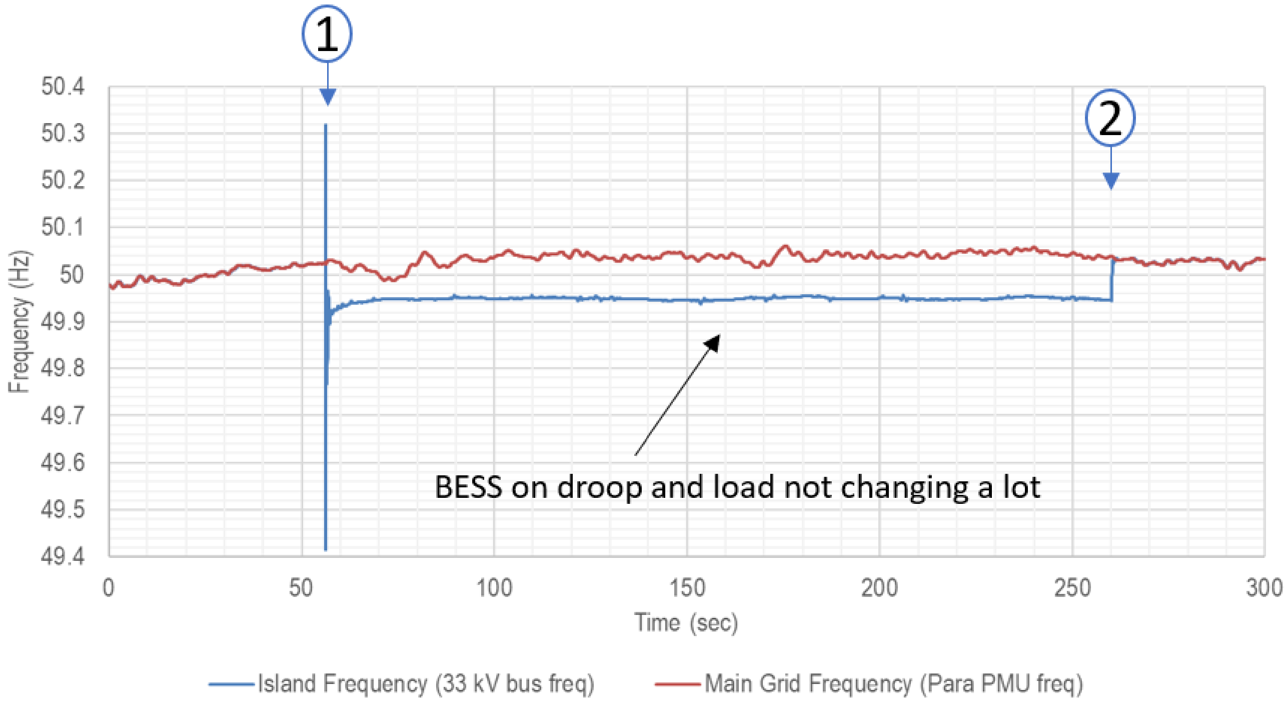


Figure 17 Frequency at the 33 kV bus – Event 4 (Hz)



3 Model validation

AEMO created a PSCAD™ case to simulate the behaviour of the islanded power system following multiple trips of the Dalrymple – Ardrossan West line on 28 December 2023, then compared the PSCAD™ results with the high-resolution data for model validation.

The PSCAD™ case was first set up to simulate the behaviour of the Dalrymple BESS and Wattle Point Wind Farm in Event 1, in which the wind farm was partly in service along with the battery after the Dalrymple – Ardrossan West line trip. The PSCAD™ case used for Event 1 was then adjusted for simulating two subsequent events with only the BESS in service while the wind farm was offline before the corresponding line trip (Events 2 and 3).

3.1 PSCAD™ case set-up and initialisation

The key steps taken to develop and initialise the PSCAD™ case were:

- The PSCAD™ model was set up to represent the power system including the Dalrymple BESS, the Wattle Point Wind Farm, two 33 kV/132 kV transformers connecting the BESS to the grid, loads at 33 kV Dalrymple substation, and the grid represented by an equivalent 132 kV voltage source. The detailed load composition at the event was unknown, therefore the standard voltage-dependent load model was used to represent the local 33 kV load.
- Initially, the primary setpoints of these components – including active power, reactive power, and voltage – were configured to represent the power system operating condition just prior to the line trip event. Subsequently, these values were fine-tuned to minimise discrepancies between the PSCAD™ results and high-resolution data prior to the first incident, where necessary.
- To simulate the line trip, a single-phase fault was introduced in the simulation followed by tripping the grid. The fault depth in the simulation was fine-tuned so the voltage dip simulated in the PSCAD™ exhibited a close alignment with the voltage dip observed in the high-resolution field data.
- As a critical step in the simulation process, the Dalrymple BESS model was configured to seamlessly transition from the grid-connected operation to the island operation mode upon each line trip. In the model this was simulated by applying appropriate logic that would enable Dalrymple BESS to sense a trip of the upstream transmission line.
- Based on information provided by ElectraNet, the Wattle Point Wind Farm is armed with a trip scheme which will shed a few turbine collector feeders upon detecting a trip of upstream transmission line. Therefore, in Event 1, after the line trip, the number of Wattle Point wind turbines was adjusted to align with the active power output depicted in the high-resolution data. To achieve this, the number of wind turbines was reduced to nine after the line trip. In Events 2 and 3, the number of wind turbines was set to zero throughout the simulation, as the wind farm did not generate during these events.

3.2 Model validation – Event 1

The PSCAD™ results were compared with the high-resolution data, spanning one second before the line trip and several seconds afterward, as presented in Figures 18 to 23. The high-resolution data presented in Section 2.1 suggested that, after the line trip at t=29 s, another fault occurred at around t=42 s. The PSCAD™ studies encompassed both faults.

The results demonstrate a close alignment between the simulation results and the high-resolution data, confirming the validity of the model developed in PSCAD™.

It is noted that, as Figure 23 shows, the PSCAD™ model closely represented the frequency during the islanding operation in terms of the steady state frequency and the maximum frequency deviation immediately following the contingency, but did not fully capture the measured transient frequency behaviour. Such transient frequency behaviour observed in the measurement could be attributed to the dynamics of the load, which is unknown at this stage.

Figure 18 Dalrymple BESS active power PSCAD™ overlay in Event 1 (MW)

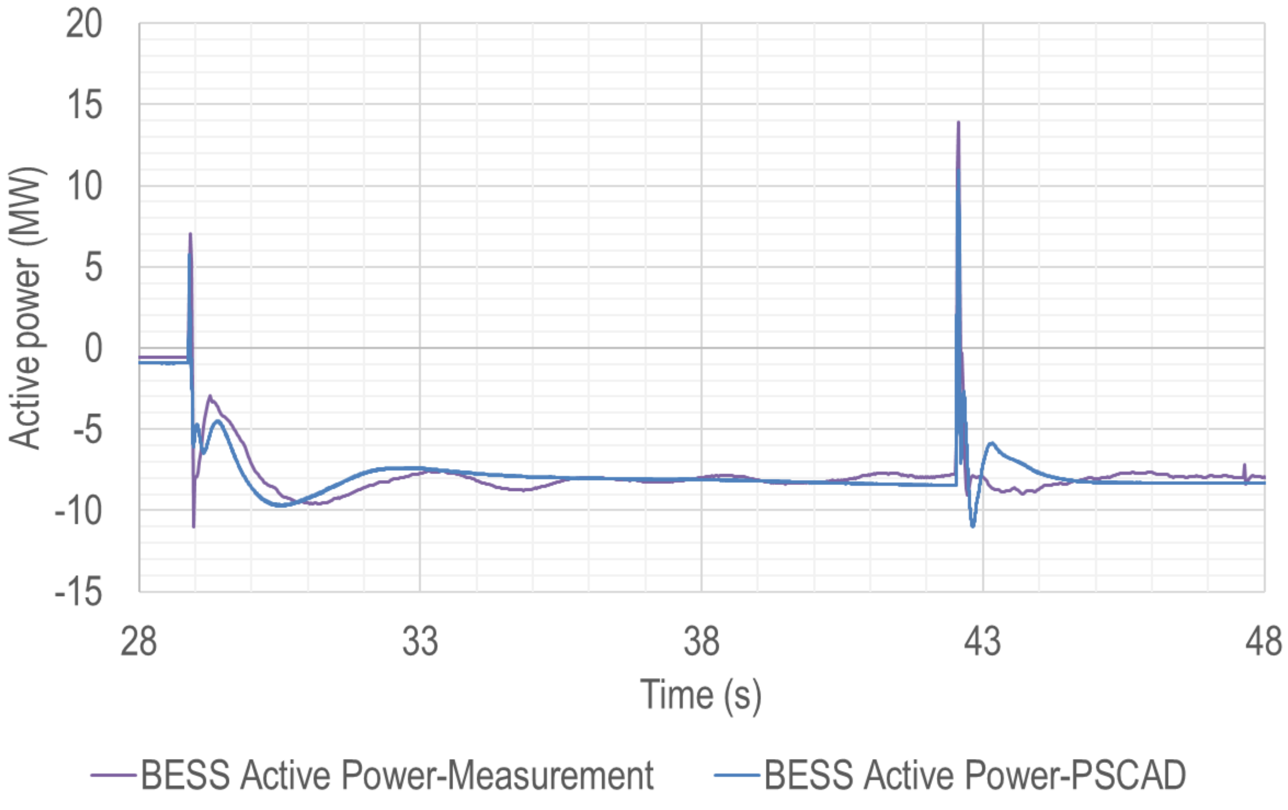
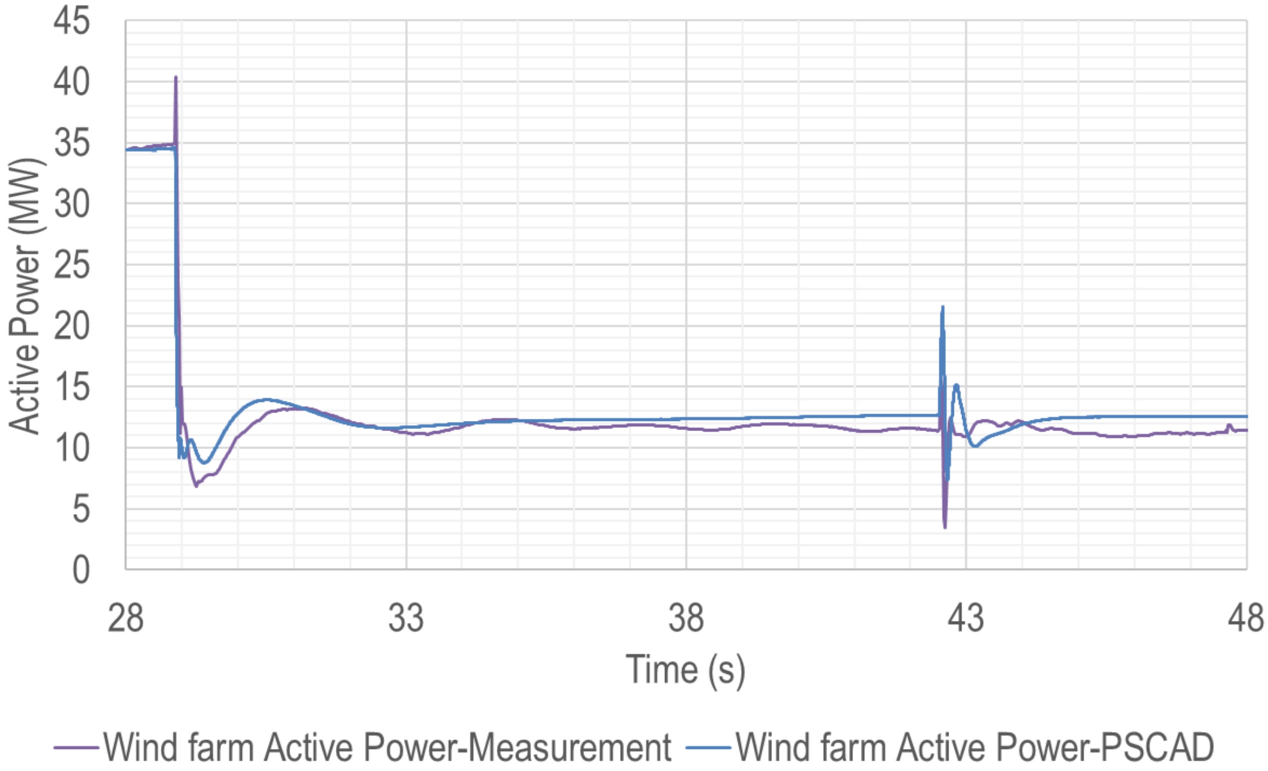


Figure 19 Wattle Point Wind Farm active power PSCAD™ overlay in Event 1 (MW)



Note: wind farm active and reactive power were inferred from synthesised high-resolution data, adjusting for inaccuracies in the island mode.

Figure 20 Dalrymple BESS reactive power PSCAD™ overlay in Event 1 (MVAr)

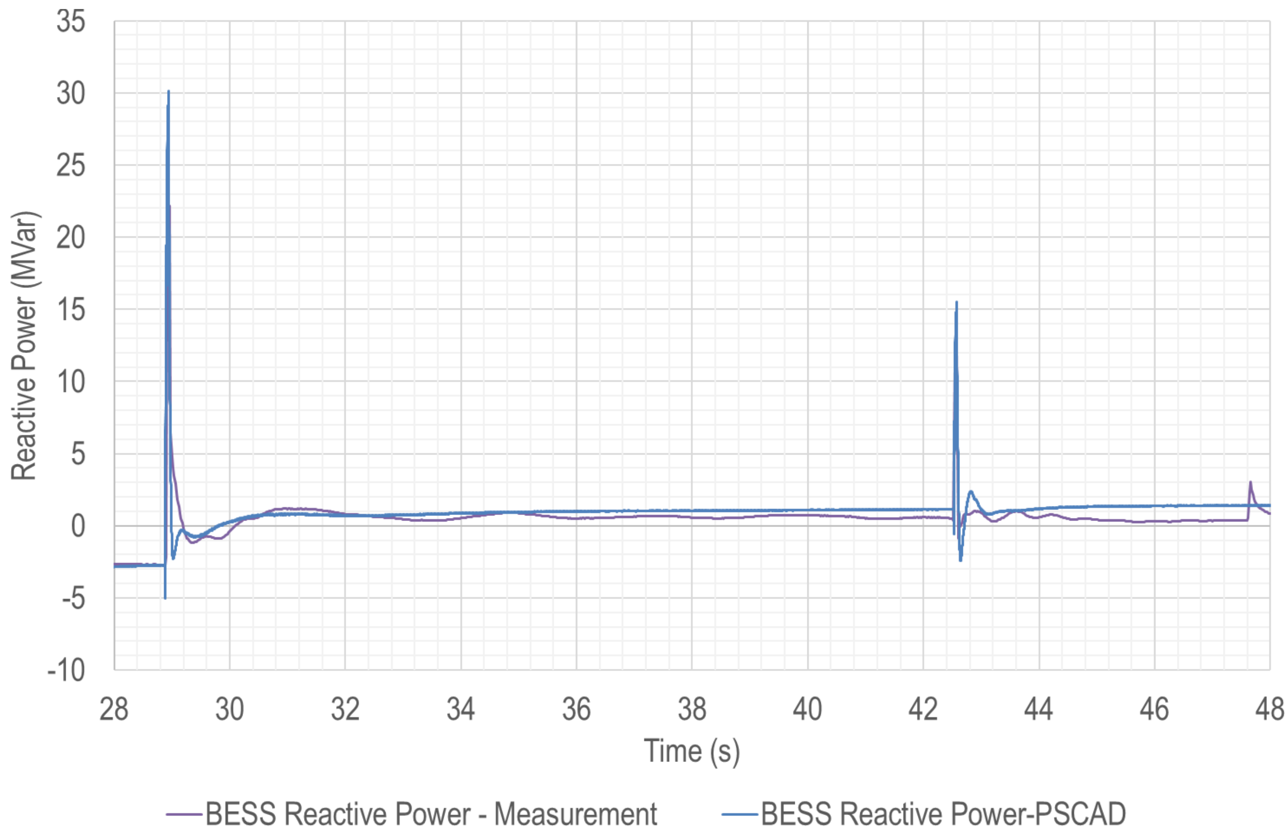


Figure 21 Wattle Point wind farm reactive power PSCAD™ overlay in Event 1 (MVAr)

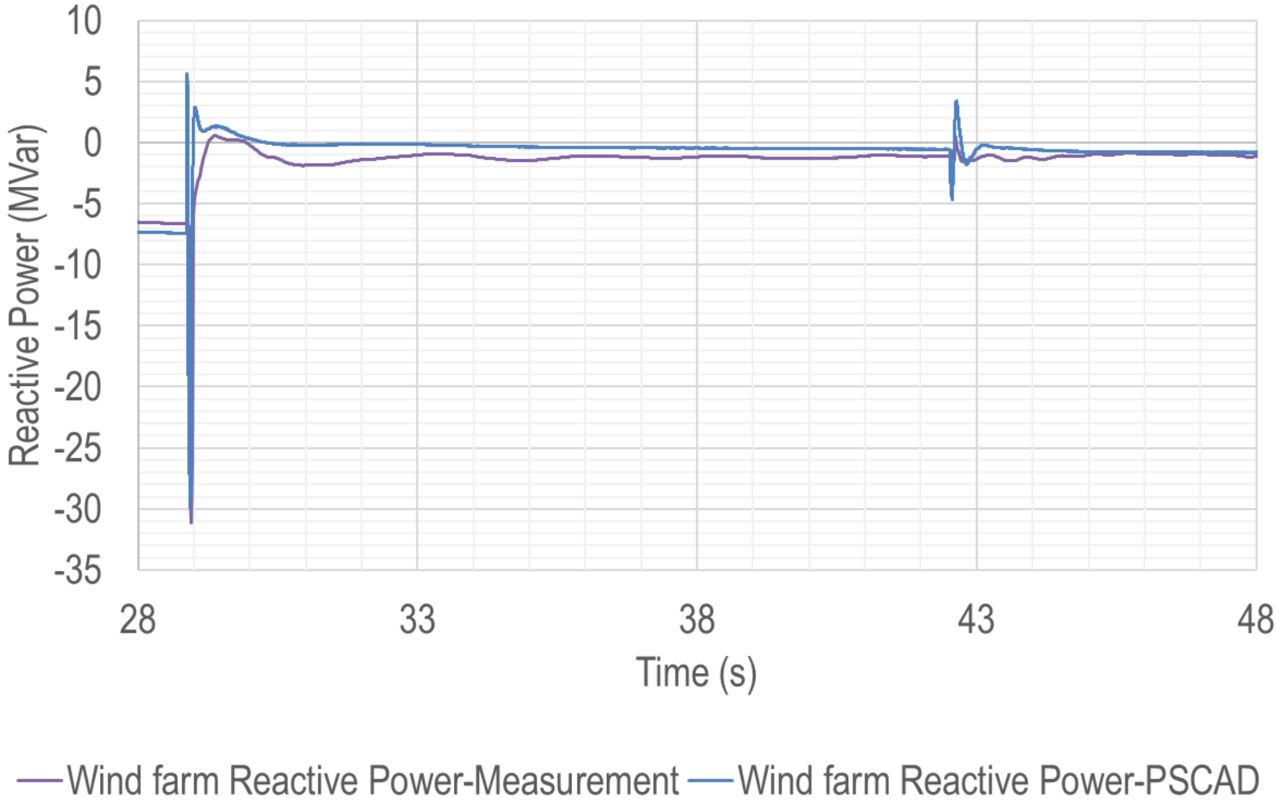


Figure 22 Voltage at the 33 kV Bus PSCAD™ overlay in Event 1 (pu)

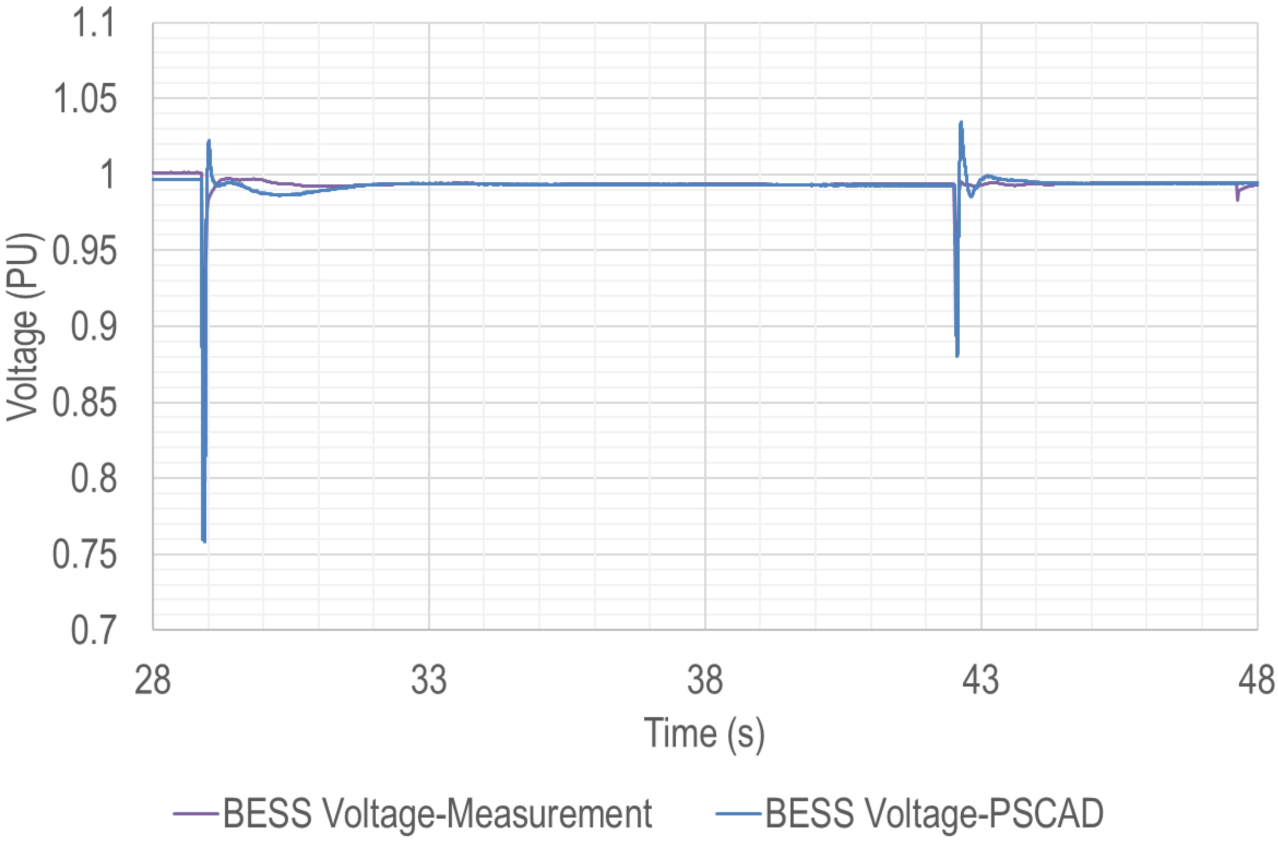
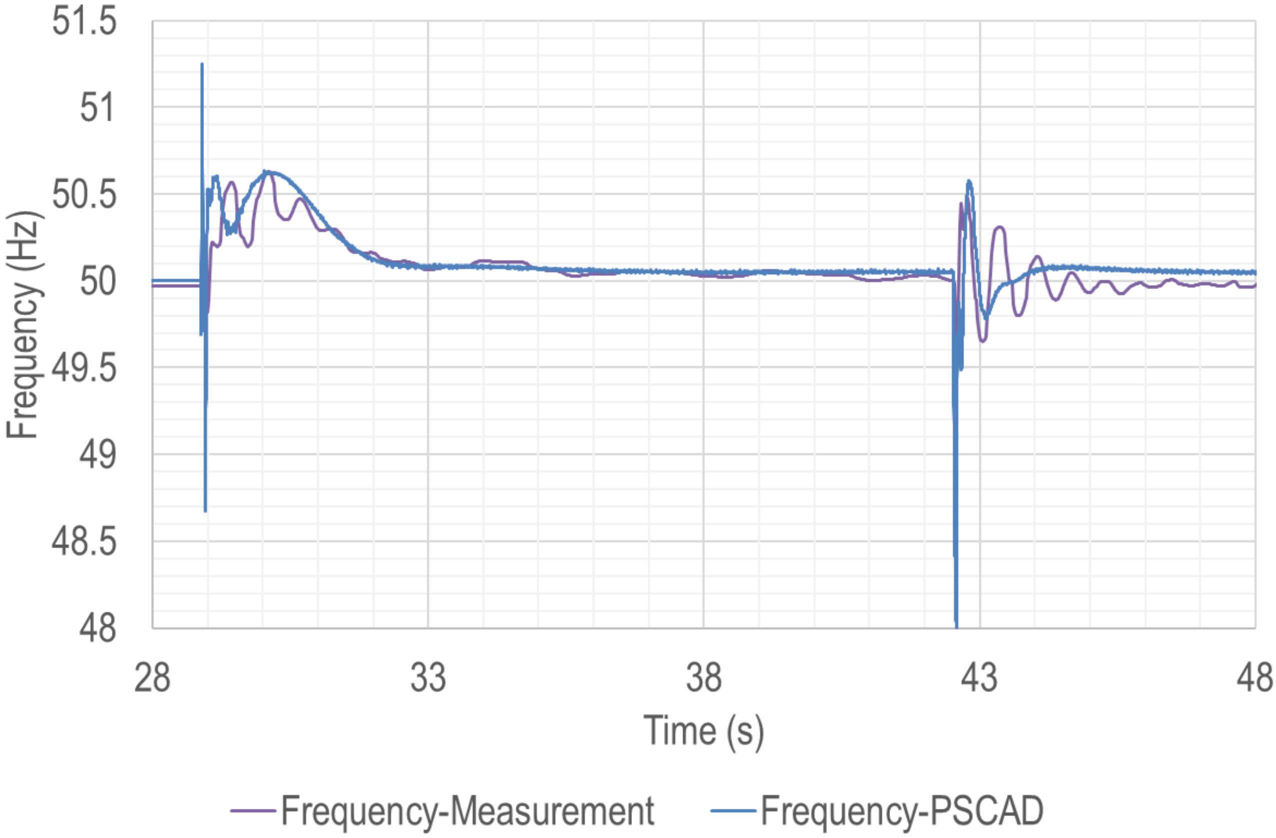


Figure 23 Frequency at the 33 kV Bus PSCAD™ overlay in Event 1 (Hz)



3.3 PSCAD™ simulation of event 2

The model validation was then carried out for Event 2, using the developed PSCAD™ case for Event 1 validation, with adjustment to represent the power system condition prior to Event 2. As detailed in Section 2.2, the Wattle Point Wind Farm remained offline throughout the event.

Figures 24 to 27 depict the overlay of PSCAD™ results on high-resolution measurements. While some frequency dynamics could not be simulated in PSCAD™, potentially due to artefacts in high-resolution data and complexities in the load model, and initial transients of BESS active power response did not closely match the high-resolution data, overall trends align reasonably well between PSCAD™ results and high-resolution data.

Figure 24 Dalrymple BESS active power PSCAD™ overlay in Event 2 (MW)

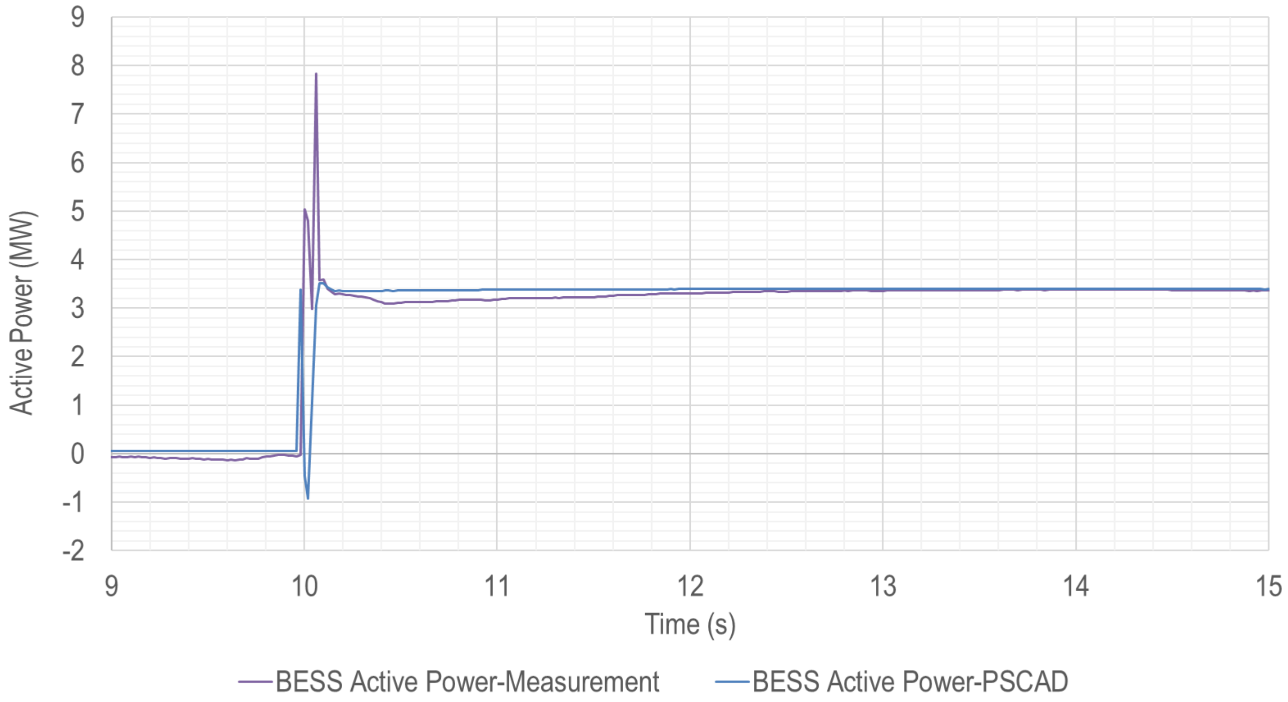


Figure 25 Dalrymple BESS reactive power PSCAD™ overlay in Event 2 (MVAr)

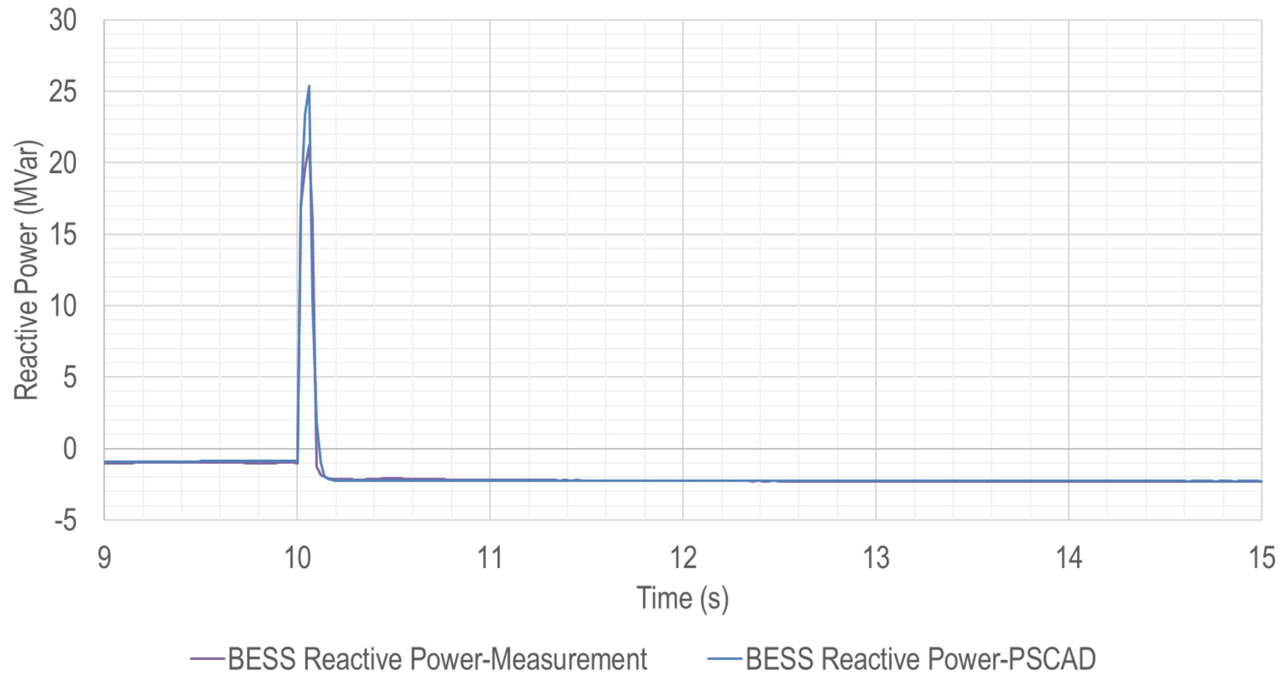


Figure 26 Voltage at the 33 kV bus PSCAD™ overlay in Event 2 (pu)

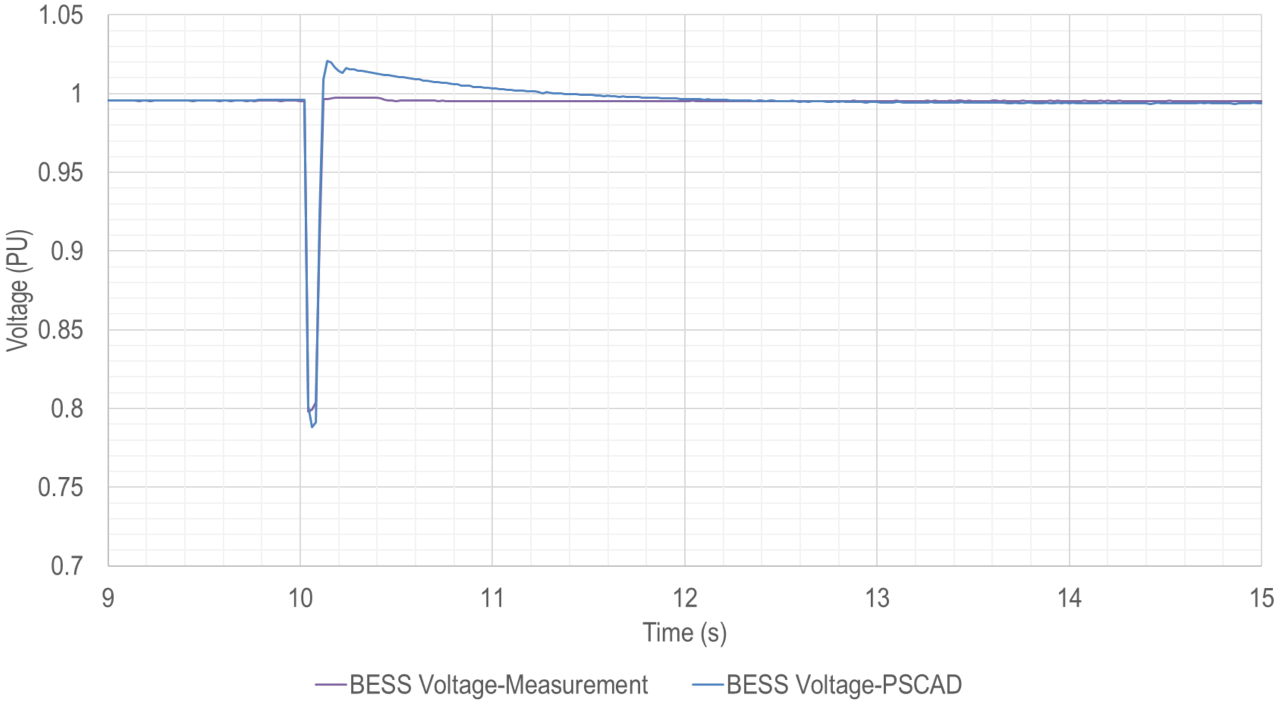
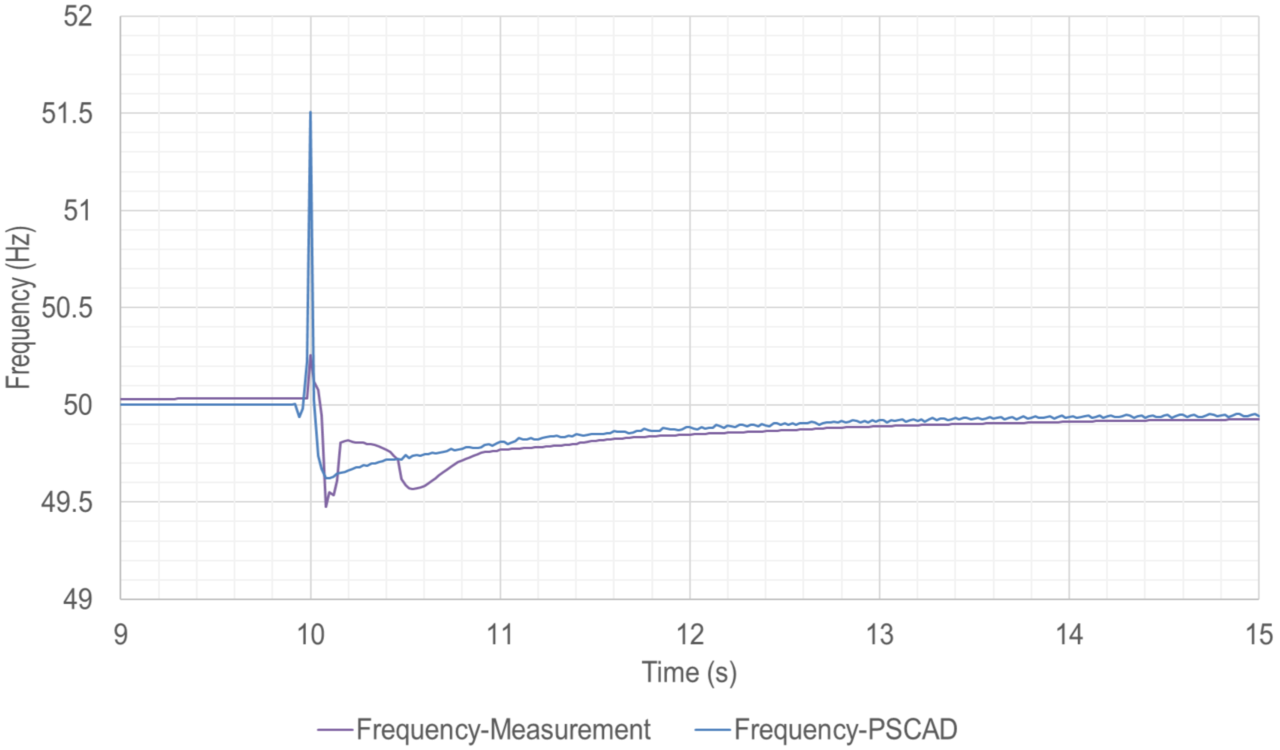


Figure 27 Frequency at the 33kV Bus PSCAD™ overlay in Event 2 (Hz)



3.4 PSCAD™ simulation of event 3

AEMO simulated Event 3 using the developed PSCAD™ case, and compared the results with the high-resolution data. The discussion above for Event 2 applies to the results obtained for Event 3, highlighting a general match between PSCAD™ and high-resolution data, although with some discrepancies, particularly in frequency.

Figure 28 Dalrymple BESS active power PSCAD™ overlay in Event 3 (MW)

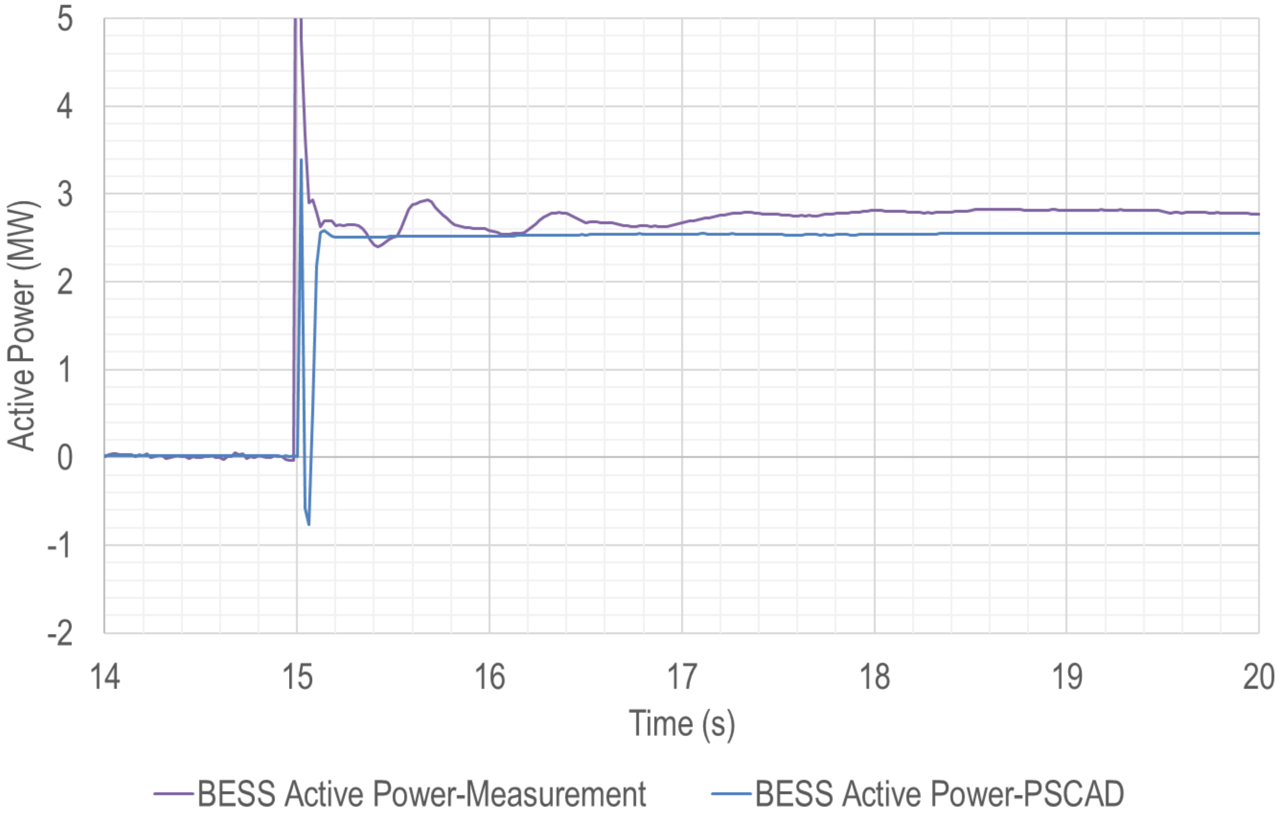


Figure 29 Dalrymple BESS reactive power PSCAD™ overlay in Event 3 (MVar)

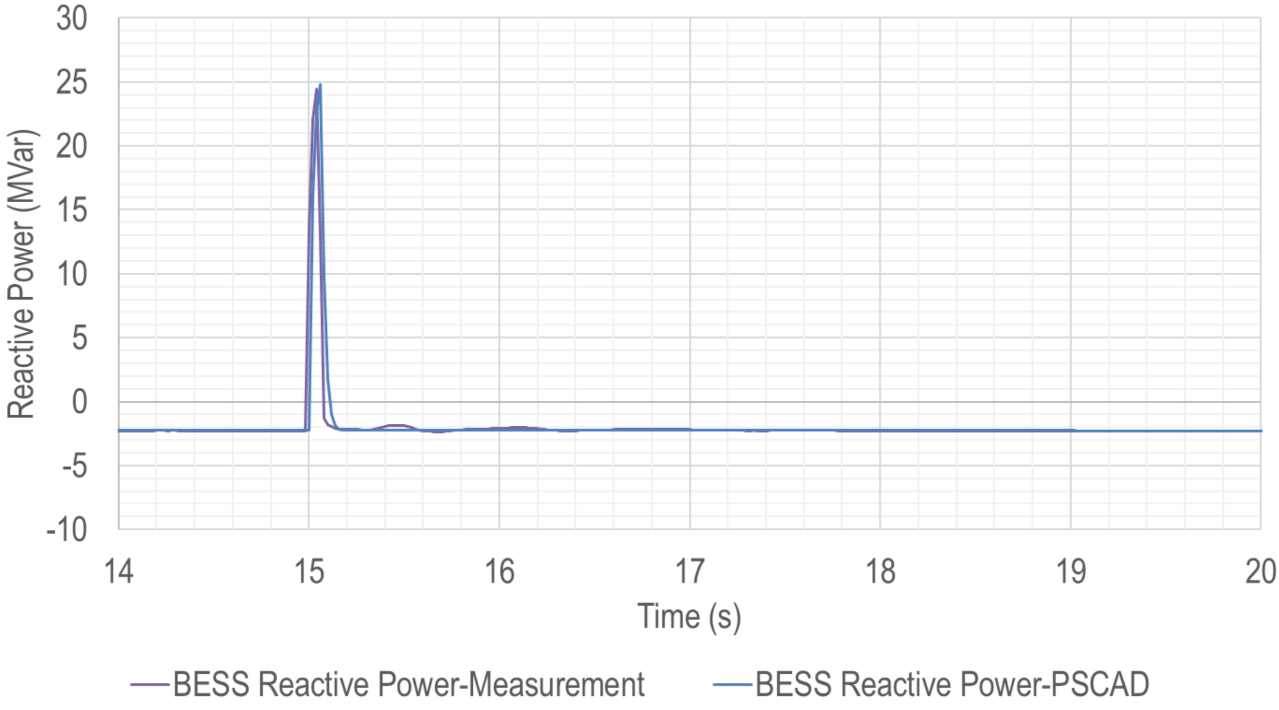


Figure 30 Voltage at the 33 kV bus PSCAD™ overlay in Event 3 (pu)

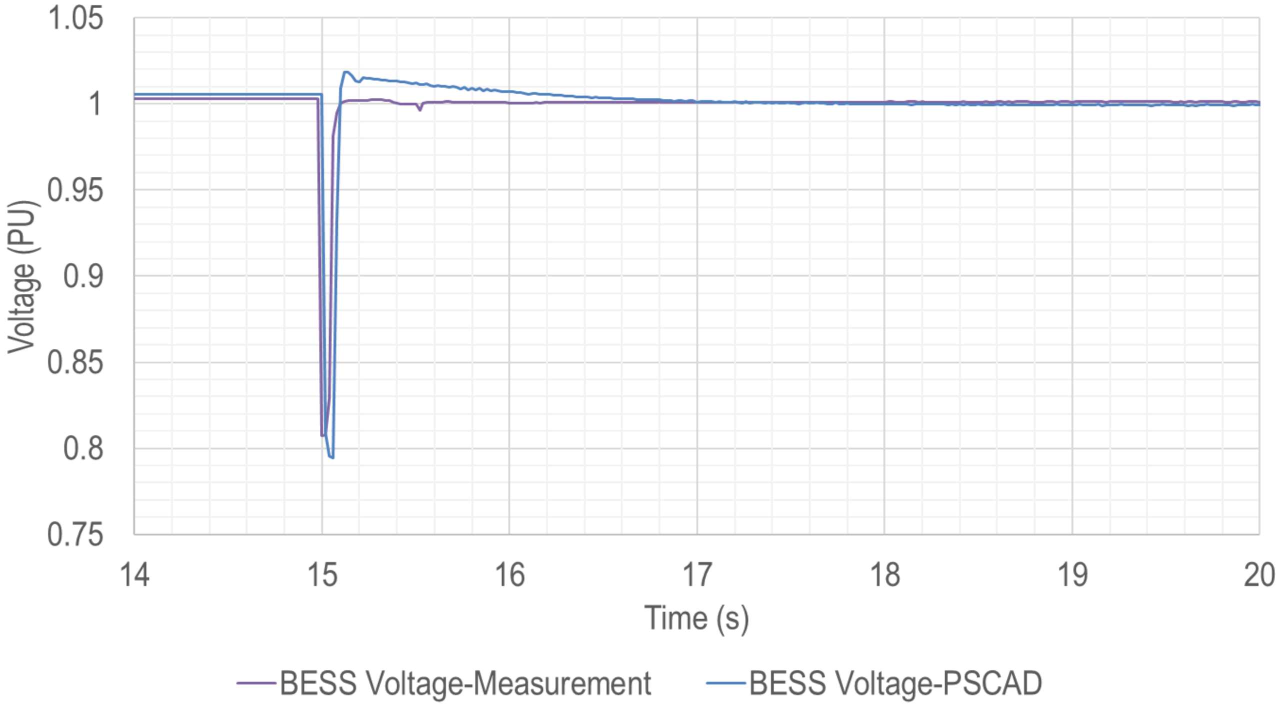


Figure 31 Frequency at the 33 kV bus PSCAD™ overlay in Event 3 (Hz)

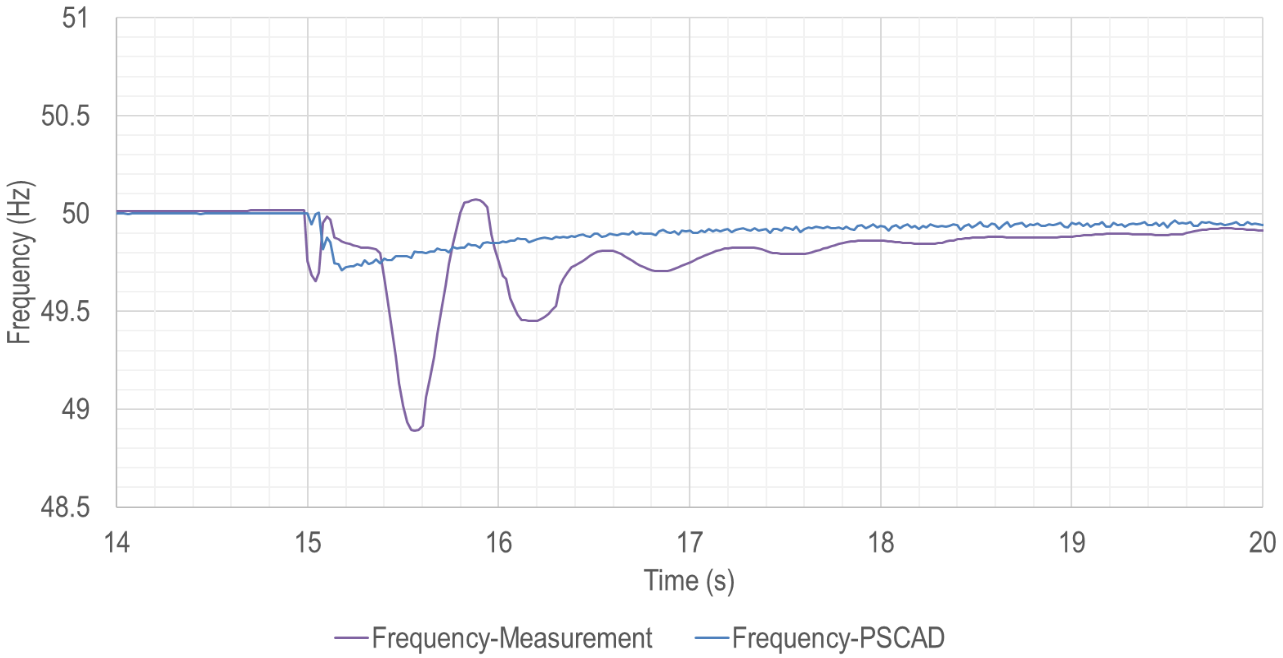


Figure 31 shows that the simulated frequency in the 33 kV island does not match the measured frequency. The measured frequency in the 33 kV island briefly reduced to 48.9 Hz before being restored to around 50.1 Hz, and eventually settled at 49.9 Hz. The measured frequency may be affected by the following factors:

- Load connection and disconnection in quick succession after the island is formed.
- Load connection and followed by under-frequency load shedding (UFLS) activation.
- BESS grid-forming frequency control behaviour.
- Load dynamics which cannot be captured by the standard voltage-dependent load models

At this moment, the simulation only captured a single-phase fault which separates the island from the main power system. It is unknown whether another event or disturbance occurred during the actual incident. Without further information on the actual sequence of events, it is difficult to recreate the measured frequency in the simulation environment.

AEMO is also investigating the output of several frequency measurement techniques used in the simulation environment, for testing the suitability of each technique in estimating the simulated frequency in different power system operation conditions.

4 Summary

The analysis and simulation conducted on the events involving the Dalrymple BESS and the Wattle Point Wind Farm yielded valuable findings regarding their operational dynamics during grid disturbances. By leveraging the PSCAD™ model and validating the results with high-resolution data, AEMO achieved a thorough assessment of the BESS's performance in maintaining grid stability and offering support during islanded operation. The outcomes of these simulations underscore the accuracy and effectiveness of the BESS in effectively managing grid disruptions, particularly through its grid-forming capabilities.

Throughout the analysis, AEMO observed that the BESS demonstrated resilience in sustaining the islanded state and facilitating re-synchronisation post-event, underlining its pivotal role in maintaining grid stability during disturbances. These findings highlight the importance of energy storage systems with grid-forming capability, like the Dalrymple BESS, in improving the reliability and resilience of power systems, especially in the face of unforeseen grid disturbances and outages.

As an important part of the model validation process, this analysis highlighted how the BESS model can be configured to seamlessly transition between the grid-connected operation and the island operation modes, depending on the battery's operational state. This finding not only enhances the understanding of the Dalrymple BESS performance, but also provides valuable guidance for future investigative tasks aimed at optimising the integration and performance of BESS.