Manitoba
HYDRO INTERNATIONAL

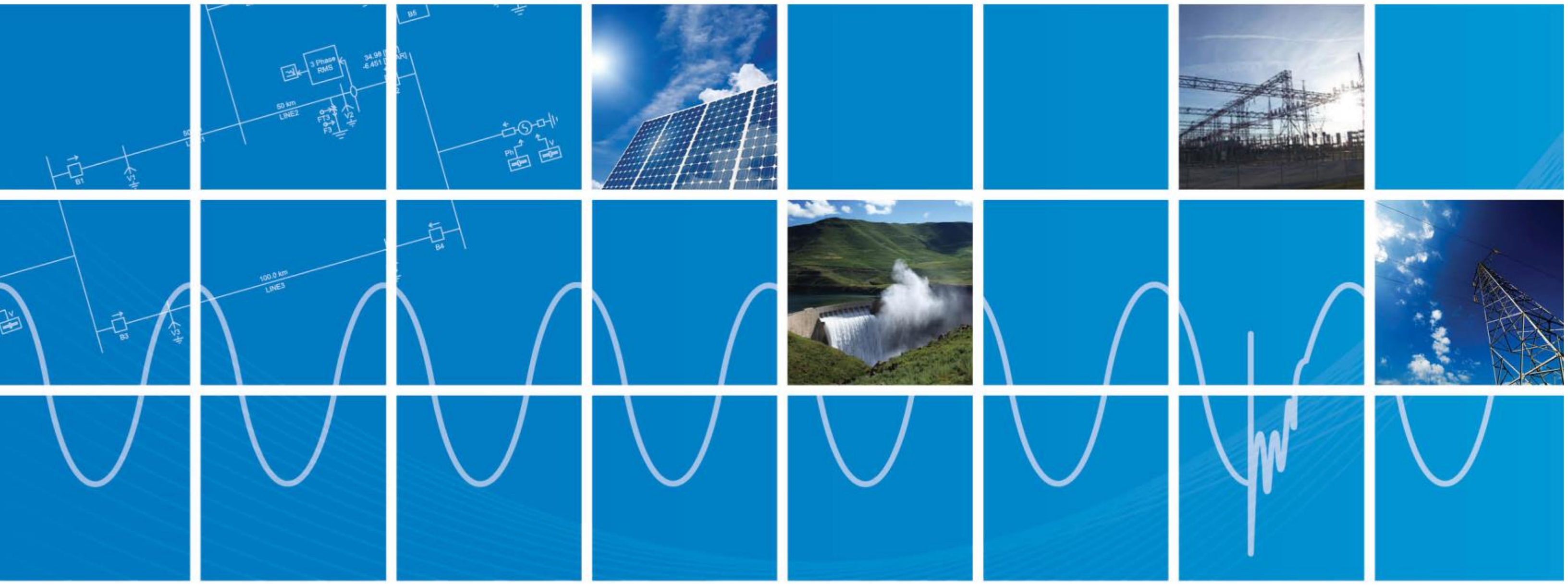
ENGINEERING CONSULTING SERVICES

Final report: Composite Load and Distributed PV Model Validation in PSCAD™/EMTDC™

AEMO
Attention:
Filip Brnadic
Filip.Brnadic@aemo.com.au

Date – January 14, 2024

File: # 20-250-00776



Powered by Manitoba Hydro International Ltd.
211 Commerce Drive
Winnipeg, Manitoba
R3P 1A3 Canada
mhi.ca

DOCUMENT TRACKING

Rev.	Description	Date
0	First issue	June 16, 2023
1	Second issue	January 14, 2024

THIRD PARTY DISCLAIMER

Power Systems Technology Centre, a division of Manitoba Hydro International Ltd. (“**MHI**”) has prepared this document for the sole use of AEMO (“**Client**”), and for the intended purposes stated in the agreement between MHI and the Client pursuant to which this document was completed.

The content of this document is not intended for the use of, nor is it intended to be relied upon by any person, firm, corporation or other governmental or legal entity (each a “**Third Party**”), other than the Client. MHI makes no warranty, express or implied, to any Third Party in relation to the contents of this document, including any conclusions or recommendations.

The use of or reliance on this document by any Third Party shall be at its own risk, and MHI accepts no responsibility or liability for the consequences of this document being used or relied upon by such Third Party. Any Third Party will, by such use or reliance, be taken to have confirmed its agreement to:

(a) Indemnify MHI, its affiliates, and any person or entity acting on their behalf (“**Indemnitees**”), for all losses, costs, damages or expenses suffered or incurred by the Indemnitees as a result of such Third Party’s use or reliance on this document; and

(b) Release the Indemnitees from any and all liability for direct, indirect, special or consequential damages (including but not limited to loss of revenue or profit, lost or damaged data, loss of goodwill or other commercial or economic loss) suffered or incurred by the Third Party, or for those at law for whom it is responsible, as a result of its or their use or reliance on this document whether based in contract, warranty or tort, (including but not limited to negligence), equity, strict liability or otherwise.

1 Executive Summary

The Power System Technology Centre (PTC), a division of Manitoba Hydro International Ltd. (MHI), was contacted by the Australian Energy Market Operator (AEMO) to validate composite load (CMLD) and distributed PV (DER) models of the National Electricity Market (NEM) using PSCAD™/EMTDC™ platform. These models are validated by comparing simulation results obtained from PSS®E cases representing historical events in the NEM and high-speed measurements (HSM) recorded for the same historical events. AEMO had previously validated the PSS®E models against HSM taken from historical events [1].

Seven historical events having voltage and frequency disturbances were selected for PSCAD™/EMTDC™ model validation. Study cases to represent these events, regions impacted by the event, and event types are shown in Table 1.

Table 1: PSCAD™/EMTDC™ study cases

Study Case	Regions Impacted by the Event	Event Type
April 17, 2019	South Australia	Voltage disturbance (without DER)
February 22, 2021	Queensland	
March 3, 2017	South Australia	Voltage disturbance (with DER)
January 18, 2018	Victoria	
March 12, 2021	South Australia	
August 25, 2018	All four regions	Frequency disturbance (with DER)
January 31, 2020	South Australia + Victoria	

In developing PSCAD™/EMTDC™ study cases representing these seven events, only the areas impacted by the event were modeled. The rest of the system was replaced by suitable equivalents.

(A) Voltage disturbance

A summary of the PSCAD™/EMTDC™ model performance for voltage disturbances is shown in Table 2. Cells in green indicate a good match with HSM data, yellow cells indicate a fair match with HSM data, and orange indicates a poor match with HSM data. A checkmark indicates a close match between the PSCAD™/EMTDC™ model performances and the PSS®E model performances.

Table 2: Voltage disturbances

Quantity	Characteristic	No DER generation		With DER generation		
		17/04/19	22/02/21	03/03/17	18/01/18	12/03/21
Voltages	Overshoot	🟨	🟩 ✓	🟩 ✓	🟩	🟩 ✓
	Recovery Rate	🟩 ✓	🟨	🟩 ✓	🟨	🟩 ✓
	Steady state post-disturbance	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓
Active power	During dynamic state	🟨 ✓	🟩 ✓	🟨 ✓	🟨	🟨 ✓
	Steady state post-disturbance	🟩 ✓	🟩 ✓	🟩 ✓	🟨	🟩 ✓
Reactive power	During dynamic state	🟨	🟨 ✓	-	🟨	🟨 ✓
	Steady state post-disturbance	🟩 ✓	🟩 ✓	-	🟩 ✓	🟩 ✓

From Table 2, the following conclusions are made:

- The PSCAD™/EMTDC™ model performances show a good match to the HSM data and the PSS®E model performances for voltage overshoot and recovery rate.

- The PSCAD™/EMTDC™ model performances show a close match to the HSM data and the PSS®E model performances in steady-state post-disturbance voltage, active power, and reactive power.

- The PSCAD™/EMTDC™ model closely matches the PSS®E model in all cases, except for the January 18, 2018 case.

Figure 1 shows the model performance considering the change in CMLD, DER, and overall operating demand (OD) for voltage disturbances. The bars represent the PSCAD™/EMTDC™ model performance (blue bars for CMLD loss, yellow bars for DER loss, and orange bars for operational demand change), the red markers represent SCADA/Solar Analytics data (target values), and the **black** lines represent the error bars (estimated range).

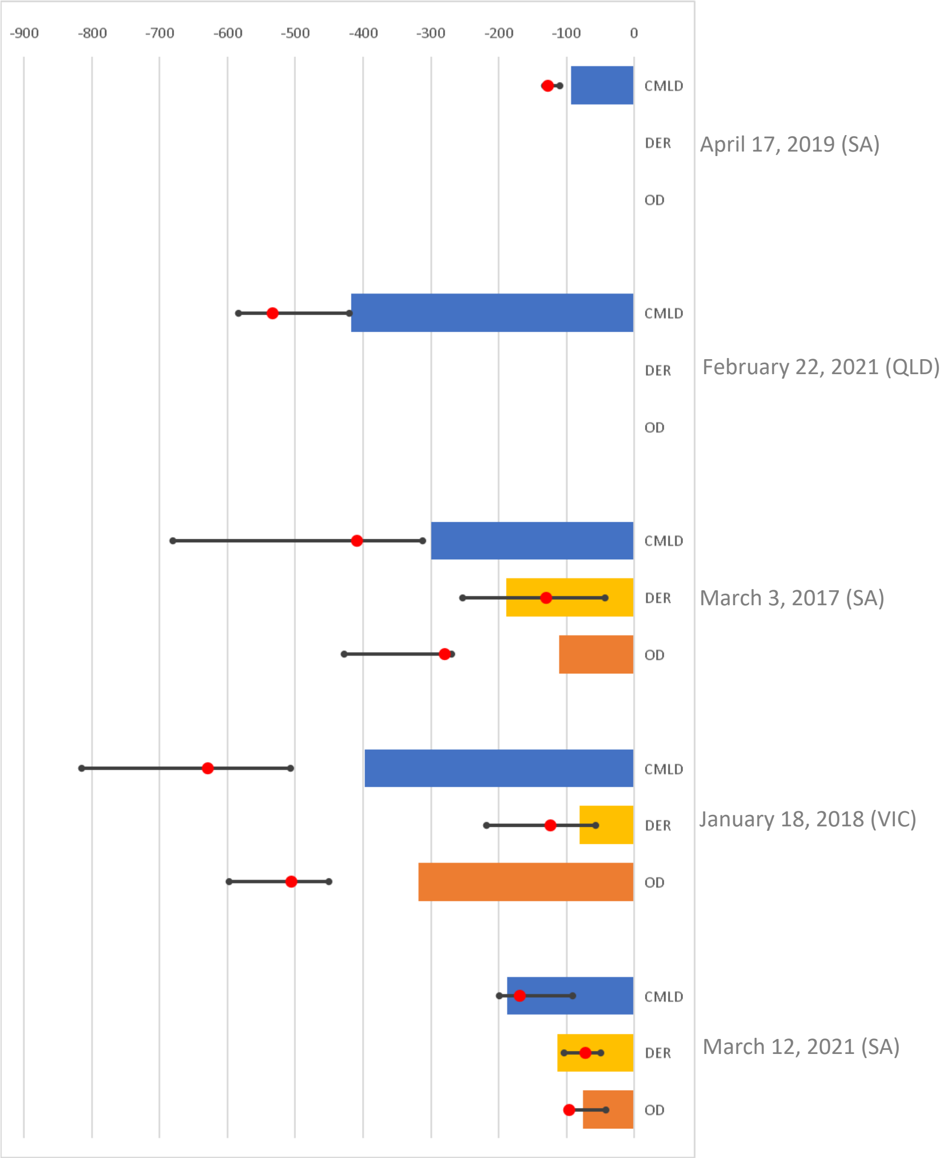


Figure 1: Voltage disturbances: model performance for CMLD load/DER loss (MW change)

From Figure 1, the following conclusions are made:

- The change in CMLD is underestimated in the PSCAD™/EMTDC™ model for all cases except for the March 12, 2021 case. However, excluding the January 18, 2018 and April 17, 2019 cases, the change in CMLD load falls inside or just outside the estimated range.

- Excluding the January 18, 2018 case, the change in DER is overestimated in the PSCAD™/EMTDC™ model. However, the change in DER is inside or just outside the estimated range for all cases.

- Operating demand is underestimated in all cases. Only in the March 12, 2021 case does the operating demand fall in the estimated range.

In addition, the following observations and recommendations are made.

- Without DER/CMLD models, PSCAD™/EMTDC™ and PSS®E result does not match with HSM data for March 3, 2017 case. Post-contingency system is stable as shown by the HSM data. However, without DER/CMLD models, both PSCAD™/EMTDC™ and PSS®E simulation platforms show the post-contingency system cannot maintain stability.

- Existing angle tripping parameters results deviate the simulation results from the HSM data. It is recommended to disable DER model phase angle tripping until the parameters are updated.

(B) Frequency disturbances

PSCAD™/EMTDC™ models were developed for the two "frequency disturbance" cases (August 25, 2018, and January 31, 2020). Before adding DER and CMLD models, the frequency observed throughout the system during and after the fault significantly differed between PSS®E and PSCAD™/EMTDC™. ™. After further investigation, it was found that the modeling of governors between the two software platforms was significantly different. Harmonization of the governor models between PSS®E and PSCAD™/EMTDC™ is essential for model validation using these two "frequency disturbance" cases. After discussions with AEMO, the model validation using these two frequency disturbances were not performed due to the unavailability of the harmonized governor modes between PSS®E and PSCAD™/EMTDC™ models.

Contents

2 Introduction

The Power System Technology Centre (PTC), a division of Manitoba Hydro International Ltd. (MHI), was contacted by the Australian Energy Market Operator (AEMO) to validate composite load (CMLD) and distributed PV (DER) models of the National Electricity Market (NEM) using PSCAD™/EMTDC™ platform. These models were validated by comparing simulation results obtained from PSS®E cases representing historical events in the NEM and high-speed measurements (HSM) recorded for the same historical events. AEMO had previously validated the PSS®E models against HSM taken from historical events [1].

The existing load models used in AEMO's models are being updated to better represent real load behavior. These updates include utilizing CMLD models as opposed to the existing exponential load models and implementing DER models to better represent the network today. In order to validate the PSCAD™/EMTDC™ models, a number of PSCAD™/EMTDC™ cases were developed from a base PSCAD™/EMTDC™ case (provided by AEMO) to represent historic operating conditions. A historic event was then applied (voltage or frequency disturbance) and the results from the PSCAD™/EMTDC™ simulation were compared to the same simulation performed in PSS®E.

Section 3 of this report outlines the methodology used to update the PSCAD™/EMTDC™ study cases and validate the models. Sections 4, 5, and 6 of this report provide details of the cases, disturbances, and study results for voltage disturbances without DER, voltage disturbances with DER, and frequency disturbances, respectively. Sections 7, 8 and 9 of this report presents how to use models in large networks, the study conclusions and future developments proposed for models.

3 Methodology

3.1 Study cases

In this study, a total of seven (7) cases were studied and are shown in Table 3.

Table 3: PSCAD™/EMTDC™ study cases

Study Case Date	Modeled Regions	Event Type
April 17, 2019	South Australia	Voltage disturbance (without DER)
February 22, 2021	Queensland	
March 3, 2017	South Australia	Voltage disturbance (with DER)
January 18, 2018	Victoria	
March 12, 2021	South Australia	
August 25, 2018	All	Frequency disturbance (with DER)
January 31, 2020	South Australia + Victoria	

As shown in Table 3, not all cases had the entire network modeled in PSCAD™/EMTDC™. This is because the disturbance in each of these cases is located far away from the other regions and has little impact on those areas (further information for each case/disturbance is provided in sections 4, 5, and 6). As such, these distant areas were replaced with suitable equivalents at the boundaries of the area of interest. For the August 25, 2018 case, multiple events were recorded in all parts of the NEM, and therefore all areas were modeled.

3.2 PSCAD™/EMTDC™ model development

3.2.1 Network development

The NEM mainland PSCAD™/EMTDC™ model [2] representing the South Australia (SA), Victoria (VIC), New South Wales (NSW) and Queensland (QLD) regions on ***August 29, 2020***, was used as the **base model** in this study. Seven (7) PSCAD™/EMTDC™ models were derived from the base model and PSS®E case as explained below.

- Selected regions of the NEM network model available in the PSS®E powerflow case (RAW data file) were converted to a PSCAD™/EMTDC™ case using PRSIM™ software. This PSCAD™/EMTDC™ case consisted of all network elements but dynamic devices such as conventional generators, SVCs, and solar/wind farms were modeled as sources.
- Dynamic models which were modeled as sources in the derived PSCAD™/EMTDC™ case were manually replaced by detailed dynamic models copied from the base model.
- When the required detailed dynamic model was not available in the base model, the following simplified modeling approach was taken.
    - Conventional generators: sources representing conventional generators were imported from the PSS®E case using PRSIM™ software.
    - Solar and wind farms: Sources representing solar or wind farm models were replaced with a generic model.
    - In addition to the above, a voltage source behind an impedance was used to replace the source in some occasions (i.e. only in voltage disturbance cases when no generator model in PSCAD™/EMTDC™ or generic model dynamic data in PSS®E was available).

3.2.2 Initialization and flat-run

A comparison between the PSS®E and the PSCAD™/EMTDC™ models was first performed during initialization and for a flat-run simulation before applying the disturbance. During initialization, the PSCAD™/EMTDC™ model had a good match in both active power and reactive power to the PSS®E model. For the flat-run test, the active powers in the PSCAD™/EMTDC™ models were slightly different than the PSS®E values, though the differences usually do not exceed 5% compared to the power being transferred with a few exceptions. The reactive power[1] had a larger difference (less than 10% difference with several exceptions) between the two models.

3.2.3 Playback model

Static network equivalents were used at the boundaries of the regions modeled in PSCAD™/EMTDC™ to represent the rest of the system. Results at the boundaries were then compared between PSS®E and PSCAD™/EMTDC™ platforms. If differences were observed, the static equivalents were replaced with playback models to accurately replicate the low-frequency response at the boundary[2]. In addition, playback models were used to represent HVDC link (i.e. Basslink and Terranorra) which does not have a PSCAD™/EMTDC™ model.

Playback model would take the active power and reactive power measurements from PSS®E simulations and were used as input signals to a dq-decoupled controller, which would then generate the correct voltage magnitude and voltage angle at the boundary. Simulation tests confirmed that the playback model was able to successfully replicate the low-frequency dynamics observed in PSS®E. Table 4 shows the locations in the PSCAD™/EMTDC™ cases where the playback model was utilized. Other boundaries were replaced with static equivalents, also shown in Table 4.

Table 4: Playback model locations per case

Study Case Date	Modeled Regions	Playback Model Locations	Static Equivalents
April 17, 2019	South Australia	-	HIC (VIC side) Murraylink (VIC side)
February 22, 2021	Queensland	QNI (NSW side)	Terranorra (QLD side)
March 3, 2017	South Australia	-	HIC (VIC side) Murraylink (VIC side)
January 18, 2018	Victoria	Basslink (VIC side)	HIC (SA side) Murraylink (VIC side) VNI (NSW side)
March 12, 2021	South Australia	-	HIC (VIC side) Murraylink (VIC side)

---

[1] In some dynamic models, the reactive power output was initialized close to the PSS®E value but deviated when the controllers were released. These model issues were discussed with AEMO, and it was decided to move on as these differences are unlikely to impact conclusions.

[2] Low-frequency transients (such as oscillations associated with inter-area modes) propagate long distances, but high-frequency transients (such as oscillations associated with sub-synchronous and inter-plant modes) propagate relatively short distances. In the validation process, equivalencing boundaries were chosen so that the resulting network equivalents were located far away from the location of the disturbance.

Study Case Date	Modeled Regions	Playback Model Locations	Static Equivalents
August 25, 2018	All	Basslink (VIC side) Terranora (QLD and NSW sides)	-
January 31, 2020	South Australia + Victoria	Basslink (VIC side) VNI (NSW side)	-

3.2.4 Simulation of the fault events

Residual voltage at the fault location matches well between PSCAD™/EMTDC™ and the PSS®E simulations for three phase faults. However, a slight difference[3] in the residual voltage was observed for some unbalanced faults. In PSS®E, the unbalanced fault is simulated by applying an equivalent 3PG fault using a shunt impedance calculated using sequence data (since PSS®E cannot explicitly simulate unbalanced faults). This same shunt impedance was used as a 3PG when applying the fault in the PSCAD™/EMTDC™ model. This was done to match the residual voltage during the fault between the PSCAD™/EMTDC™ and the PSS®E simulations.

Note: Whenever an equivalent 3PG fault is applied to simulate an unbalanced fault in PSCAD™/EMTDC™, sensitivity analysis was performed using the actual unbalanced fault to identify the impact of CMLD load and DER tripping.

3.2.5 Development of DER and CMLD models in PSCAD™/EMTDC™

The DER and CMLD models in the PSCAD™/EMTDC™ cases were previously developed in [3][4]. The models were updated and validated in a single-machine infinite-bus (SMIB) system in [5].

---

[3] Slight differences in zero-sequence network data in PSCAD™/EMTDC™ and the PSS®E may have resulted in these differences.

4 Model validation: Voltage disturbances without DER

4.1 April 17, 2019 – South Australia

4.1.1 Case description

On April 17, 2019, the event described in Table 5 occurred in South Australia.

Table 5: Description of the event on April 17, 2019

Date and time	April 17, 2019, 06:13
Region	South Australia
Description of the event	Torrens Island – Magill 275 kV line tripped due to a bushfire.
Minimum voltage recorded	0.63 pu positive sequence at Torrens Island B Power Station (TIPS B) (from HSM Data)
Operational demand prior to the event	1,389 MW (from SCADA data)
Estimated change in operational demand	127 MW decrease (from SCADA data)

A map of this event is shown in Figure 2.

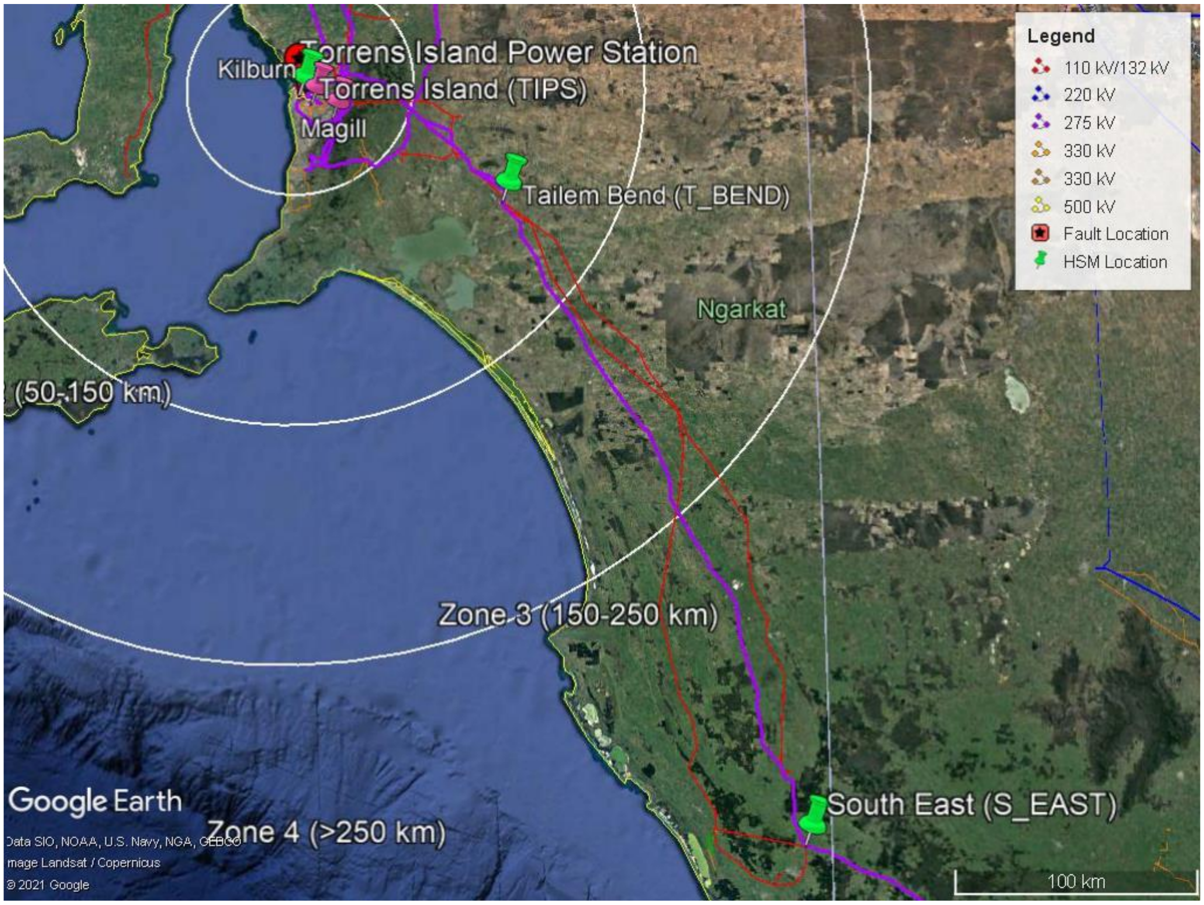


Figure 2: Map of the event on April 17, 2019

This event was replicated in PSCAD™/EMTDC™ using the event description shown in Table 6.

Table 6: Event summary for April 17, 2019

Time (seconds)	Event Description
0.0	Time when PSCAD™/EMTDC™ case finished initializing.
1.0	3PG fault applied at the 275 kV Torrens Island A substation.
1.1	Clear 3PG fault. Trip 275 kV Torrens Island A – Magill circuit.
20.0	End of simulation

4.1.2 PSCAD™/EMTDC™ modeling

After consulting with AEMO and considering the fault location was far away from VIC, NSW and QLD, it was decided to model only the SA region in PSCAD™/EMTDC™. Connections to VIC were replaced by static equivalents at the VIC end of the Murraylink HVDC link and the Heywood interconnector.

After deriving the PSCAD™/EMTDC™ case using the April 17, 2019, PSS®E case and the base PSCAD™/EMTDC™ case, the following issues were observed:

- Lincoln Gap WF had compilation errors.
- Wattle Point WF and Dalrymple BESS resulted in the power flow going to an unacceptable level (active power of Wattle Point WF during initialization increased to 5000 MW).

After consulting with AEMO, it was decided to replace these models with voltage-behind-impedance source models. This may result in smaller variations in voltage around these sources, resulting in less DER and CMLD being tripped. However, these plants are located far away from the event and it is unlikely for the dynamic performance of these plants to have a significant impact on the results.

4.1.3 Comparison

4.1.3.1 PSCAD™/EMTDC™ model comparison to HSM and PSS®E model

Figure 3 shows the voltage at Torrens Island A 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model. HSM data is shown in blue, PSS®E results (without CMLD models) are shown in orange, PSS®E results (with CMLD models) are shown in green, PSCAD™/EMTDC™ results (without CMLD models) are shown in purple, and PSCAD™/EMTDC™ results (with CMLD models) are shown in red.

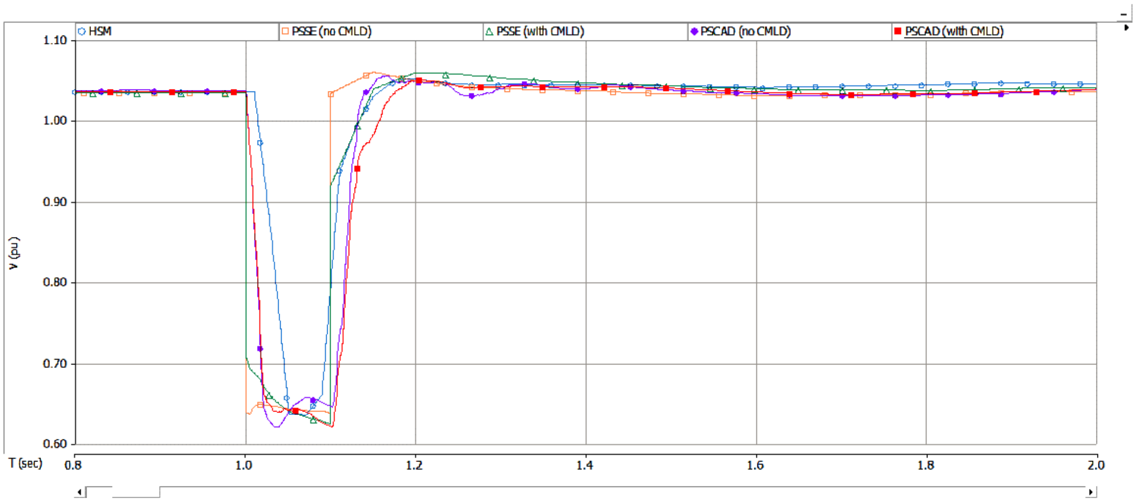


Figure 3: Torrens Island A 275 kV voltage

As shown in Figure 3 the PSCAD™/EMTDC™ model closely follows the response observed with the HSM data and the PSS®E model. The steady state value of the voltage is also comparable between the three sets of results.

Figure 4 shows the voltage at South East 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model.

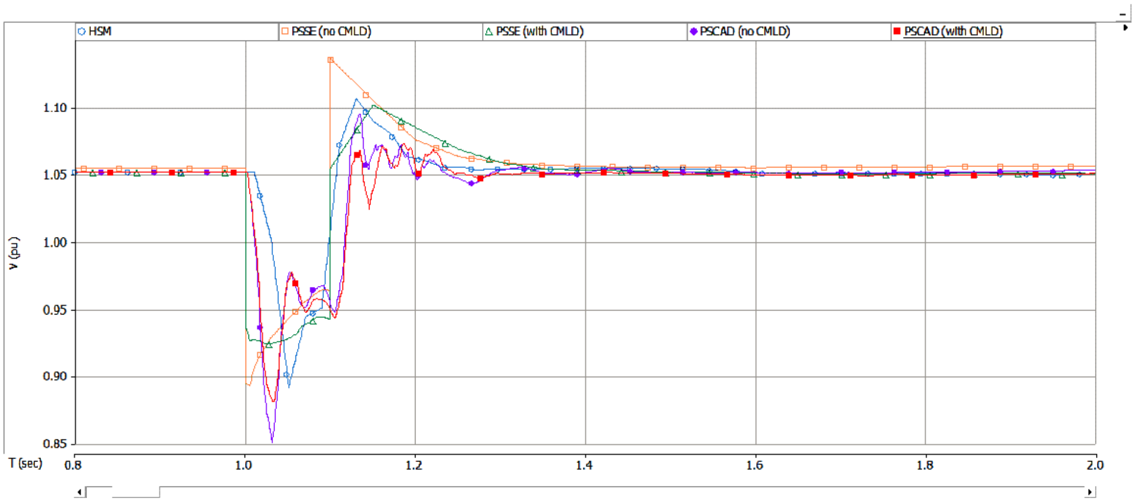


Figure 4: South East 275 kV voltage

As shown in Figure 4, the PSCAD™/EMTDC™ model has a good match during the fault, and the steady state value of the voltage is the same between the three sets of results. However, the overshoot at the fault clearance is slightly less in the PSCAD™/EMTDC™ results compared to the HSM data and the PSS®E results.

The active power in the Torrens Island A – Kilburn 275 kV circuit is shown in Figure 5 (zoomed in around the fault period) and Figure 6 (zoomed out showing the entire simulation run).

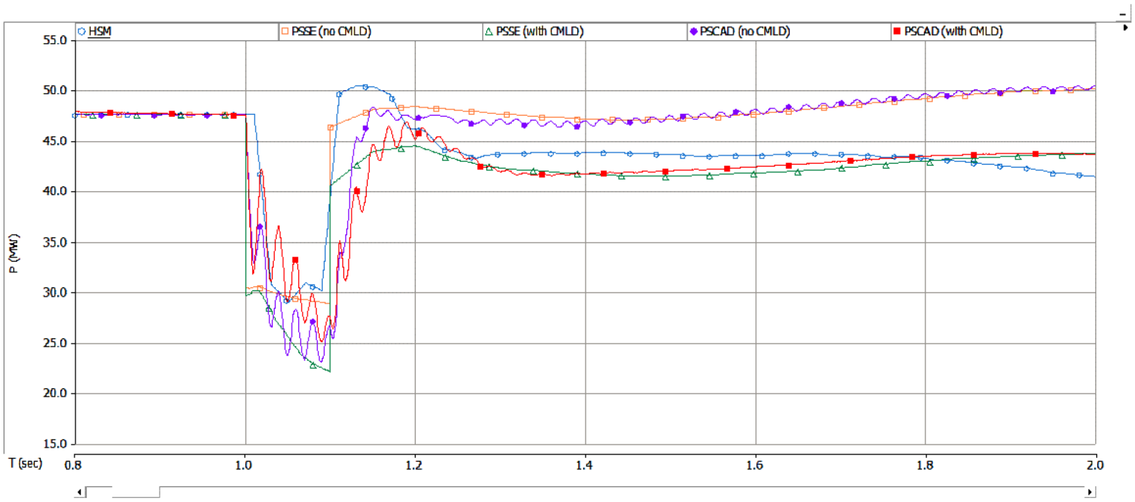


Figure 5: Torrens Island A – Kilburn 275 kV active power (zoomed in)

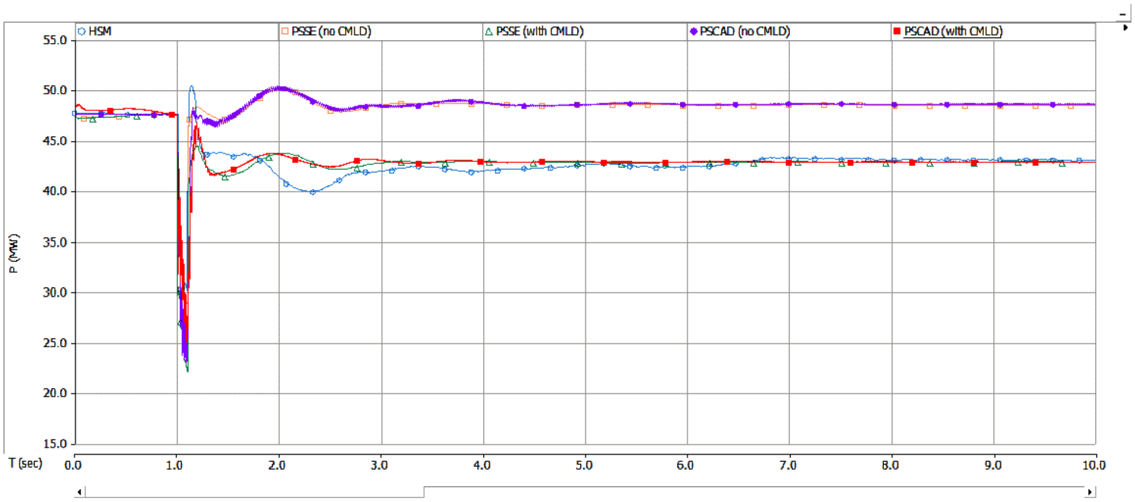


Figure 6: Torrens Island A – Kilburn 275 kV active power (zoomed out)

As shown in Figure 5, more oscillations were observed with the PSCAD™/EMTDC™ model during the fault and shortly after the fault. These are network oscillations (50 Hz frequency) commonly found in EMT simulations[4]. In addition, the PSCAD™/EMTDC™ model underestimates the peak active power immediately after the fault, similar to the PSS®E model. Also, the oscillations in the active power after fault clearance match with the PSS®E model. In the post-contingency steady state, active power transfer estimated by both simulation platforms (i.e. PSS®E and PSCAD™/EMTDC™) matches well with the HSM data when the CMLD models are included. Without, CMLD models, there is about 10% difference in active power transfer in the post-contingency steady states operation.

---

[4] These oscillations after fault inception and clearance are a result of interactions between 50 Hz components and DC components of voltages and currents. The magnitude of the DC components depends on the point-on-wave switching and resultant 50 Hz oscillations decay faster in parts of the network with lower X/R ratios. Hence, these oscillations are not always observable. RMS simulation platforms (like PSS®E) do not model network RLC dynamics; hence, these oscillations do not appear in RMS platforms.

As shown in Figure 6, the steady state value of the active power with the PSCAD™/EMTDC™ model matches the HSM data and the PSS®E model.

The active power in the South East - Heywood 275 kV circuit is shown in Figure 7 (zoomed in around the fault period) and Figure 8 (zoomed out showing the entire simulation run).

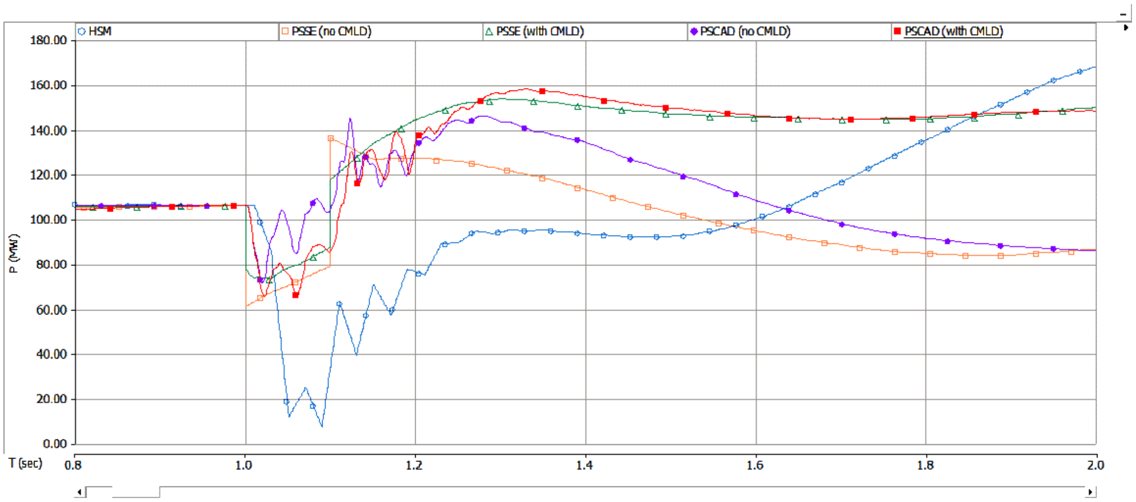


Figure 7: South East – Heywood 275 kV (circuit 1) active power (zoomed in)

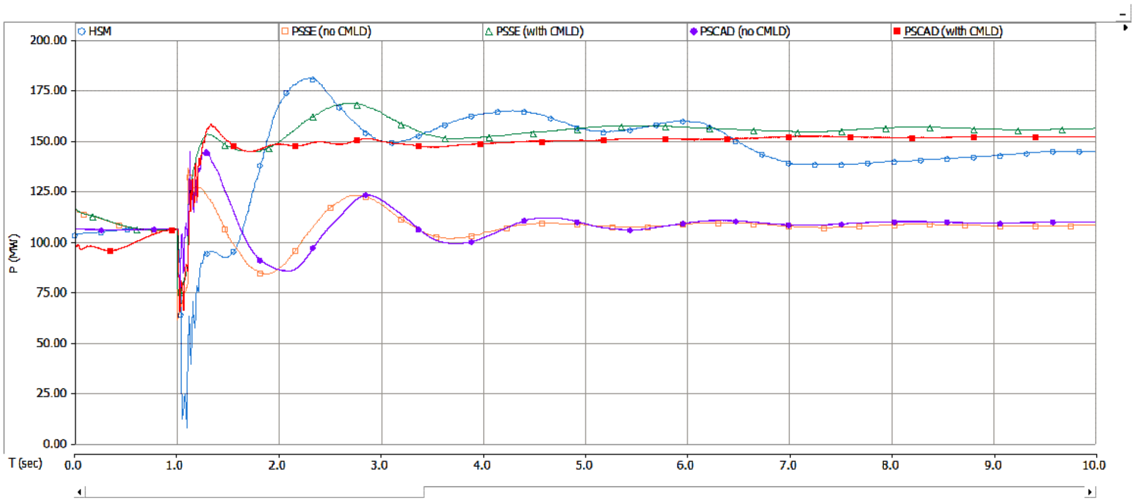


Figure 8: South East – Heywood 275 kV (circuit 1) active power (zoomed out)

As shown in Figure 7 and Figure 8, the PSCAD™/EMTDC™ model does not quite match with the HSM data, as a smaller drop in active power is observed during the fault with the PSCAD™/EMTDC™ model, and the oscillations after the fault are adequately damped. However, when compared to the PSS®E model, the results are very close. The steady state reactive power matches with the HSM data when the CMLD models are included. Without, CMLD models, there is about 40% difference in active power transfer in the post-contingency steady states operation.

Figure 9 and Figure 10 show the reactive power at the same locations (Torrens Island A – Kilburn 275 kV and South East – Heywood 275 kV (circuit 1), respectively).

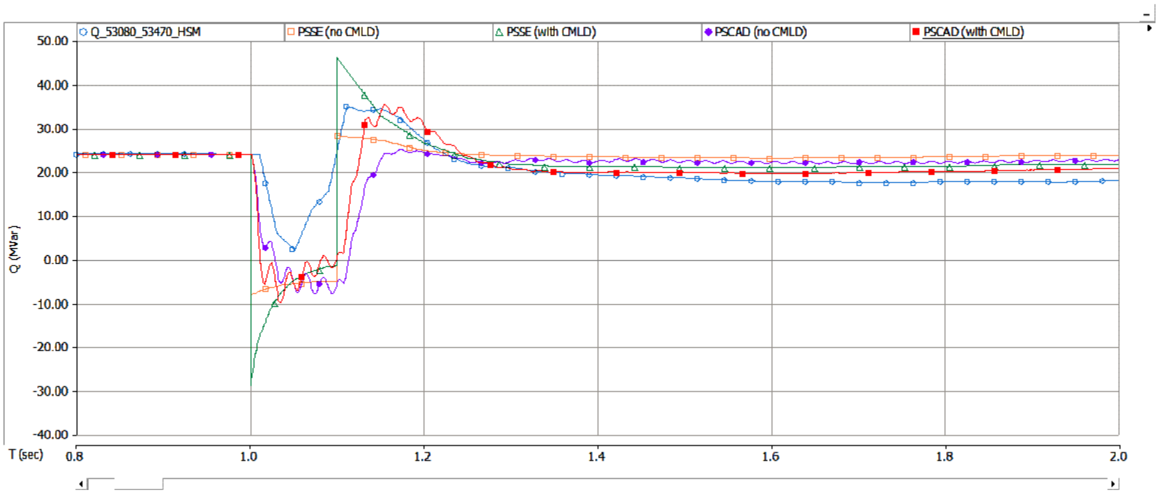


Figure 9: Torrens Island A – Kilburn 275 kV reactive power

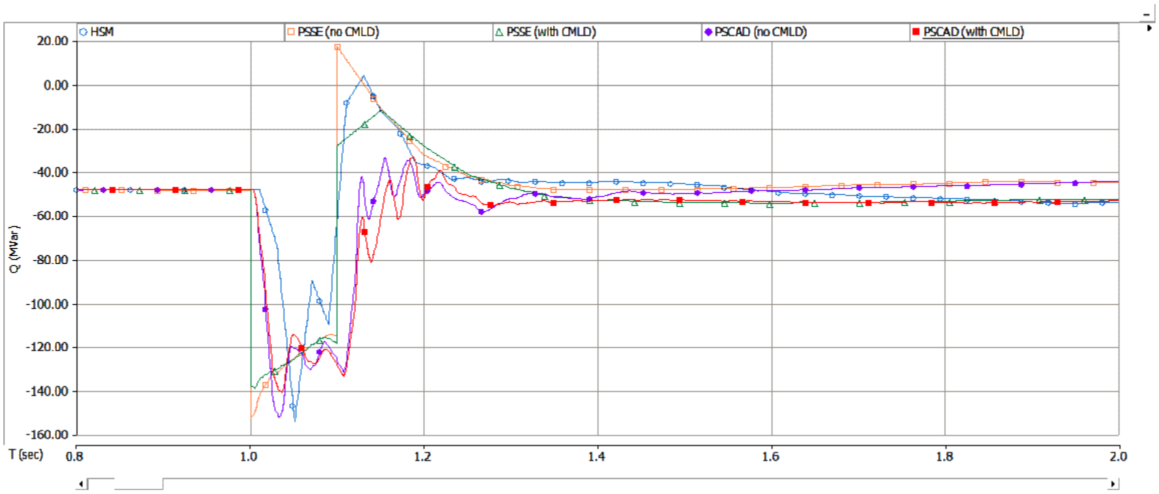


Figure 10: South East – Heywood 275 kV (circuit 1) reactive power

As shown in Figure 9, the PSCAD™/EMTDC™ model closely matches the PSS®E results. As shown in Figure 10, the PSCAD™/EMTDC™ model underestimates the peak reactive power after the fault, similar to how the voltage was also underestimated with the PSCAD™/EMTDC™ model at this location. The steady state reactive power matches with the HSM data when the CMLD models are included.

When the same smoothing time constant[5] used in the PSCAD™/EMTDC™ results is applied to the PSS®E results (20 ms), the dynamic response during the fault period match much closer between PSS®E and PSCAD™/EMTDC™. The PSS®E results with the smoothing for the reactive power at Torrens Island A – Kilburn 275 kV and South East – Heywood 275 kV (circuit 1) are shown in Figure 11 and Figure 12, respectively.

---

[5] The multimeter component in the base PSCAD™/EMTDC™ model has a 20 ms default smoothing time constant, representing the time delay for measuring equipment. In PSS®E simulations, no smoothing is applied. In order to compare PSS®E and PSCAD™/EMTDC™ traces closely, one should apply the same measuring time constant to PSS®E traces.

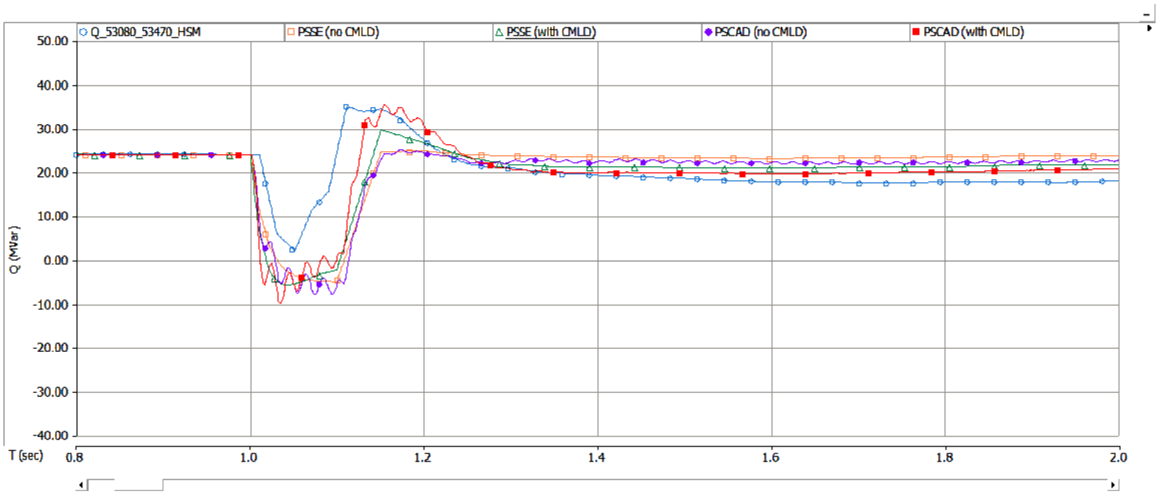


Figure 11: Torrens Island A – Kilburn 275 kV reactive power (PSS®E results smoothed)

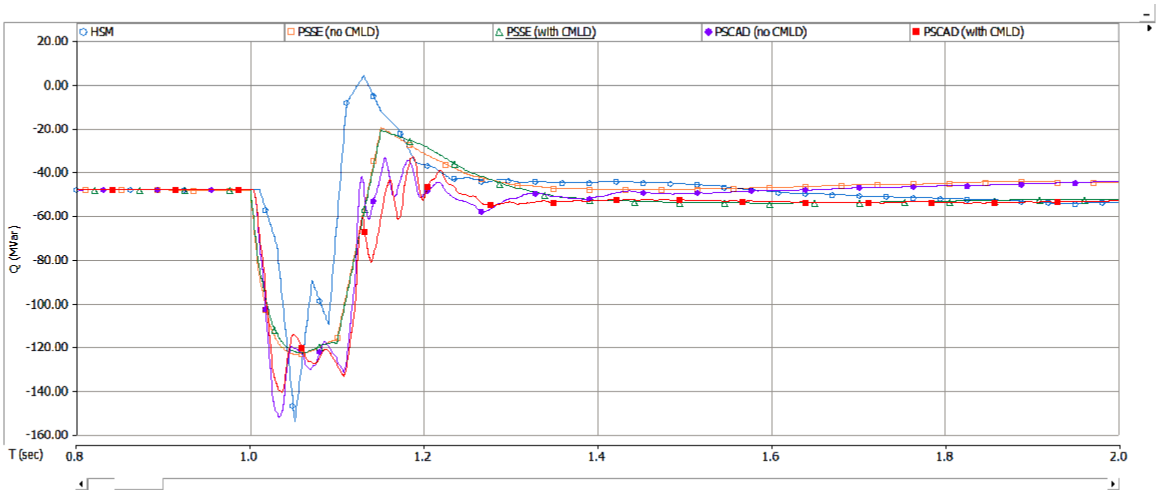


Figure 12: South East – Heywood 275 kV (circuit 1) reactive power (PSS®E results smoothed)

4.1.3.2 CMLD change comparison

Figure 13 shows the total load in SA for measurements from the PSCAD™/EMTDC™ model, with and without the CMLD models.

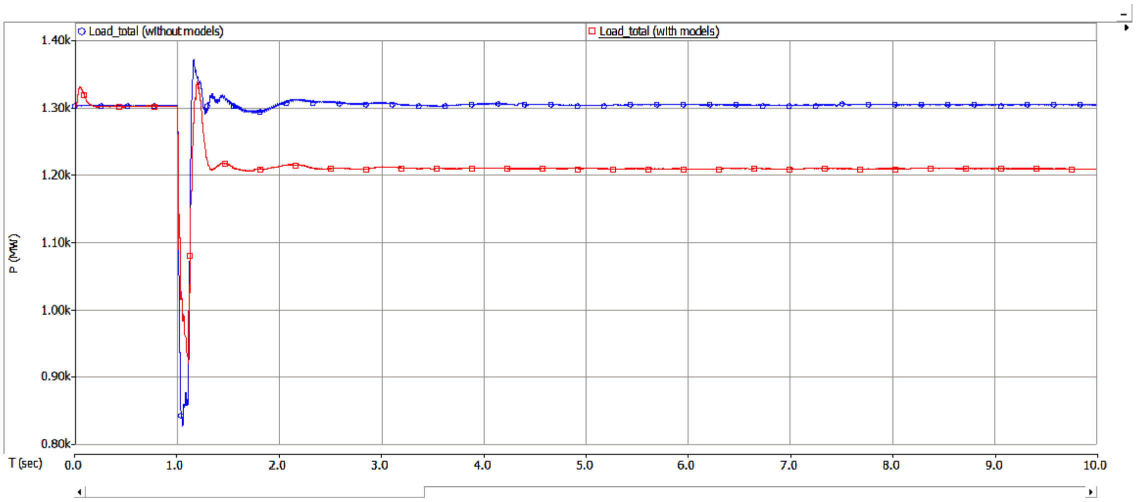


Figure 13: CMLD in SA

The post-contingency steady states load in SA drops by about 7% with CMLD models compared to the simulation without CMLD models.

Table 7 shows a comparison of the total CMLD load change based on SCADA measurements, the PSS®E model and the PSCAD™/EMTDC™ model.

Table 7: CMLD MW change comparison – April 17, 2019

Model	CMLD (MW)
SCADA Estimate	127
Estimated Range	110 – 132
PSS®E	111
PSCAD™/EMTDC™	93

As shown in Table 7, the PSCAD™/EMTDC™ model underestimates the change in CMLD load in SA by 34 MW (27%) and is outside the estimated range.

4.1.4 Conclusions

The conclusions for the April 17, 2019 case are shown in Table 8. Cells in green indicate a good match with the HSM data, yellow cells indicate a fair match with the HSM data, and orange indicates a poor match with HSM data.

Table 8: Assessment of model performance – April 17, 2019

Quantity	**Characteristic**	**Match to HSM**	**Match to PSS®E**	**Comment**
Voltages	Overshoot	Fair	Fair	Model underestimates the peak voltage overshoot.
	Recovery Rate	Good	Good	Model closely matches HSM and PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Active power	During dynamic state	Fair	Good	Model matches the general trajectory but underestimates the peak active power after fault recovery.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Reactive power	During dynamic state	Fair	Fair	Model matches the general trajectory but underestimates the peak reactive power after fault recovery.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Load	Load change	Fair	Fair	PSCAD™/EMTDC™: 93 MW PSS®E: 111 MW Actual: 127 MW Model underestimates CMLD change by 34 MW (27%).

4.2 February 22, 2021 – Queensland

4.2.1 Case description

On February 22, 2021, the event described in Table 9 occurred in Queensland.

Table 9: Description of the event on February 22, 2021

Date and time	February 22, 2021, 21:20
Region	Queensland
Description of the event	2PHG fault (from a direct lightning strike) on the Mt. England – Wivenhoe 275 kV line. South Pine SVC tripped due to an AC changeover failure. All equipment returned to service by 22:14 hrs.
Minimum voltage recorded	0.15 pu positive sequence recorded at Swanbank E Substation (from HSM data)
Operational demand prior to the event	7,977 MW (from SCADA data)
Estimated change in operational demand	533 MW decrease (from SCADA data)

A map of this event is shown in Figure 14.

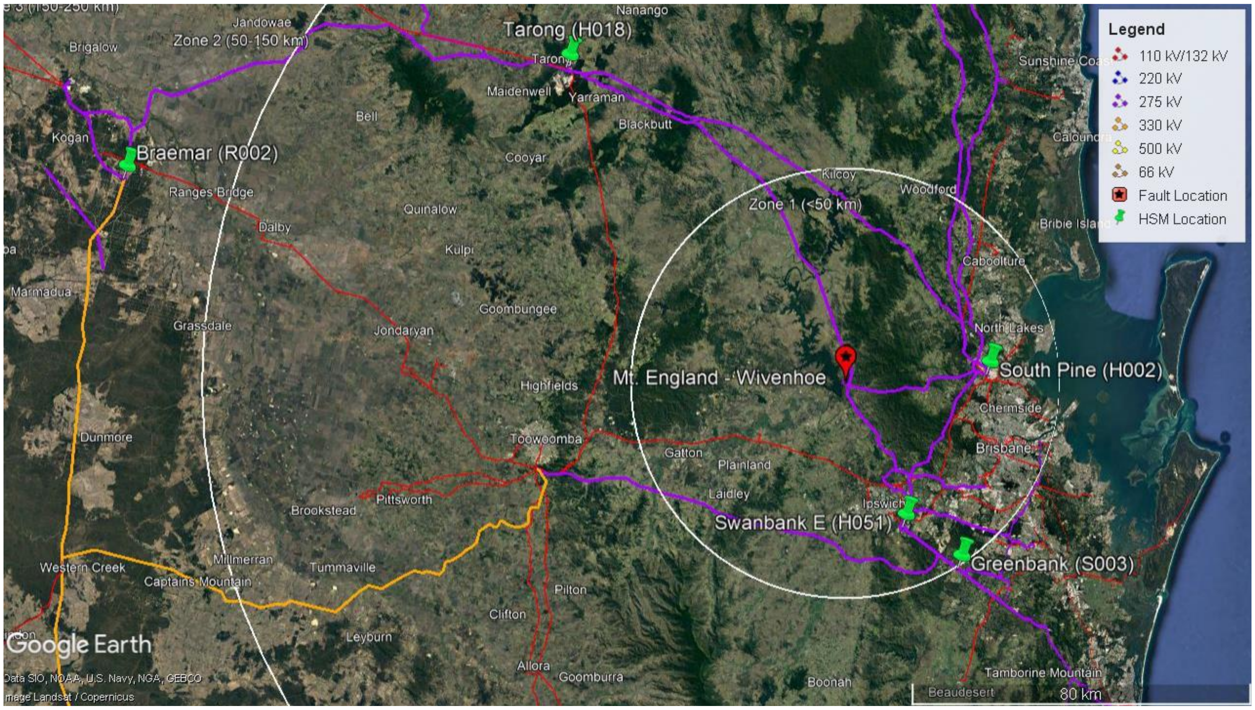


Figure 14: Map of the event on February 22, 2021

This event was replicated in PSCAD™/EMTDC™ using the event description shown in Table 10.

Table 10: Event summary for February 22, 2021

Time (seconds)	Event Description
0.0	Time when PSCAD™/EMTDC™ case finished initializing.
1.0	Apply 2PG fault (phases B and C) at 275 kV Mt. England substation.
1.07	Clear 2PG fault. Trip 275 kV Mt. England – Wivenhoe circuit 2.
3.07	Trip South Pine SVC.
30.0	End of simulation

4.2.2 *PSCAD™/EMTDC™ modeling*

After consulting with AEMO and considering the fault location is far away from VIC, NSW and SA, it was decided to model only the QLD region in PSCAD™/EMTDC™. Connections to NSW were replaced by a playback model at the NSW end of the QNI and static equivalents at the QLD end of the Terranorra.

After deriving the PSCAD™/EMTDC™ case using the February 22, 2021 PSS®E case and the base PSCAD™/EMTDC™ case, the following issues were observed:

- In the PSCAD™/EMTDC™ base model provided by AEMO, there are some synchronous generator units without the dynamic models represented using source models. A list of these units are provided in Table 11.

  Table 11: Units missing detailed machine models

Connected Bus	Base Voltage (L-L, RMS)	Base MVA
B447106_4DDWNPS__G2A	15	145.1
B447107_4DDWNPS__G3A	15	145.1
B444801_4BRM2PS___G1	15.75	194
B444802_4BRM2PS___G2	15.75	194
B420021_4CONDPS_GT2B	11	60
B420020_4CONDPS_GT1B	11	60
B418801_4DAANDI___G1	33	33
B445501_4SWNEPS___G1	21	500
B403201_4BLKWTR___S1	132	100

  In consultation with AEMO, it was decided to replace sources with synchronous machine models. The parameters[6] were based on the corresponding PSS®E dynamic data.

- The generator Braemar U2 uses a custom user model which requires a dynamic data file that was not included with the model files. This unit was out-of-service in the original PSCAD™/EMTDC™

---

[6] These units have generic machine models, but custom models were used for exciters and governors. As such, only the generator data from PSS®E were used when creating the synchronous machines in PSCAD™/EMTDC™.

model and was brought in-service when matching the operating conditions. A dynamic data file for this generator was provided by AEMO. However, when applying this file, it appeared to cause unstable oscillations when the unit switches from source to machine. Therefore, the detailed machine model was not used in the PSCAD™/EMTDC™ simulations, and a simplified synchronous machine was added to replace the detailed model.

4.2.3 Comparison

4.2.3.1 PSCAD™/EMTDC™ model comparison to HSM and PSS®E model

Figure 15 shows the voltage at South Pine 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model. HSM data is shown in blue, PSS®E results (without CMLD models) are shown in orange, PSS®E results (with CMLD models) are shown in green, PSCAD™/EMTDC™ results (without CMLD models) are shown in purple, and PSCAD™/EMTDC™ results (with CMLD models) are shown in red.

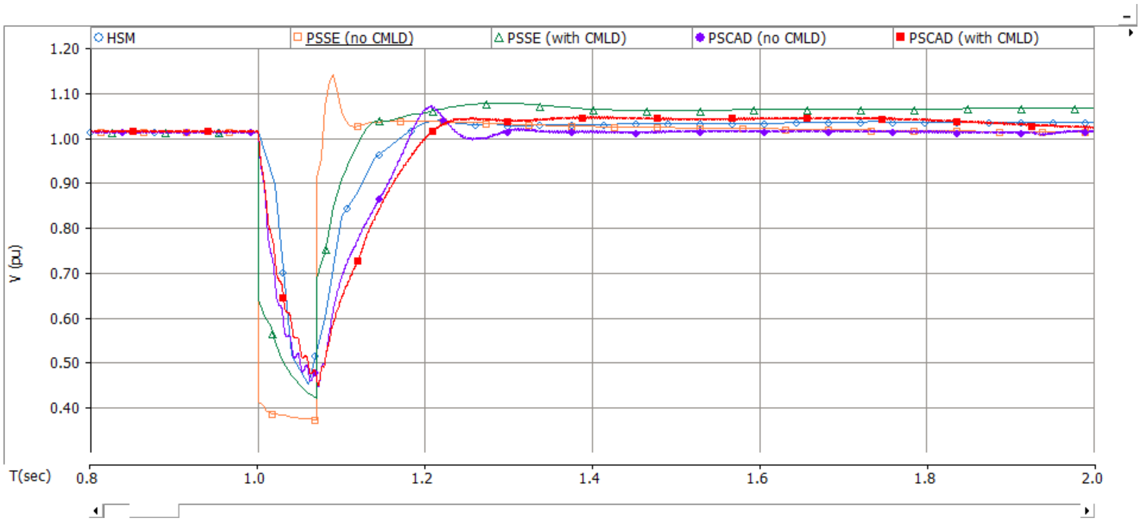


Figure 15: South Pine 275 kV voltage

As shown in Figure 15 the PSCAD™/EMTDC™ model closely follows the response observed with the PSS®E model and the PSCAD™/EMTDC™ model has a slower recovery time after the fault. The steady state value of the voltage is also comparable between the results.

When the same smoothing time constant used in the PSCAD™/EMTDC™ results is applied to the PSS®E results (20 ms), the dynamic response during the fault period match much closer between PSS®E and PSCAD™/EMTDC™. The PSS®E results with the smoothing for the voltage at South Pine 275 kV bus are shown in Figure 16.

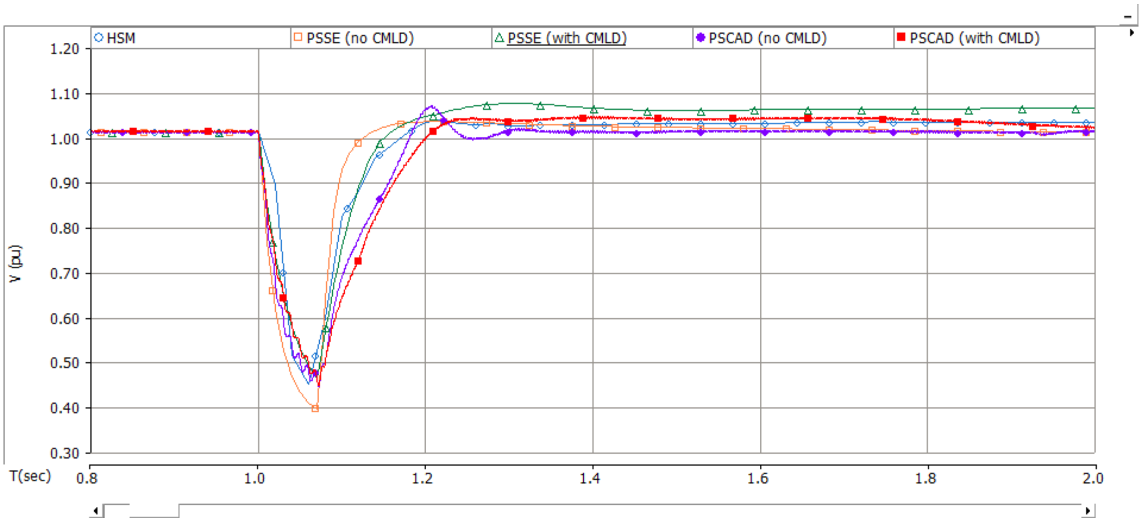


Figure 16: South Pine 275 kV voltage (PSS®E results smoothed)

Figure 17 shows the voltage at Swanbank 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model.

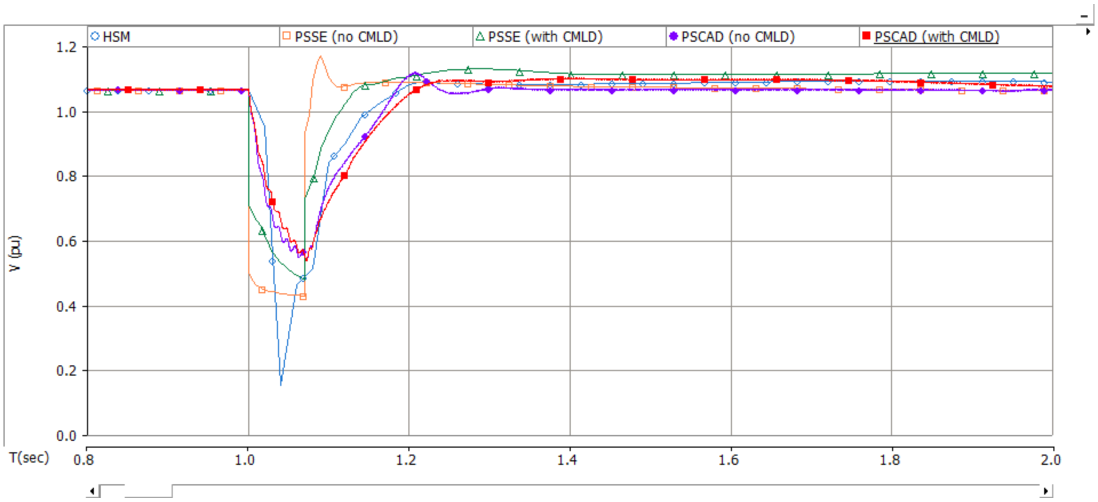


Figure 17: Swanbank 275 kV voltage

As shown in Figure 17, the PSCAD™/EMTDC™ model has a good match during the fault to the PSS®E model, and the steady state value of the voltage is the same between the three sets of results. However, the PSCAD™/EMTDC™ model has a slower recovery time after the fault.

When the same smoothing time constant used in the PSCAD™/EMTDC™ results is applied to the PSS®E results (20 ms), the dynamic response during the fault period match much closer between PSS®E and PSCAD™/EMTDC™. The PSS®E results with the smoothing for the at Swanbank 275 kV bus are shown in Figure 18.

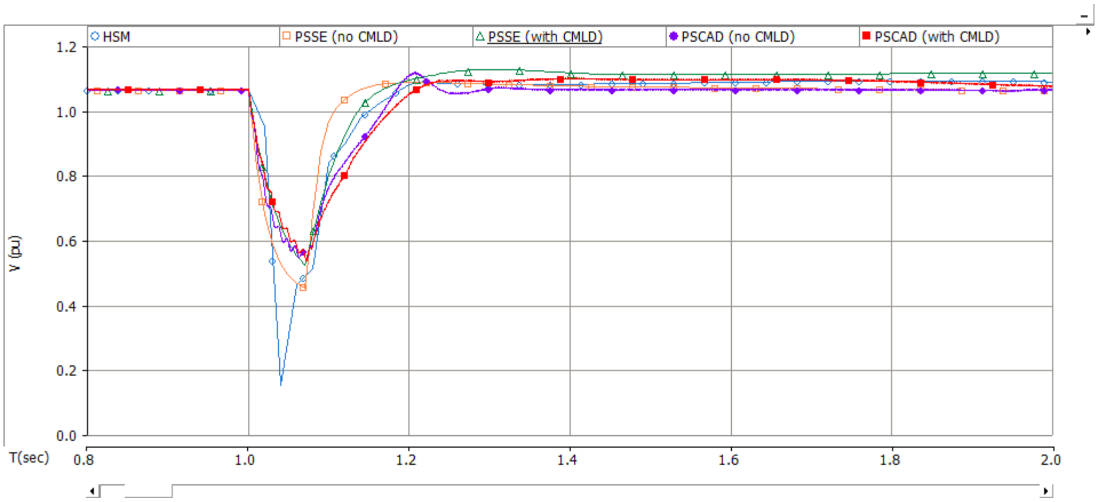


Figure 18: Swanbank 275 kV voltage (PSS®E results smoothed)

The active power in the South Pine 275/110 kV transformer is shown in Figure 19 and the active power in the Swanbank - Greenbank 275 kV circuit is shown in Figure 20.

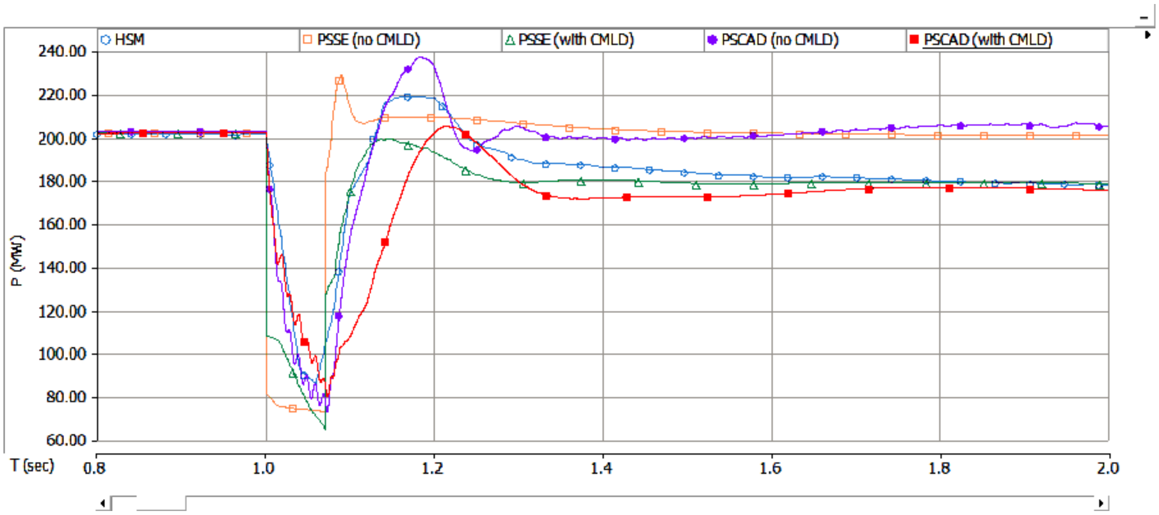


Figure 19: South Pine 275/110 kV transformer active power

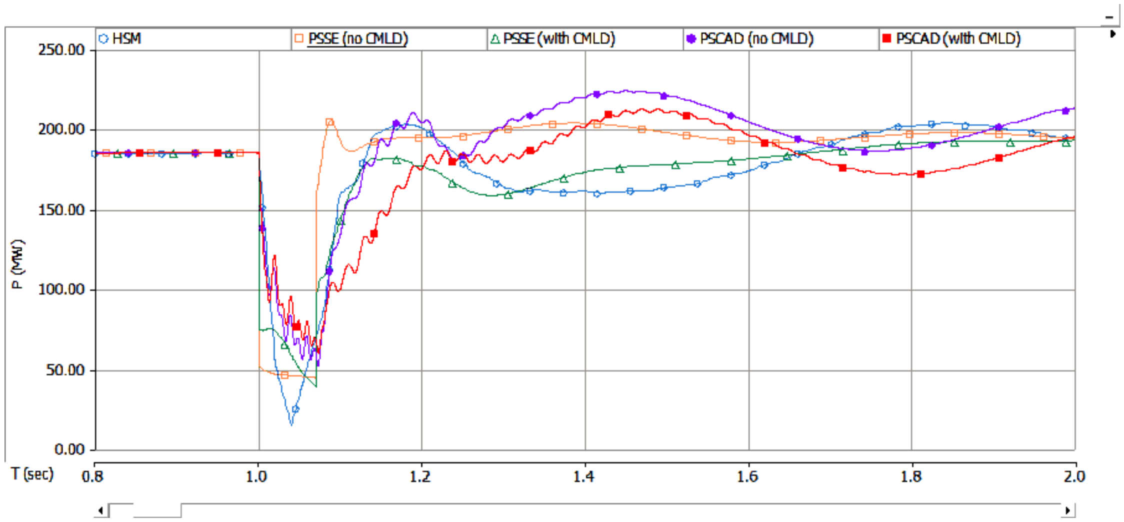


Figure 20: Swanbank - Greenbank 275 kV circuit 1 active power

As shown in Figure 19 and Figure 20, the active power in the PSCAD™/EMTDC™ model closely matches with the HSM data and PSS®E model during the fault. After the fault, the recovery period is slower with the PSCAD™/EMTDC™ model. However, the overshoot magnitude observed with the PSCAD™/EMTDC™ model matches closely with the HSM data. The steady state active power matches with the HSM data when the CMLD models are included.

Figure 21 and Figure 22 show the reactive power at the same locations (South Pine 275/110 kV transformer and Swanbank – Greenbank 275 kV circuit, respectively).

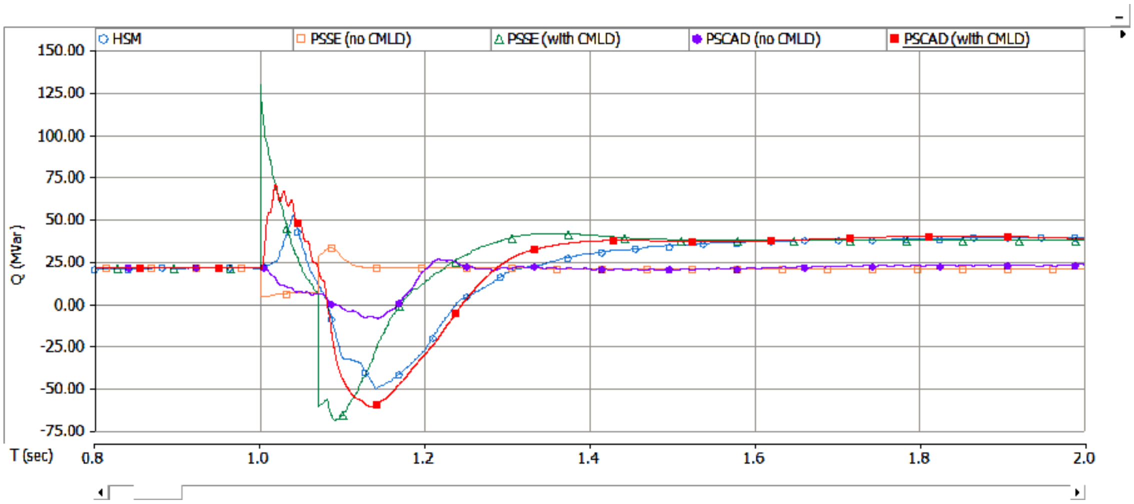


Figure 21: South Pine 275/110 kV transformer reactive power

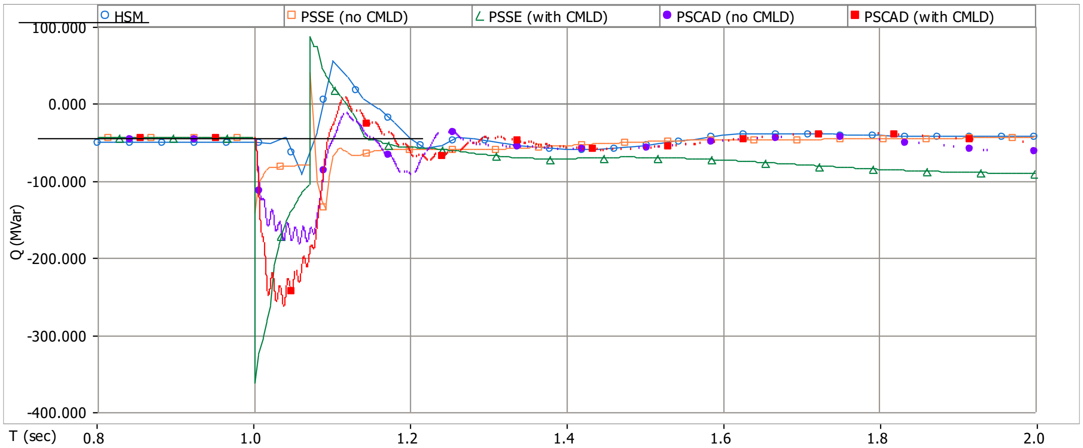


Figure 22: Swanbank - Greenbank 275 kV circuit 1 reactive power

As shown in Figure 21, the PSCAD™/EMTDC™ model closely matches the HSM data and PSS®E model. As shown in Figure 22, the PSCAD™/EMTDC™ model matches closely with the PSS®E model, but the reactive power is grossly overestimated when compared to the HSM data during the fault. The steady state reactive power matches with the HSM data when the CMLD models are included.

When the same smoothing time constant used in the PSCAD™/EMTDC™ results is applied to the PSS®E results (20 ms), the dynamic response during the fault period match much closer between PSS®E and PSCAD™/EMTDC™. These results for the reactive power at South Pine 275/110 kV transformer and Swanbank – Greenbank 275 kV circuit are shown in Figure 23 and Figure 24, respectively.

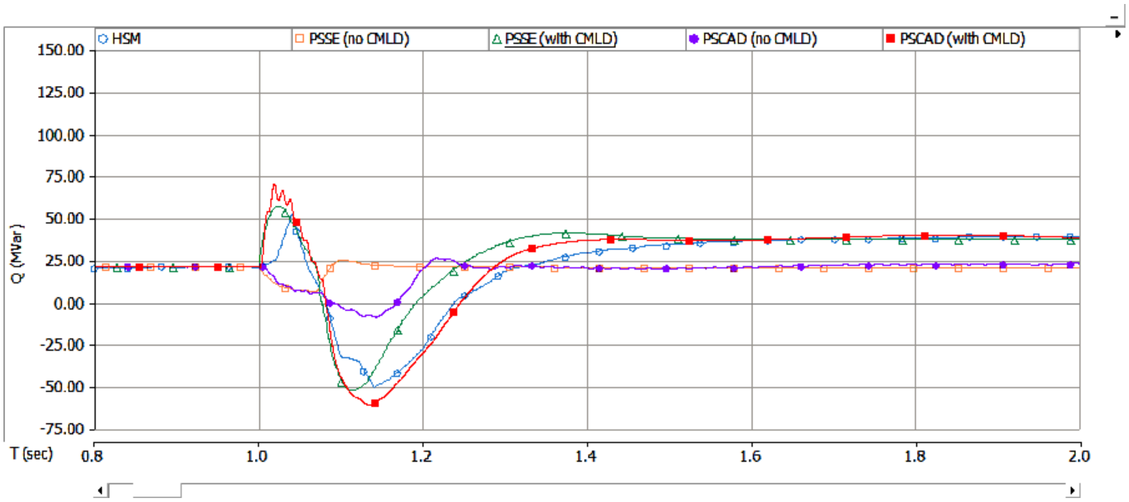


Figure 23: South Pine 275/110 kV transformer reactive power (PSS®E results smoothed)

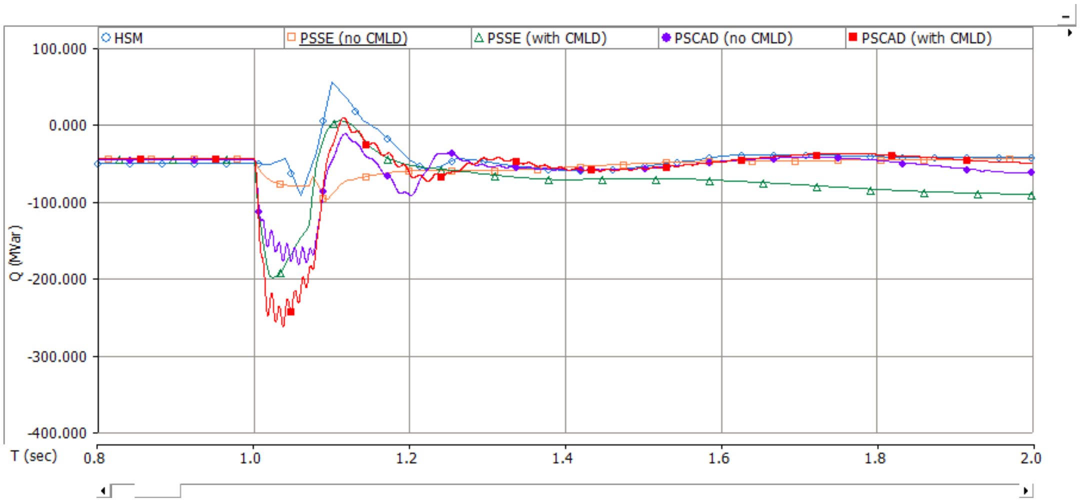


Figure 24: Swanbank - Greenbank 275 kV circuit 1 reactive power (PSS®E results smoothed)

4.2.3.2 CMLD change comparison

Figure 25 shows the total load in QLD for measurements of the PSCAD™/EMTDC™ model, with and without the CMLD models.

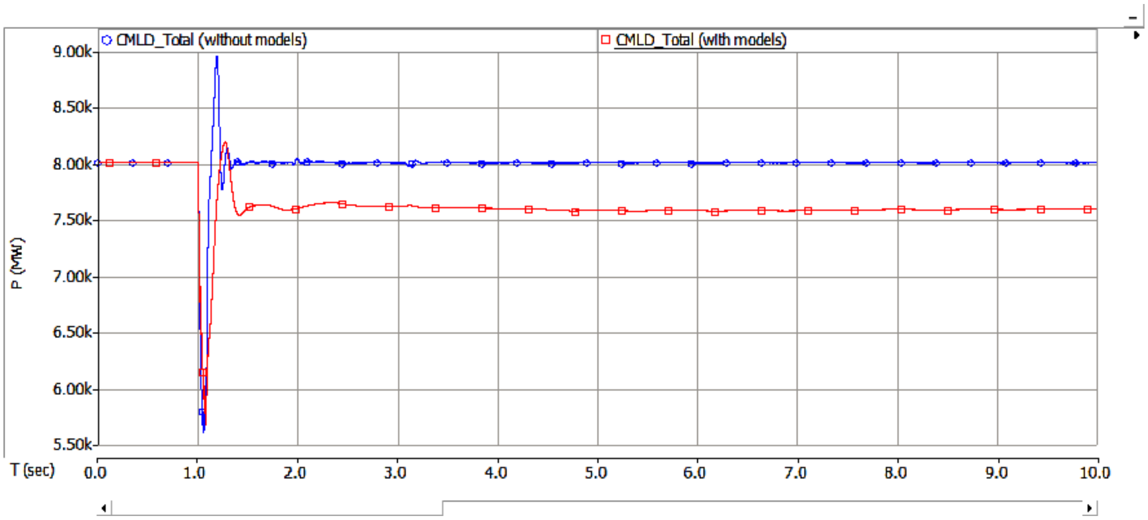


Figure 25: CMLD in QLD

The post-contingency steady states load in QLD drops by about 5% with CMLD models compared to the simulation without CMLD models.

Table 12 shows a comparison of the total CMLD load change based on SCADA measurements, the PSS®E model and the PSCAD™/EMTDC™ model.

Table 12: CMLD MW change comparison – February 22, 2021

Model	CMLD (MW)
SCADA Estimate	533
Expected Range	420 – 584
PSS®E	486
PSCAD™/EMTDC™	418

As shown in Table 12, the PSCAD™/EMTDC™ model underestimates the change in CMLD load by 115 MW (22%) and is just outside the estimated range.

4.2.4 Conclusions

The conclusions for February 22, 2021 case are shown in Table 13. Cells in green indicate a good match with the HSM data, yellow cells indicate a fair match with the HSM data, and orange indicates a poor match with HSM data.

Table 13: Assessment of model performance – February 22, 2021

Quantity	Characteristic	Match to HSM	Match to PSS®E	Comment
Voltages	Overshoot	Good	Good	Model closely matches with HSM and PSS®E model.
	Recovery Rate	Fair	Fair	Model has a slower recovery time than HSM/PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches with HSM and PSS®E model.
Active power	During dynamic state	Good	Good	Model closely matches with HSM and PSS®E model during the fault, has a slower recovery time than HSM/PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches with HSM and PSS®E model.
Reactive power	During dynamic state	Fair	Good	Model closely matches with HSM and PSS®E model during the fault, has a slower recovery time than HSM/PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches with HSM and PSS®E model.
CMLD	Load change	Fair	Fair	PSCAD™/EMTDC™: 418 MW PSS®E: 486 MW Actual: 533 MW Model underestimates CMLD change by 115 MW (22%).

5 Model validation: Voltage disturbances with DER

5.1 March 3, 2017 – South Australia

5.1.1 Case description

On March 3, 2017, the event described in Table 14 occurred in South Australia.

Table 14: Description of the event on March 3, 2017

Date and time		March 3, 2017, 15:03
Region		South Australia
Description of the event		A series of three faults occurred at the Torrens Island switchyard. These faults resulted in the loss of five generating units in South Australia. The event is summarised as: **Fault 1 (15:03:46):** Capacitor Voltage Transformer (CVT) at Torrens Island Switchyard • Trip of TIPS B unit 4 from 134 MW • Trip of PPCCGT from 218 MW (steam turbine trip at 15:05) **Fault 2 (15:03:46):** Torrens Island Switchyard tripped due to debris/smoke from the explosion of the CVT. • Trip of TIPS B 275 kV West Bus **Fault 3 (15:03:47):** TIPS B3 tripped due to debris/smoke from the explosion of the CVT causing a flashover of TIPS B3 bus support insulators. • Trip of TIPS B unit 3 from 134 MW • TIPS B unit 2 started run back from 132 MW due to the boiler air pre-heater drive loss
Minimum voltage recorded		0.48 pu positive sequence recorded at Lefevre (from HSM data)
Installed capacity of DER		Total installed capacity in South Australia: 739 MW (from APVI) • 95% installed under AS4777.3:2005 (from CER) • 5% installed under AS/NZS4777.2:2015 (from CER)
Prior to the event	**DER**	440 MW, 66% capacity factor (from ASEFS2, interpolated)
	Operational demand	1,987 MW (from SCADA data)
	Underlying demand	2,427 MW (estimate from SCADA + ASEFS2)
Estimated change	**DER**	133 MW (range of 44-260 MW) decrease (from Solar Analytics data)
	Operational demand	280 MW (range of 269-428 MW) decrease (from SCADA data)
	Underlying demand	413 MW (range of 313-687 MW) decrease (from SCADA & Solar Analytics data)

A map of this event is shown in Figure 26.

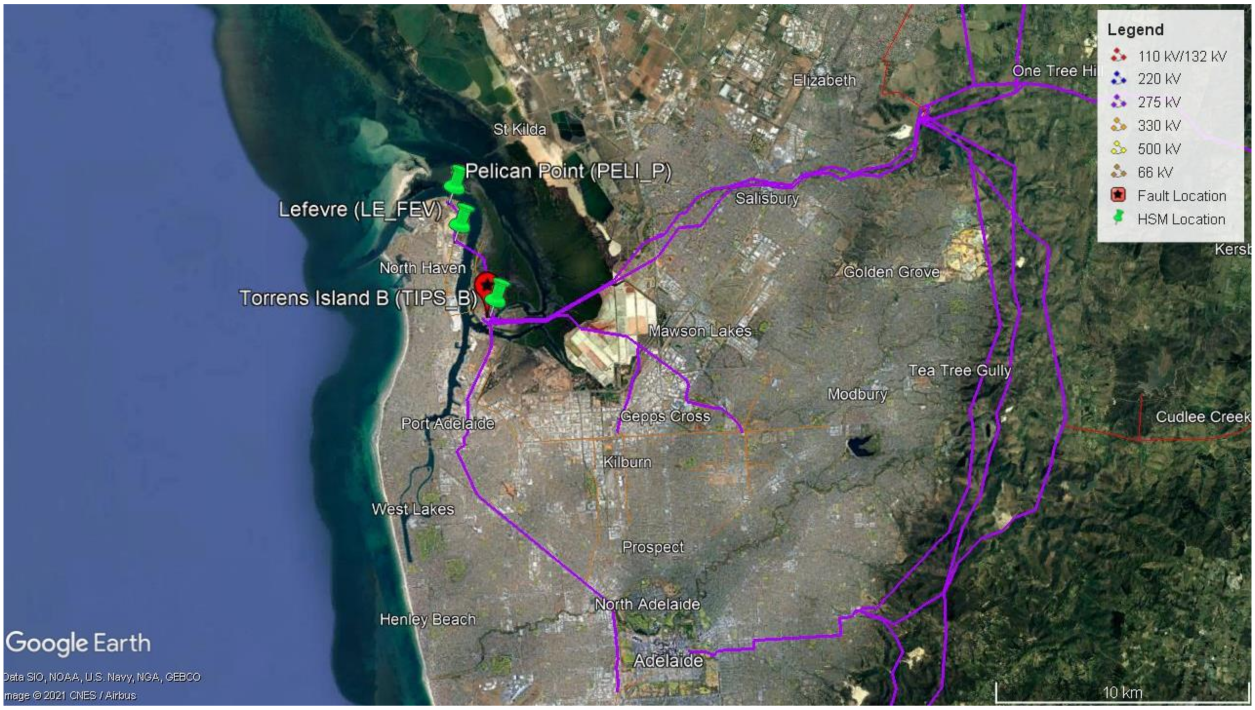


Figure 26: Map of the event on March 3, 2017

This event was replicated in PSCAD™/EMTDC™ using the event description shown in Table 15.

Table 15: Event summary for March 3, 2017

Time (seconds)	Event Description
0.0	Time when PSCAD™/EMTDC™ case finished initializing.
1.28	Apply 1PG fault at 275 kV Torrens Island B substation.
1.38	Clear 1PG fault. Trip TIPS B G4 generator. Trip TIPS B G4 275/16 kV transformer. Trip Pelican Point GT11 generator. Trip Pelican Point GT11 275/16 kV transformer.
1.88	Apply 2PG fault at 275 kV Torrens Island B substation.
1.98	Clear 2PG fault
2.78	Apply 1PG fault at 275 kV Torrens Island B substation.
2.88	Clear 1PG fault. Trip TIPS B G3 generator. Trip TIPS B G3 275/16 kV transformer.
30.0	End of simulation

5.1.2 PSCAD™/EMTDC™ modeling

After consulting with AEMO and considering the fault location was far away from VIC, NSW and QLD, it was decided to model only the SA region in PSCAD™/EMTDC™. Connections to VIC were replaced by static equivalents at the VIC end of the Murraylink HVDC link and the Heywood interconnector.

After deriving the PSCAD™/EMTDC™ case using the March 3, 2017 PSS®E case and the base PSCAD™/EMTDC™ case, it was noted that Wattle Point WF tripped after the controllers were released. After consulting with AEMO, it was decided to replace this model with voltage-behind-impedance source models. This may result in smaller variations in voltage around these sources, resulting in less DER and CMLD being tripped. However, these plants are located far away from the event and it is unlikely for the dynamic performance of these plants to have a significant impact on the results.

Note: Although the real event consists of three consecutive unbalance faults (i.e. SLG, 2PG, and SLG), three consecutive 3PG balanced faults in series with an impedance were applied in the PSCAD™/EMTDC™ simulations as explained in 3.2.4. As a sensitivity check, analysis was performed using the actual unbalanced fault to identify the impact of CMLD load and DER tripping.

5.1.3 Comparison

5.1.3.1 PSCAD™/EMTDC™ model comparison to HSM and PSS®E model

Figure 27 shows the voltage at Torrens Island A 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model. HSM data is shown in blue, PSS®E results (without DER/CMLD models) are shown in orange, PSS®E results (with DER/CMLD models) are shown in green, PSCAD™/EMTDC™ results (without DER/CMLD models) are shown in purple, and PSCAD™/EMTDC™ results (with DER/CMLD models) are shown in red[7].

---

[7] Transient stability cannot be maintained in the PSS®E and PSCAD™/EMTDC™ models when the CMLD/DER models are not included. This is because without the CMLD models, the post-contingency load is similar to the pre-contingency load (due to no load tripping), which results in transient instability. This shows that the CMLD/DER models should be included to accurately represent the dynamic response observed with the HSM data.

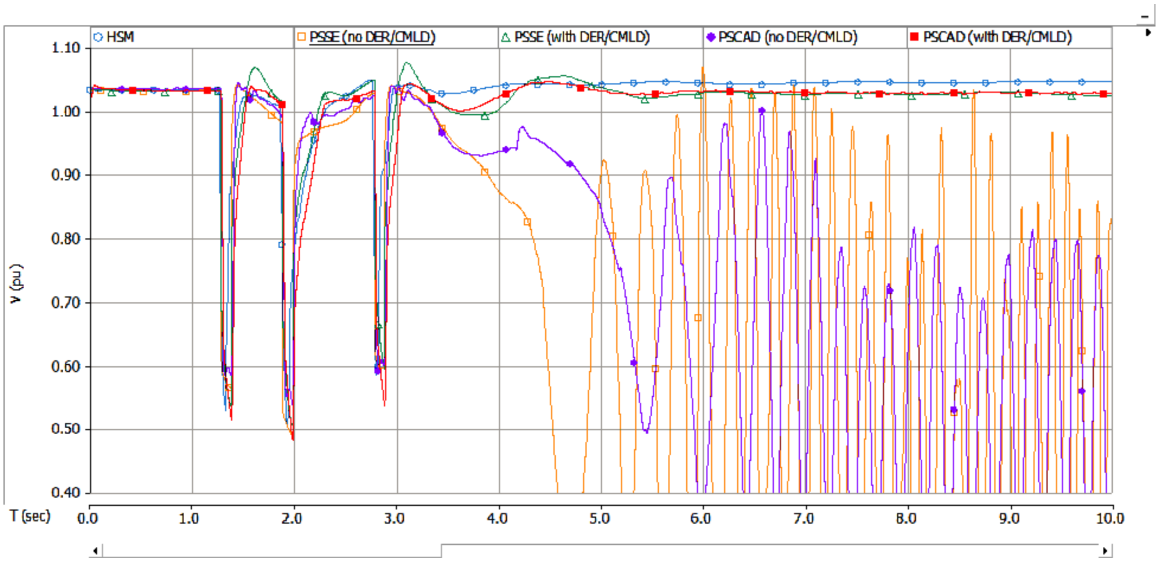


Figure 27: Torrens Island A 275 kV voltage

As shown in Figure 27, the PSCAD™/EMTDC™ model closely follows the response observed with the HSM data and PSS®E model and has a smaller overshoot after each fault clearance compared to the PSS®E model. The steady state value of the voltage is also comparable between the three sets of results with the CMLD and DER models included.

When applying the correct unbalanced faults in PSCAD™/EMTDC™ instead of an equivalent balanced fault, different residual voltages were observed for each of the faults. A comparison of the voltage at Torrens Island A 275 kV bus for unbalanced and balanced faults is shown in Figure 28.

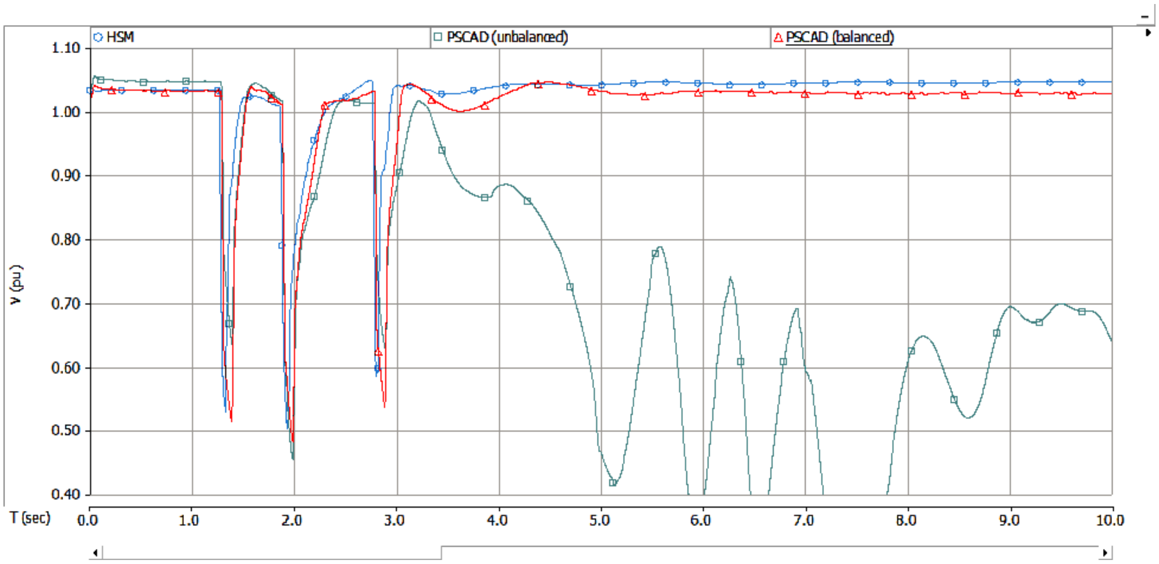


Figure 28: Torrens Island A 275 kV voltage (unbalanced fault)

As shown in Figure 28, the first and third unbalanced faults show a higher residual voltage during the fault as compared to their respective equivalent three phase fault, while the second unbalanced fault shows a lower residual voltage than the corresponding equivalent three phase fault. The lower voltage in the second fault results in more DER phase-angle tripping, leading to transient instability. A comparison of the voltage at Torrens Island A 275 kV bus for unbalanced and balanced faults (DER phase-angle tripping disabled) is shown in Figure 29.

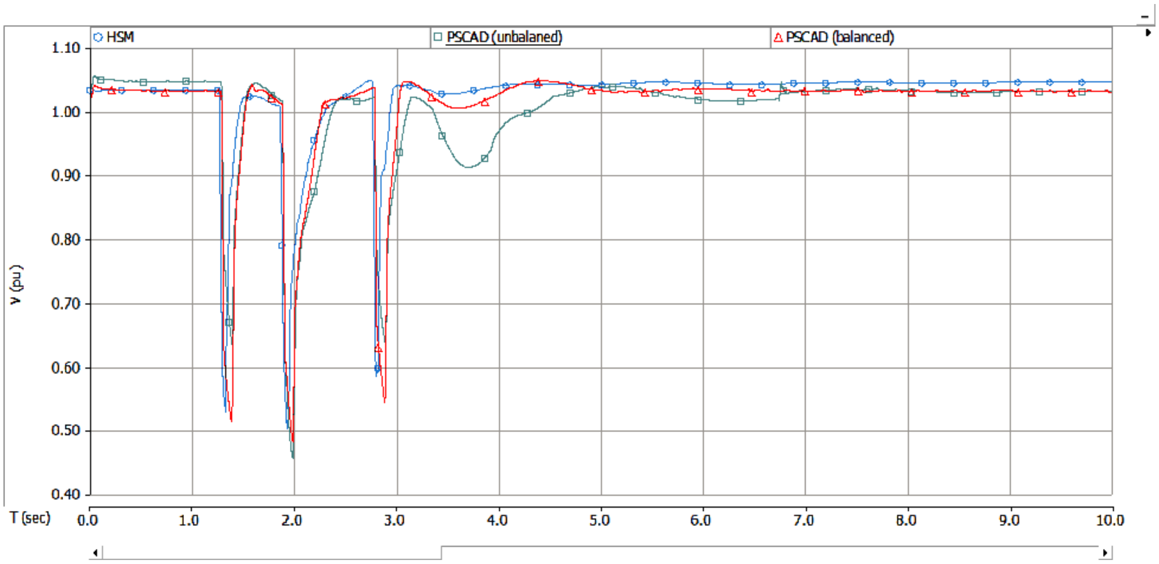


Figure 29: Torrens Island A 275 kV voltage (unbalanced fault, DER phase-angle tripping disabled)

As shown in Figure 29, the results with the unbalanced fault are now transiently stable. Comparisons of the DER and CMLD being tripped for unbalanced faults is discussed at the end of this section.
Note: These observations suggest that the parameters of the DER phase angle tripping logic may require to be updated. It is recommended to disable DER model phase angle tripping until the parameters are updated.

The active power in the TIPS B1 generator feeder is shown in Figure 30.

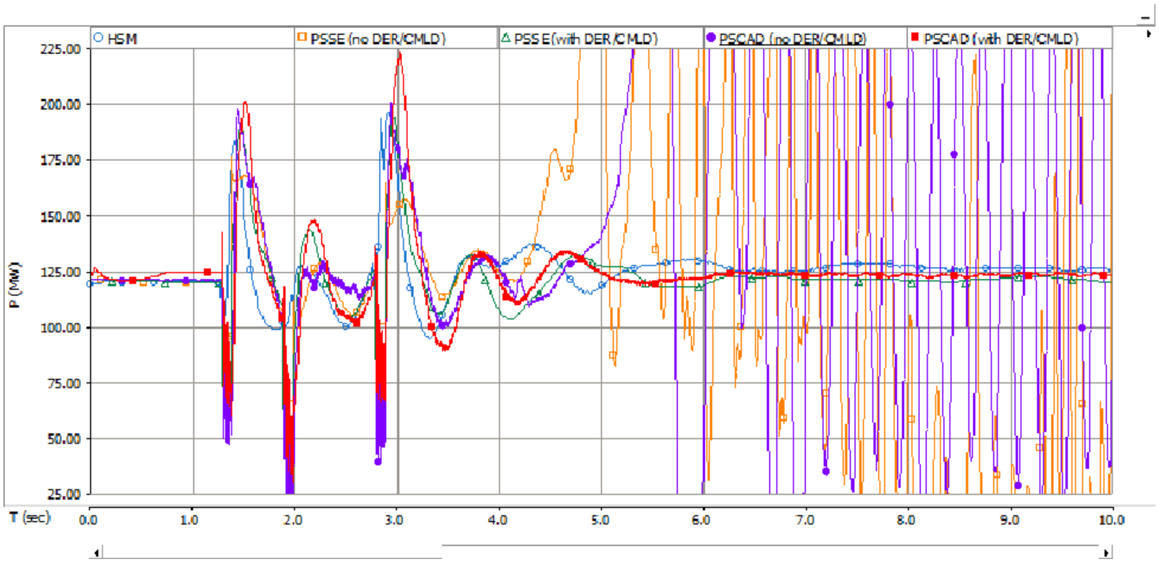


Figure 30: TIPS B1 generator active power

As shown in Figure 30, oscillations were observed with the PSCAD™/EMTDC™ model during the fault, and there is a larger drop in active power during the faults. In addition, the PSCAD™/EMTDC™ model overestimates the peak active power immediately after each fault, similar to the PSS®E model.
HSM data show that the system can maintain stability after the fault. PSCAD™/EMTDC™ and PSS®E result with DER/CMLD models also show that the system can maintain stability after the fault. However, without DER/CMLD models, both simulations platforms show the system cannot maintain stability after the fault. This result shows the importance of using DER and CMLD models.

5.1.3.2 CMLD/DER comparison

Figure 31 shows the total DER generation in SA for measurements from the PSCAD™/EMTDC™ model.

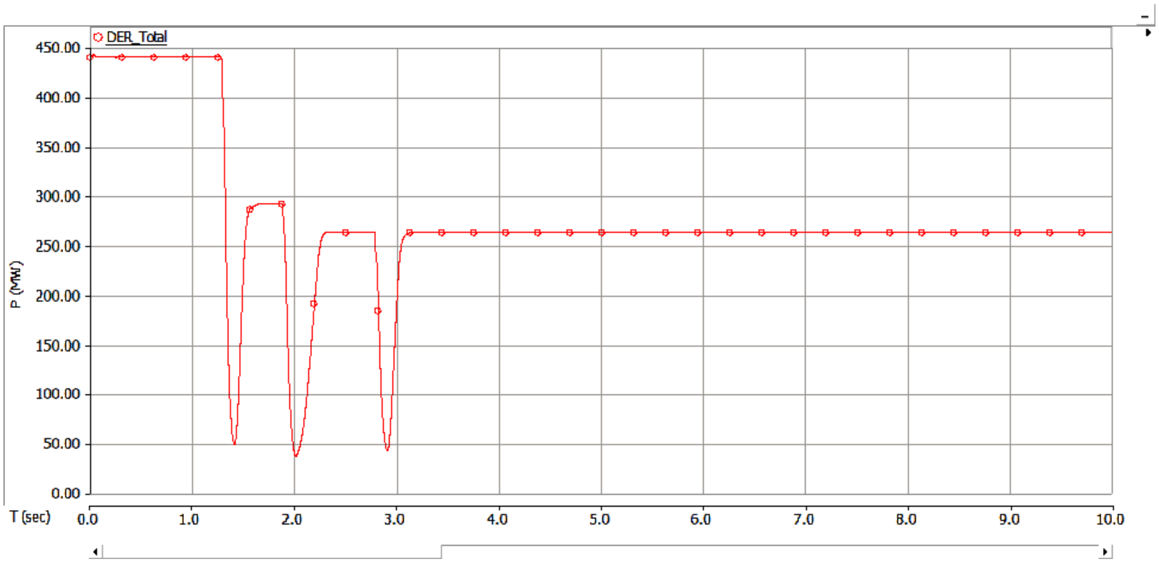


Figure 31: DER in SA

Note: the second drop in the total DER is a result of phase-angle tripping in the DER model. A comparison between the total DER with phase-angle tripping enabled and disabled is shown in Figure 32.

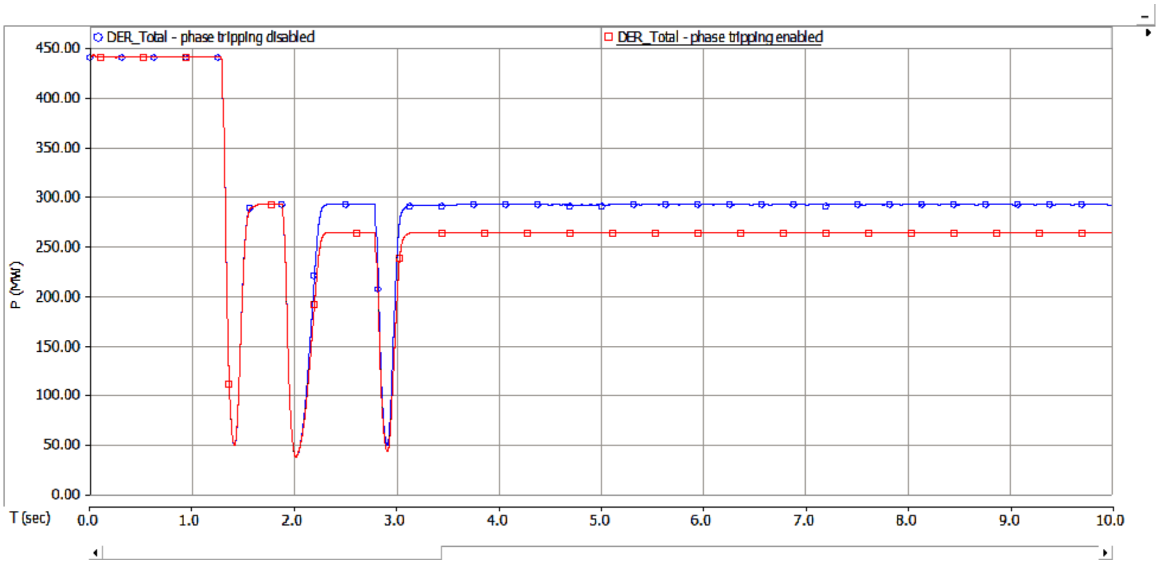


Figure 32: DER in SA (phase-angle tripping enabled and disabled)

Figure 33 shows the CMLD load in SA for the PSCAD™/EMTDC™ model.

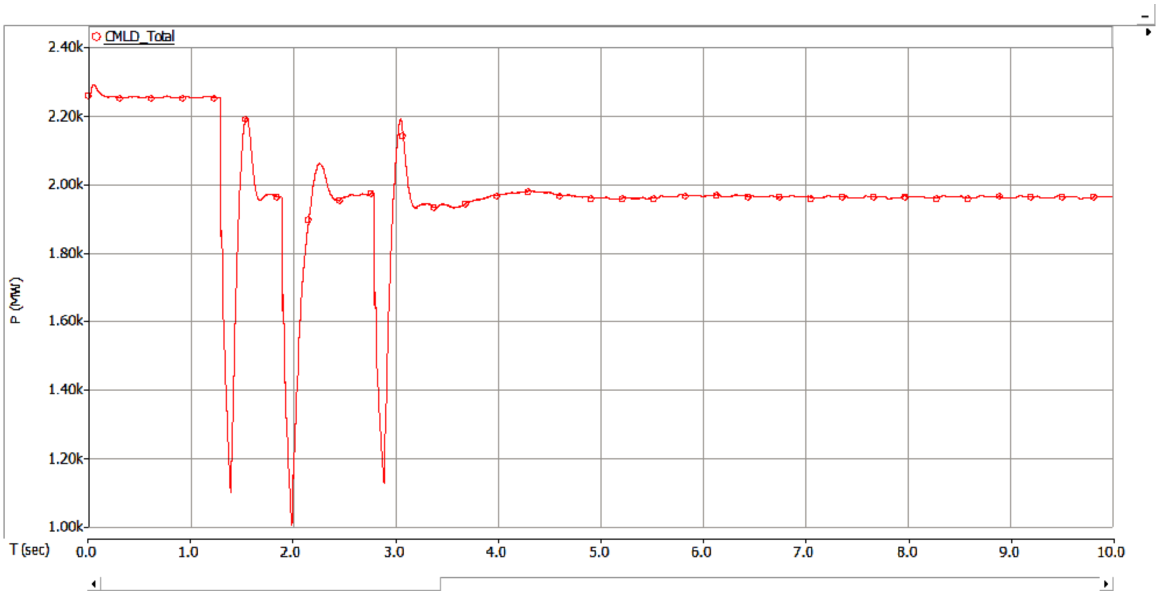


Figure 33: CMLD in SA

Figure 34 shows a comparison of the change in operational demand in SA with and without the CMLD and DER models.

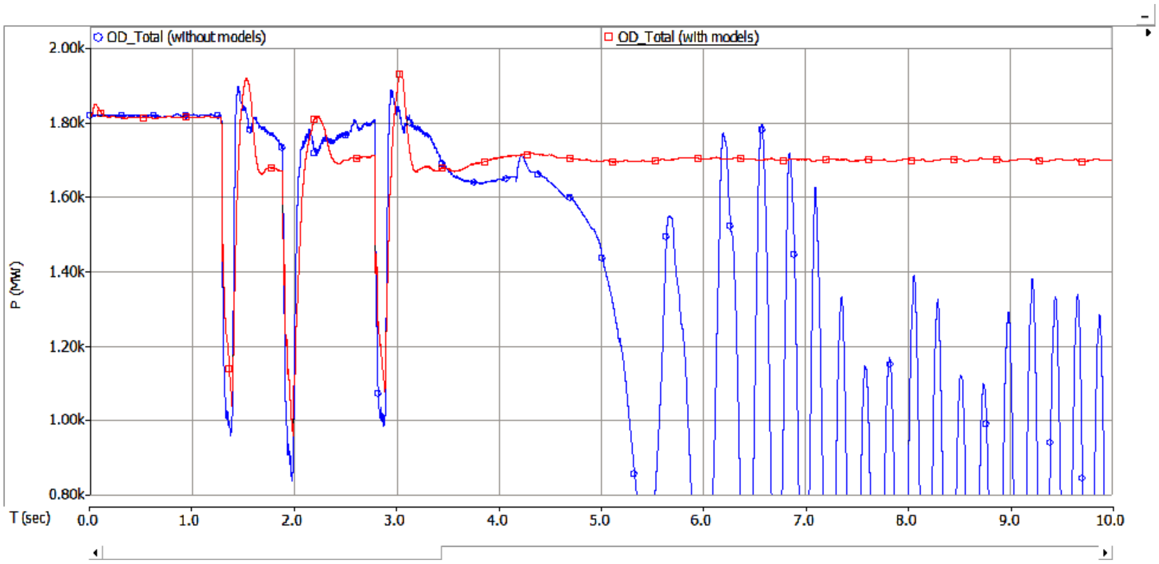


Figure 34: Operational demand in SA

Table 16 shows a comparison of the total CMLD load and DER change based on SCADA measurements, the PSS®E model and the PSCAD™/EMTDC™ model.

Table 16: DER/CMLD MW change comparison – March 3, 2017

Model	**DER (MW)**	**CMLD (MW)**	**Operational Demand (MW)**
Solar Analytics/SCADA Estimate	130	409	280
Estimated Range	43 – 253	312 – 681	269 – 428
PSS®E	145	338	193
PSCAD™/EMTDC™	189	300	111

As shown in Table 16,

- The PSCAD™/EMTDC™ model overestimates the change in DER by 69 MW (45%) but is within the estimated range.
- The PSCAD™/EMTDC™ model underestimates the change in CMLD load by 109 MW (27%) and is outside the estimated range.
- The PSCAD™/EMTDC™ model underestimates the change in operational demand by 169 MW (60%) and is outside the estimated range.

Figure 35 and Figure 36 show comparisons of total DER loss (phase tripping enabled) and total DER loss (phase angle tripping disabled) for applying unbalanced faults and equivalent balanced faults, respectively.

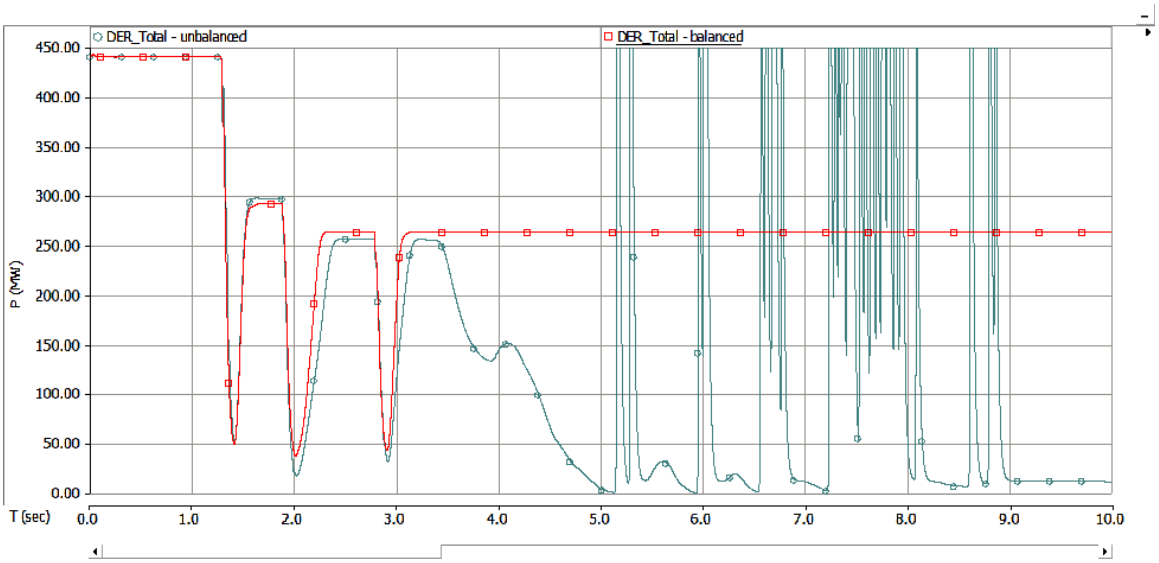


Figure 35: DER in SA (unbalanced and equivalent balanced faults, phase angle tripping enabled)

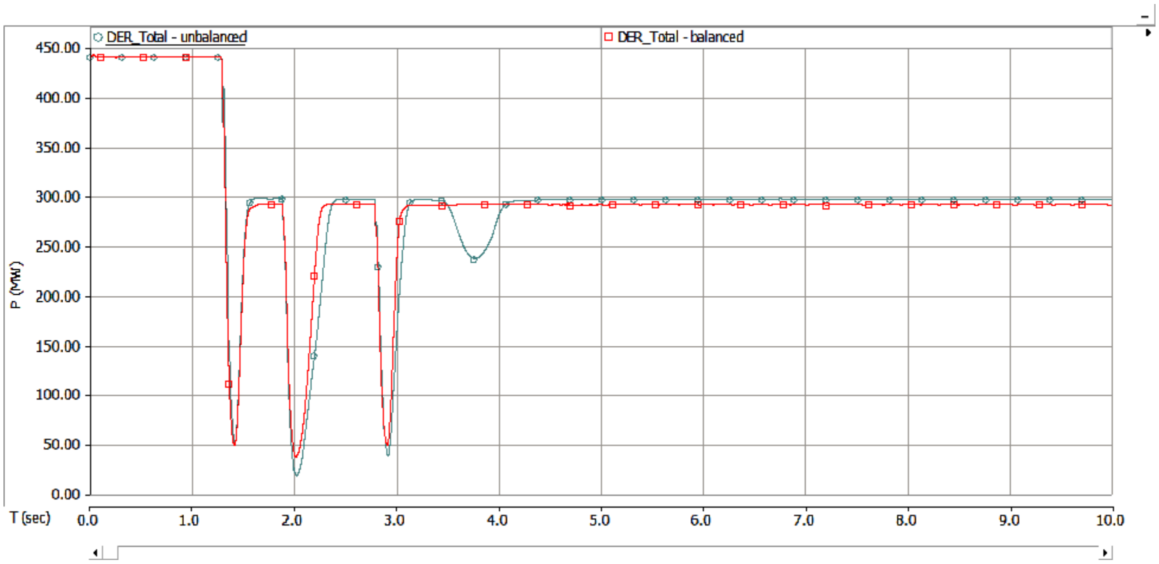


Figure 36: DER in SA (unbalanced and equivalent balanced faults, phase angle tripping disabled)

As shown in Figure 35 and Figure 36, more DER is tripped with phase-angle tripping enabled, leading towards transient instability. When the phase-angle tripping is disabled, less DER is tripped, likely due to a higher residual voltage during the first and third faults.

Figure 37 and Figure 38 show comparisons of total DER loss (phase tripping enabled) and total DER loss (phase angle tripping disabled) for applying unbalanced faults and equivalent balanced faults, respectively.

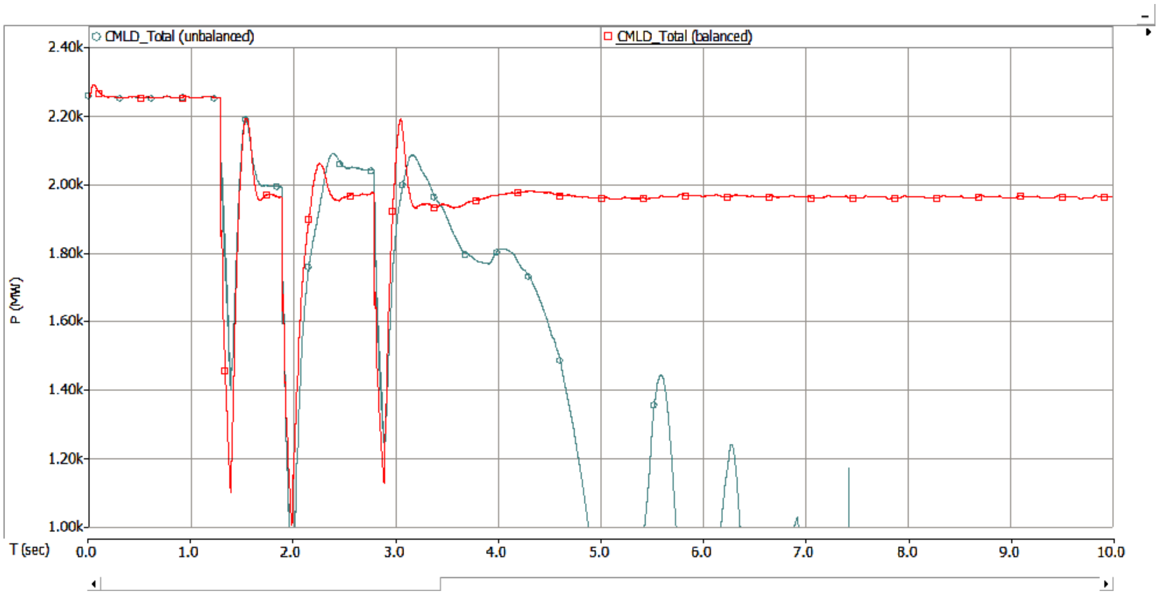


Figure 37: CMLD in SA (unbalanced and equivalent balanced faults, phase angle tripping enabled)

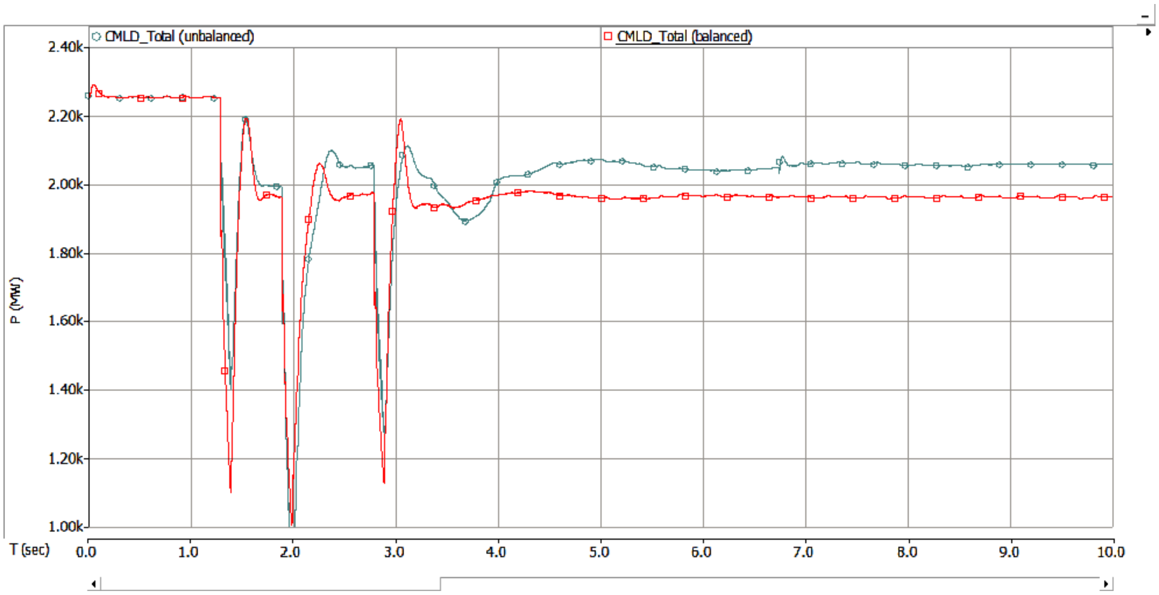


Figure 38: CMLD in SA (unbalanced and equivalent balanced faults, phase angle tripping disabled)

As shown in Figure 37 and Figure 38, less CMLD is tripped when applying the unbalanced fault (with DER phase angle tripping disabled), likely due to a higher residual voltage during the first and third faults.

5.1.4 Conclusions

The conclusions for the March 3, 2017 case are shown in Table 17. Cells in green indicate a good match with the HSM data, yellow cells indicate a fair match with the HSM data, and orange indicates a poor match with HSM data.

Table 17: Assessment of model performance – March 3, 2017

Quantity	**Characteristic**	**Match to HSM**	**Match to PSS®E**	**Comment**
Voltages	Overshoot	Good	Good	Model closely matches HSM and PSS®E model.
	Recovery Rate	Good	Good	Model closely matches HSM and PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Active power	During dynamic state	Fair	Good	Model matches well with PSS®E model. Follows a similar trajectory to HSM data, but overestimates flows during the fault.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Reactive power	During dynamic state	-	-	Reactive power data not available.
	Steady state post-disturbance	-	-	Reactive power data not available.
DER	DER Change	Fair	Good	PSCAD™/EMTDC™: 189 MW PSS®E: 145 MW Actual: 130 MW Model overestimates DER loss by 59 MW (45%) but within range.
CMLD	Load change	Fair	Good	PSCAD™/EMTDC™: 300 MW PSS®E: 338 MW Actual: 409 MW Model underestimates CMLD loss by 94 MW (23%), and is outside the range.
Operational Demand	Net demand change	Fair	Fair	PSCAD™/EMTDC™: 111 MW PSS®E: 193 MW Actual: 280 MW Model underestimates OD change by 169 MW (60%) and is outside the range.

Additionally, the following conclusions can be made for this case:

- Existing angle tripping parameters results deviate the simulation results from the HSM data. It is recommended to disable DER model phase angle tripping until the parameters are updated.
- Without DER/CMLD models, PSCAD™/EMTDC™ and PSS®E result does not match with HSM data for March 3, 2017 case. Post-contingency system is stable as shown by the HSM data. However, without DER/CMLD models, both PSCAD™/EMTDC™ and PSS®E simulation platforms show the post-contingency system cannot maintain stability.

5.2 January 18, 2018 – Victoria

5.2.1 Case description

On January 18, 2018, the event described in Table 18 occurred in Victoria.

Table 18: Description of the event on January 18, 2018

Date and time		January 18, 2018, 15:19
Region		Victoria
Description of the event		A 1PG fault occurred at the Rowville terminal station due to a 500 kV CT failure associated with the A2 busbar. The event is summarised as: • Fault at Rowville (ROTS) No 2 500 kV Busbar • Trip of ROTS No 2 500/220 kV Transformer • Rowville - South Morang No 3 500 kV line (ROTS–SMTS line) opened at South Morang The load loss occurred in the distribution networks, and no bulk transmission network supply points were disconnected.
Minimum voltage recorded		0.64 pu positive sequence recorded at Cranbourne Terminal Station (from HSM data)
Installed capacity of DER		Total installed capacity: 1,237 MW (from APVI) • 80% installed under AS4777.3:2005 (from CER) • 20% installed under AS/NZS4777.2:2015 (from CER)
Prior to the event	**DER**	680 MW, 55% capacity factor (from ASEFS2, interpolated)
	Operational demand	8,736 MW (from SCADA data)
	Underlying demand	9,416 (estimate from SCADA + ASEFS2)
Estimated change	**DER**	123 MW (range of 57-218 MW) decrease (from Solar Analytics data)
	Operational demand	506 MW (range of 450-598 MW) decrease (from SCADA data)
	Underlying demand	629 MW (range of 507-815 MW) decrease (estimate from SCADA + Solar Analytics data)

A map of this event is shown in Figure 39.

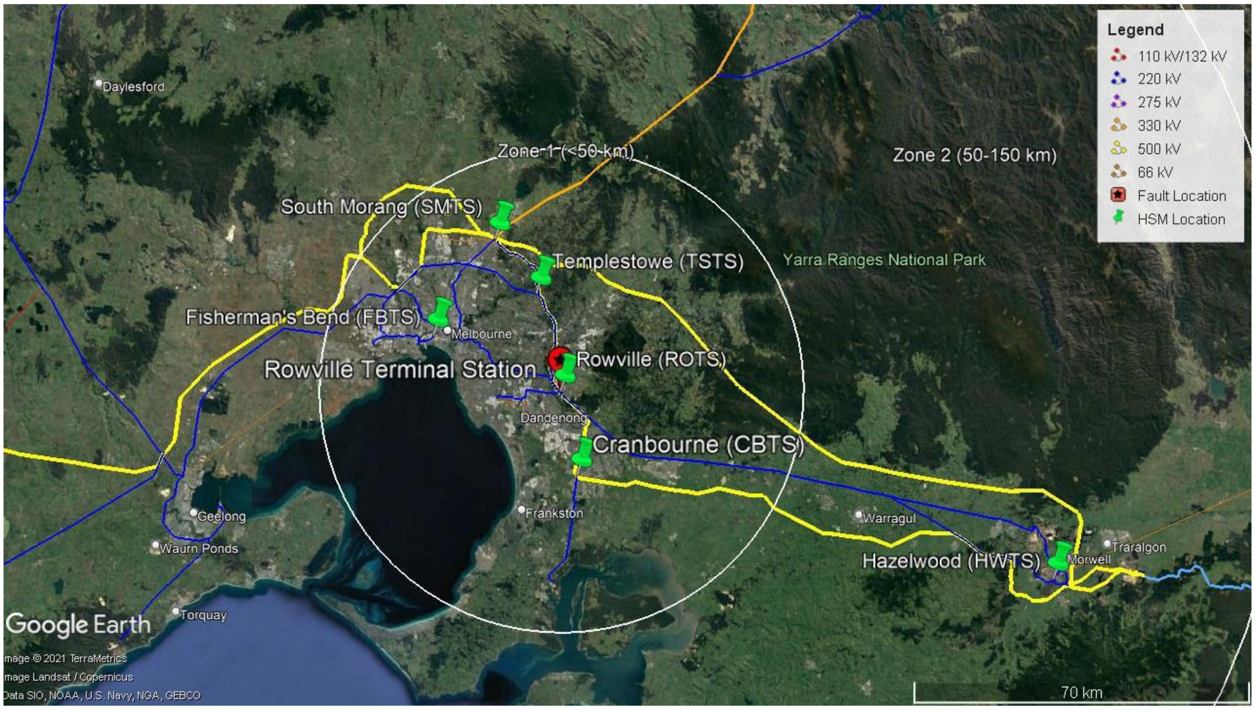


Figure 39: Map of the event on January 18, 2018

This event was replicated in PSCAD™/EMTDC™ using the event description shown in Table 19.

Table 19: Event summary for January 18, 2018

Time (seconds)	Event Description
0.0	Time when PSCAD™/EMTDC™ case finished initializing.
1.0	Apply 3PG fault at 500 kV Rowville No.2 substation.
1.08	Trip Rowville No.2 500/220 kV transformer.
1.16	Clear 3PG fault. Trip 500 kV Rowville – South Morang circuit.
30.0	End of simulation

5.2.2 PSCAD™/EMTDC™ modeling

Consulting with AEMO and considering the fault location, it was decided to model only the VIC region in PSCAD™/EMTDC™. Connections to VIC from the rest of the system were replaced by static equivalents at the VIC end of the Murraylink HVDC link and the Heywood interconnector, as well as at the VIC to NSW Interconnector (VNI) on the NSW side. A playback model was used at the VIC end of the Basslink to model the HVDC link to Tasmania. The PSCAD™/EMTDC™ case for the VIC region was derived using the March 3, 2017 PSS®E case and the base PSCAD™/EMTDC™ case.

Note: Although the real event consisted of a SLG fault, an equivalent 3PG fault was applied as explained in 3.2.4. When applying the equivalent 3PG fault, the residual voltage in the PSCAD™/EMTDC™ model was higher than in the PSS®E model or the HSM data. This led to significantly less CMLD load/DER tripping. In order to obtain a closer match between the results/models, the equivalent 3PG fault impedance was reduced in the PSCAD™/EMTDC™ model (X/R ratio was kept the same). A sensitivity analysis was performed using the actual unbalanced fault to identify the impact of CMLD load and DER tripping.

5.2.3 *Comparison*

5.2.3.1 *PSCAD™/EMTDC™ model comparison to HSM and PSS®E model*

Figure 40 shows the voltage at Rowville 220 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model. HSM data is shown in blue, PSS®E results (without DER/CMLD models) are shown in orange, PSS®E results (with DER/CMLD models) are shown in green, PSCAD™/EMTDC™ results (without DER/CMLD models) are shown in purple, and PSCAD™/EMTDC™ results (with DER/CMLD models) are shown in red.

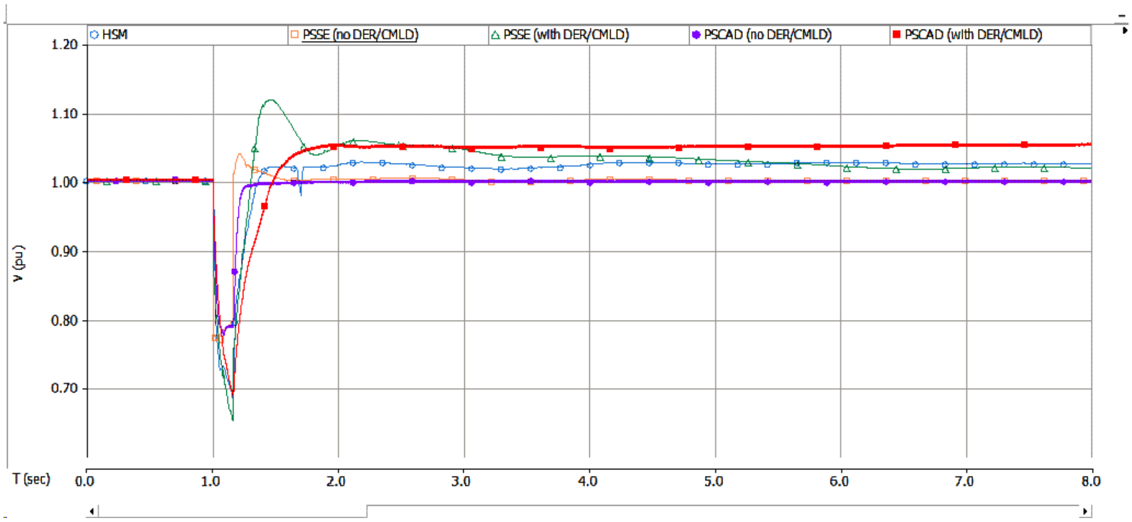


Figure 40: Rowville 220 kV voltage

As shown in Figure 40 the PSCAD™/EMTDC™ model closely follows the response observed with the HSM data and has a much smaller overshoot than the PSS®E model. The steady state value of the voltage is also comparable between the three sets of results.

When applying an unbalanced fault instead of an equivalent balanced fault, a different residual voltage was observed. The voltage at Rowville 220 kV bus for an unbalanced fault is shown in Figure 56.

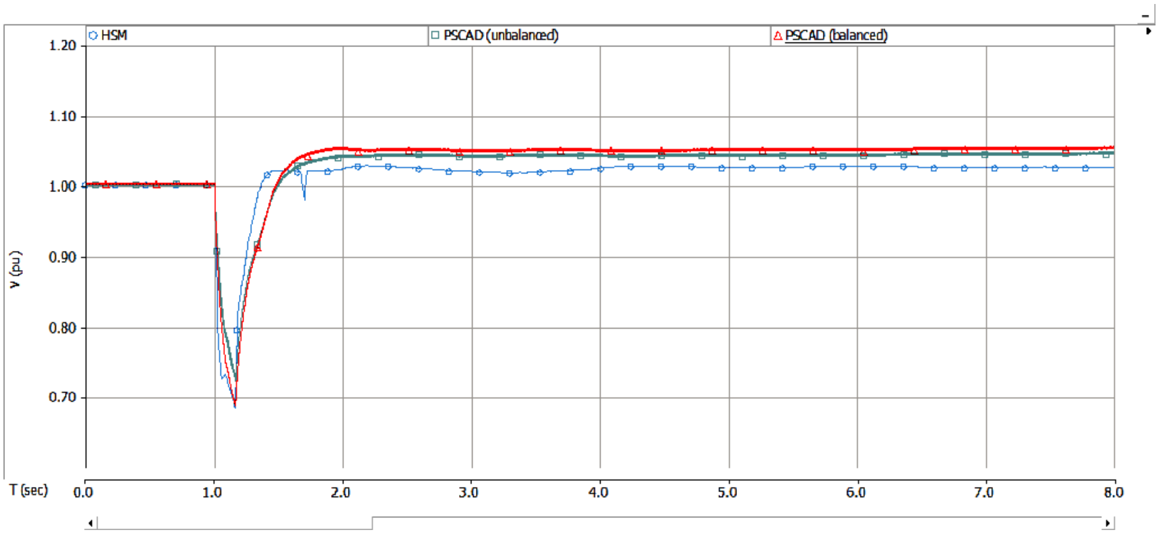


Figure 41: Rowville 220 kV voltage (unbalanced fault)

As shown in Figure 56, the residual voltage for the unbalanced fault is slightly higher than the residual voltage of the equivalent balanced fault. This difference in voltage will likely result in different amounts of DER and CMLD tripping.

Figure 42 shows the voltage at Swanbank 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model.

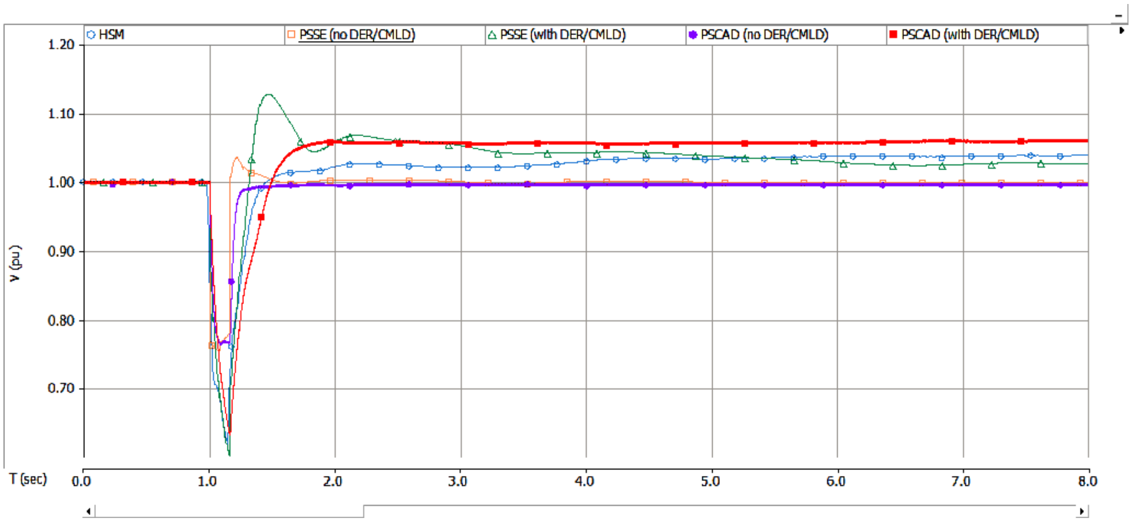


Figure 42: Cranbourne 66 kV voltage

As shown in Figure 42, the PSCAD™/EMTDC™ model has a good match during the fault, and the steady state value of the voltage is the same between the three sets of results. However, a smaller overshoot after fault clearance was observed in the PSCAD™/EMTDC™ model as compared to the PSS®E model.

The active power in the Rowville – Springvale 220 kV circuit 1 is shown in Figure 43.

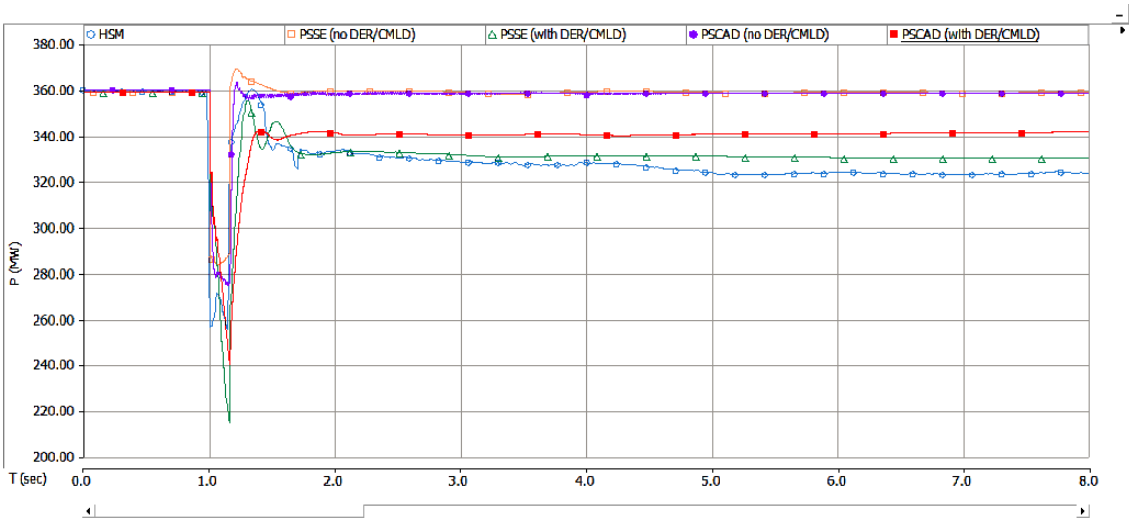


Figure 43: Rowville – Springvale 220 kV circuit 1 active power

As shown in Figure 43, the PSCAD™/EMTDC™ has a good match during the fault and there is a smaller overshoot after the fault is cleared. In addition, the steady state power is slightly higher compared to both PSS®E and HSM data. The steady state active power matches closer to the HSM data when the CMLD and DER models are included.

The active power in the Cranbourne 220/66 kV transformer is shown in Figure 44.

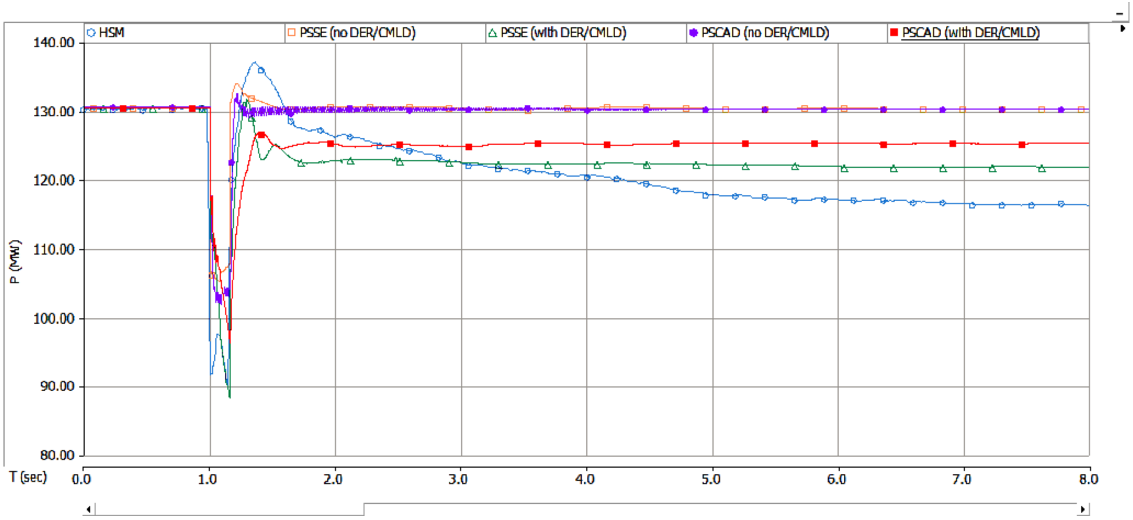


Figure 44: Cranbourne 220/66 kV transformer active power

As shown in Figure 44, the PSCAD™/EMTDC™ has a good match during the fault and there is a smaller overshoot after the fault is cleared. In addition, the steady state power is slightly higher compared to both PSS®E and HSM data. The steady state active power matches closer to the HSM data when the CMLD and DER models are included.

Figure 45 and Figure 46 show the reactive power at the same locations (Rowville – Springvale 220 kV circuit 1 and Cranbourne 220/66 kV transformer, respectively).

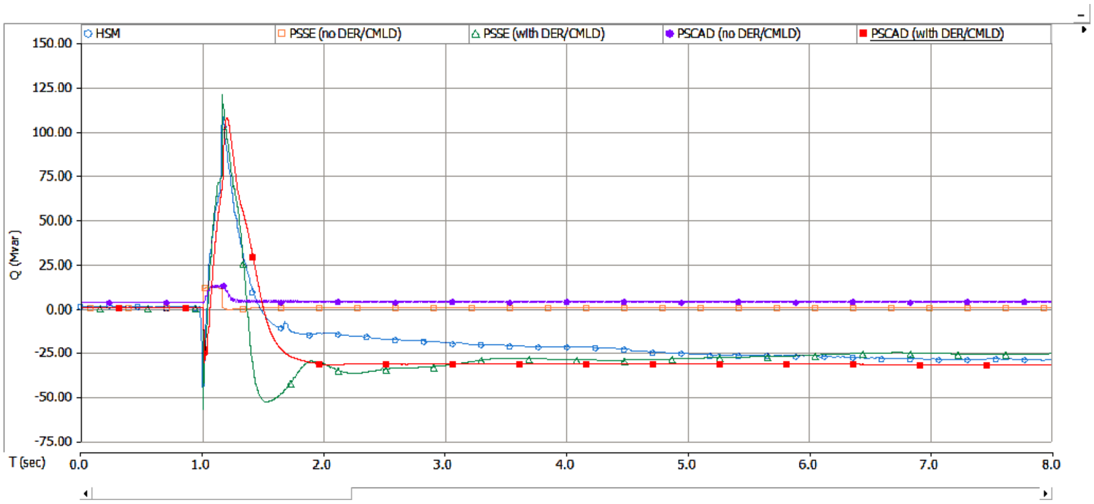


Figure 45: Rowville – Springvale 220 kV circuit 1 reactive power

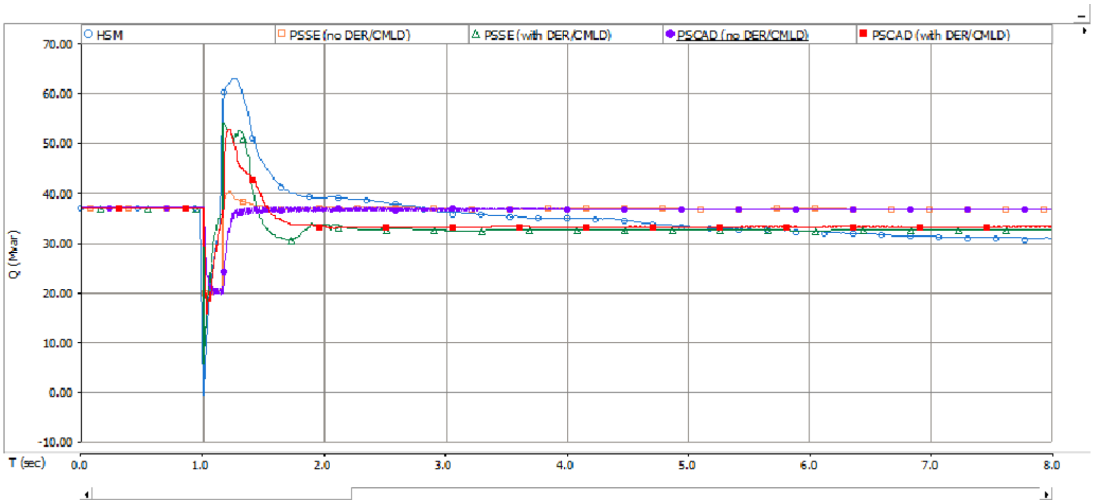


Figure 46: Cranbourne 220/66 kV transformer reactive power

As shown in Figure 45, the PSCAD™/EMTDC™ model closely matches with the HSM data. As shown in Figure 46, the PSCAD™/EMTDC™ model underestimates the peak reactive power after the fault, similar to how the voltage was also underestimated with the PSCAD™/EMTDC™ model at this location. The steady state reactive power matches with the HSM data when the CMLD and DER models are included.

5.2.3.2 CMLD/DER comparison

Figure 47 shows the total DER generation in VIC for measurements from the PSCAD™/EMTDC™ model.

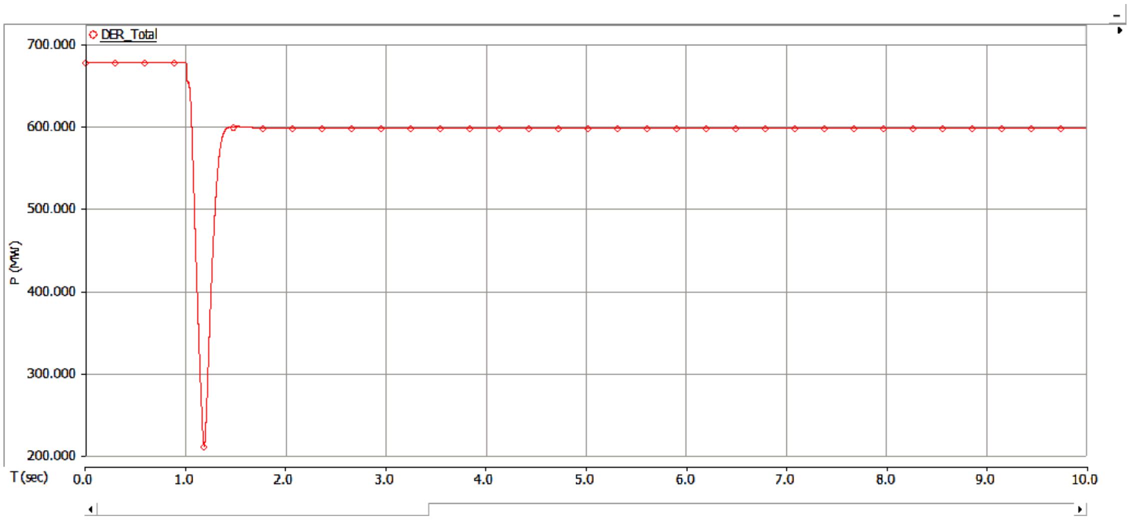


Figure 47: DER in VIC

Figure 48 shows a comparison of the change in DER with phase-angle tripping enabled and disabled.

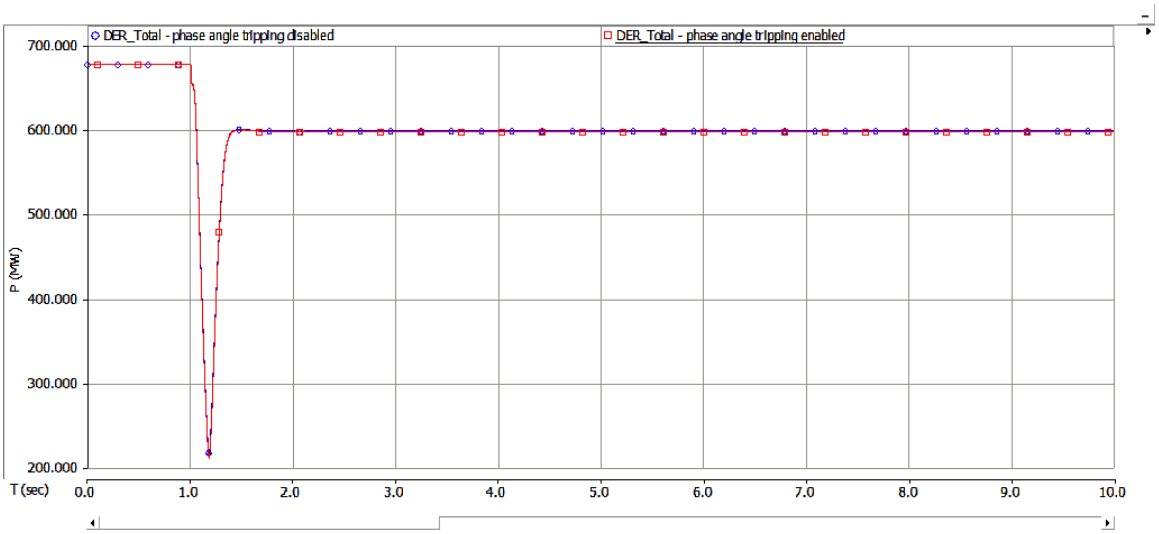


Figure 48: DER in SA (phase-angle tripping enabled and disabled)

As shown in Figure 48, no difference in the change of DER was observed.

Figure 49 shows the CMLD load in VIC for the PSCAD™/EMTDC™ model.

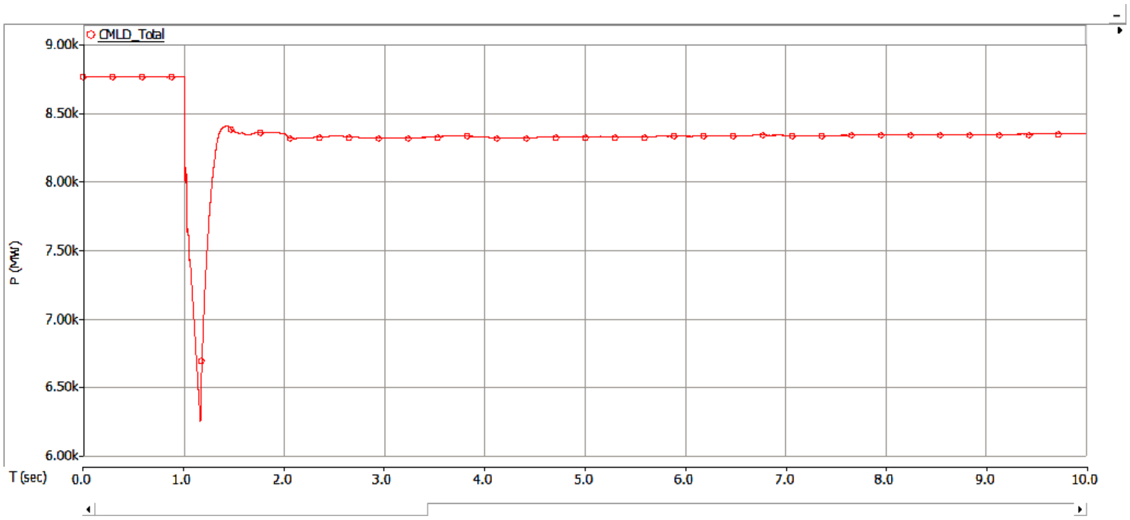


Figure 49: CMLD in VIC

Figure 50 shows a comparison of the change in operational demand in VIC with and without the CMLD and DER models.

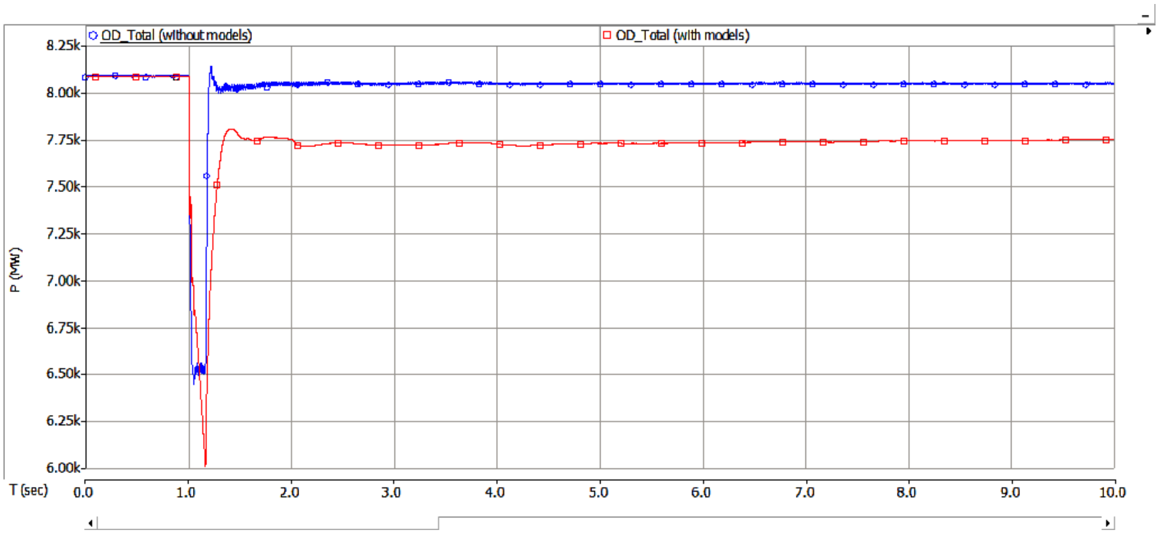


Figure 50: Operational demand in VIC

The post-contingency steady states operational demand in VIC drops by about 4% with DER and CMLD models compared to the simulation without DER and CMLD models.

Table 20 shows a comparison of the total CMLD load and DER change based on SCADA measurements, the PSS®E model and the PSCAD™/EMTDC™ model.

Table 20: DER/CMLD MW change comparison – January 18, 2018

Model	DER (MW)	CMLD (MW)	Operational Demand (MW)
Solar Analytics/SCADA Estimate	123	629	506
Estimated Range	57 – 218	507 – 815	450 – 598
PSS®E	88	637	549
PSCAD™/EMTDC™	80	398	318

As shown in Table 20,

- The PSCAD™/EMTDC™ model underestimates the change in DER by 43 MW (35%) but is inside the estimated range.
- The PSCAD™/EMTDC™ model underestimates the change in CMLD load by 231 MW (37%) and is outside the estimated range.
- The PSCAD™/EMTDC™ model underestimates the change in operational demand by 188 MW (37%) and is outside the estimate range.

Figure 51 and Figure 52 show comparisons of total DER and CMLD loss for applying an unbalanced fault and an equivalent balanced fault.

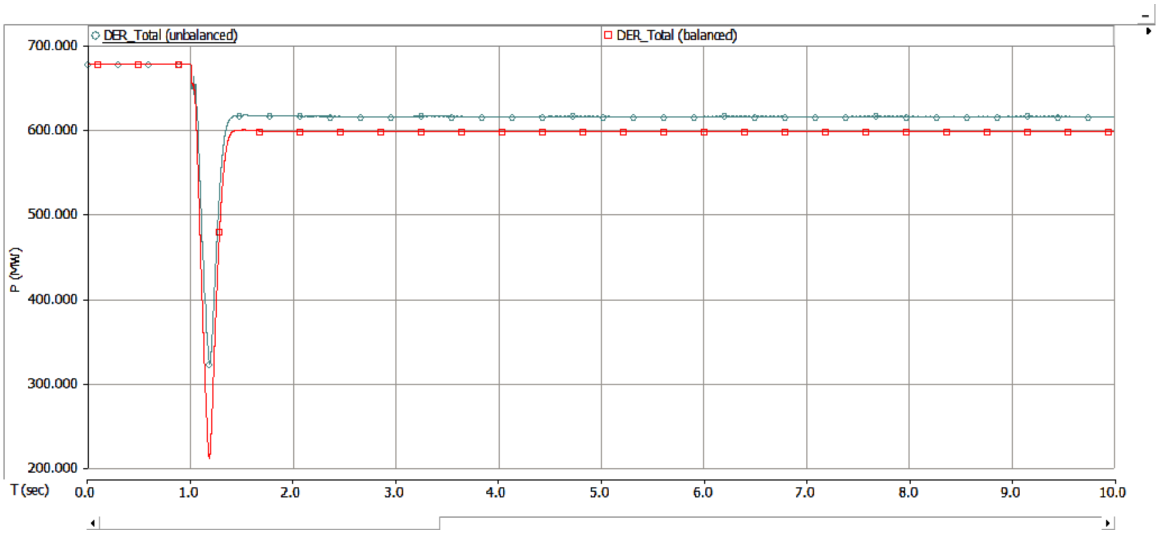


Figure 51: DER in SA (unbalanced and equivalent balanced faults)

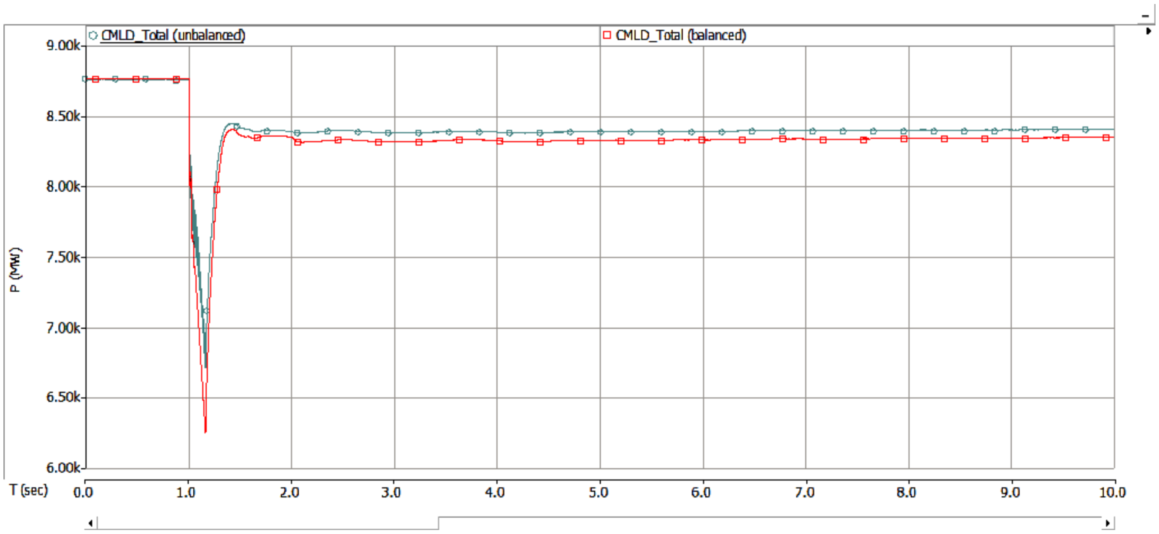


Figure 52: CMLD in SA (unbalanced and equivalent balanced faults)

As shown in Figure 51 and Figure 52, less DER and CMLD is tripped when applying the unbalanced fault, likely due to a higher residual voltage during the fault.

5.2.4 Conclusions

The conclusions for the January 18, 2018 case are shown in Table 21. Cells in green indicate a good match with the HSM data, yellow cells indicate a fair match with the HSM data, and orange indicates a poor match with HSM data.

Table 21: Assessment of model performance – January 18, 2018

Quantity	**Characteristic**	**Match to HSM**	**Match to PSS®E**	**Comment**
Voltages	Overshoot	Good	Fair	Model closely matches HSM and shows improvement over the PSS®E model.
	Recovery Rate	Fair	Fair	Model has a slower recovery rate compared to HSM and PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Active power	During dynamic state	Fair	Fair	Model underestimates drop in active power during fault and overshoot after fault is cleared.
	Steady state post-disturbance	Fair	Fair	Model shows smaller drop in active power between pre-fault and post-fault conditions.
Reactive power	During dynamic state	Fair	Fair	Model has similar trajectory to HSM/PSS®E models, but may underestimate peak flows.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
DER	DER Change	Good	Good	PSCAD™/EMTDC™: 80 MW PSS®E: 88 MW Actual: 123 MW Model underestimates DER change by 43 MW (35%), is close to the PSS®E model, and within range.
CMLD	Load change	Poor	Poor	PSCAD™/EMTDC™: 398 MW PSS®E: 637 MW Actual: 629 MW Model underestimates CMLD change by 231 MW (37%) and is outside the range.
Operational Demand	Net demand change	Poor	Poor	PSCAD™/EMTDC™: 296 MW PSS®E: 549 MW Actual: 506 MW Model underestimates OD change by 188 MW (37%) and is outside the range.

5.3 March 12, 2021 – South Australia

5.3.1 Case description

On March 12, 2021, the event described in Table 22 occurred in South Australia.

Table 22: Description of the event on March 12, 2021

Date and time		March 12, 2021, 17:08
Region		South Australia
Description of the event		Torrens Island A and B West 275 kV Busbars tripped due to a current transformer failure associated with the Torrens Island substation West bus section circuit breaker. This disconnected Barkers Inlet power station from 111 MW and the Torrens West 275/66 kV West transformer. All equipment was returned to service at 0922 hrs on 14 March.
Minimum voltage recorded		0.54 pu positive sequence at Torrens Island Power Station A (from HSM Data)
Installed capacity of DER		Total installed capacity: 1,637 MW • 43% installed under AS4777.3:2005 (from CER) • 7% installed under AS/NZS4777.2:2015 (from CER) • 41% installed under AS/NZS4777.2:2015 with Volt-VAR Enabled (from CER) • 9% installed under AS/NZS4777.2:2015 with Volt-VAR Enabled and VDRT compliance141 (from CER)
Prior to the event	**DER**	460 MW, 28% capacity factor (from ASEFS2, interpolated)
	Operational demand	1,516 MW (from SCADA data)
	Underlying demand	1,976 MW (estimate from SCADA + ASEFS2)
Estimated change	**DER**	72 MW (range of 49-103 MW) decrease (from Solar Analytics data)
	Operational demand	96 MW (range of 42-96 MW) decrease (from SCADA data)
	Underlying demand	168 MW (range of 91-199 MW) decrease (estimate from SCADA + Solar Analytics data)

A map of this event is shown in Figure 53.

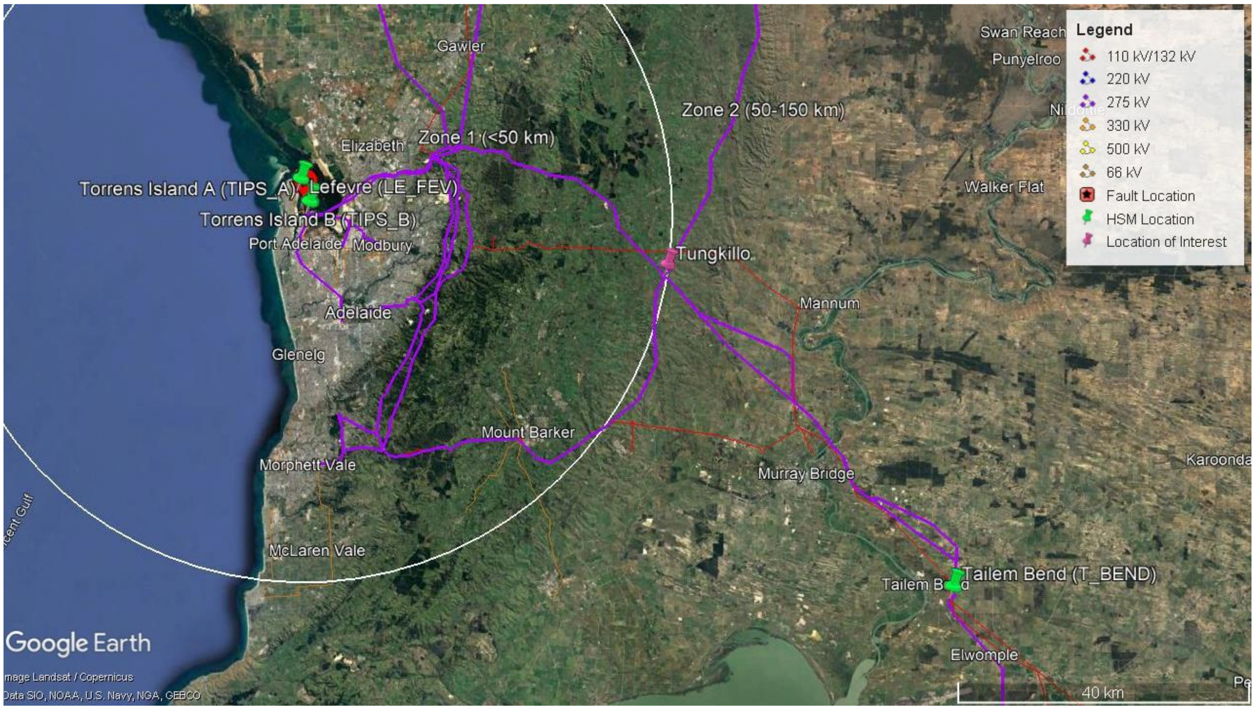


Figure 53: Map of the event on March 12, 2021

This event was replicated in PSCAD™/EMTDC™ using the event description shown in Table 23.

Table 23: Event summary for March 12, 2021

Time (seconds)	Event Description
0.0	Time when PSCAD™/EMTDC™ case finished initializing.
1.0	Apply 1PG fault at 275 kV Torrens Island A substation.
1.08	Clear 1PG fault. Trip 275 kV Torrens Island A – Torrens Island B circuit 2. Trip 275 kV Barker Inlet substation. Trip 275 kV Barker Inlet – Torrens Island B. Trip BIPS GN1 275/15 kV transformer. Trip 15 kV BIPS GN1 – 5DMY02421 circuit. Trip BIPS GN1 generator. Trip TIPS A 275/66 kV transformer.
30.0	End of simulation

5.3.2 PSCAD™/EMTDC™ modeling

After consulting with AEMO and considering the fault location was far away from VIC, NSW and QLD, it was decided to model only the SA region in PSCAD™/EMTDC™. Connections to VIC were replaced by static equivalents at the VIC end of the Murraylink HVDC link and the Heywood interconnector. The PSCAD™/EMTDC™ case was derived using the March 12, 2021 PSS®E case and the base PSCAD™/EMTDC™ case.

Note: Although the real event consisted of a SLG fault, an equivalent 3PG fault was applied as explained in 3.2.4. A sensitivity analysis was performed using the actual unbalanced fault to identify the impact of CMLD load and DER tripping.

5.3.3 Comparison

5.3.3.1 PSCAD™/EMTDC™ model comparison to HSM and PSS®E model

Figure 54 shows the voltage at Torrens Island A 275 kV bus for the HSM data, the PSS®E model and the PSCAD™/EMTDC™ model. HSM data is shown in blue, PSS®E results (without DER/CMLD models) are shown in orange, PSS®E results (with DER/CMLD models) are shown in green, PSCAD™/EMTDC™ results (without DER/CMLD models) are shown in purple, and PSCAD™/EMTDC™ results (with DER/CMLD models) are shown in red.

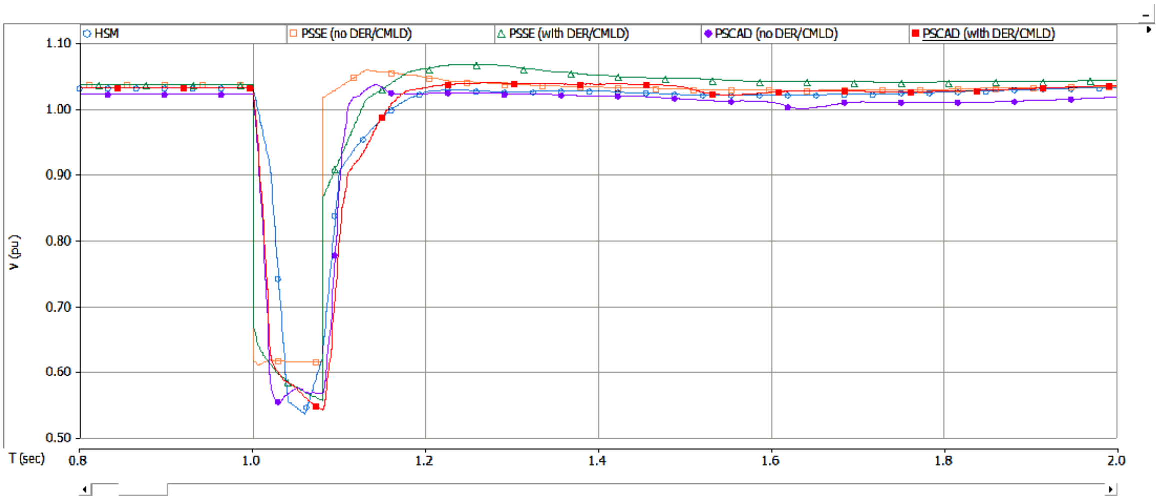


Figure 54: Torrens Island A 275 kV voltage

As shown in Figure 54 the PSCAD™/EMTDC™ model closely follows the response observed with the HSM data and the PSS®E model. The steady state value of the voltage is also comparable between the three sets of results.

The active power in the Torrens Island A – Kilburn 275 kV circuit is shown in Figure 55.

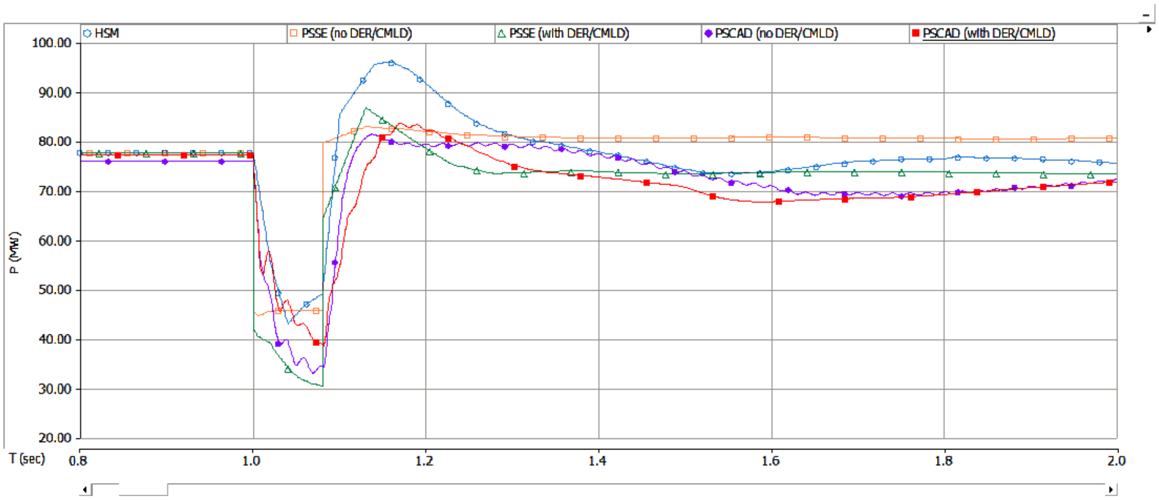


Figure 55: Torrens Island A – Kilburn 275 kV active power

As shown in Figure 55, small oscillations were observed with the PSCAD™/EMTDC™ model during the fault, and the drop in active power during the fault is closer to the HSM data than the PSS®E model. In addition, the PSCAD™/EMTDC™ model underestimates the peak active power immediately after the fault, similar to the PSS®E model. The steady state active power matches with the HSM data when the CMLD and DER models are included.

When applying an unbalanced fault instead of an equivalent balanced fault, a different residual voltage was observed. The voltage at Torrens Island A 275 kV bus for an unbalanced fault is shown in Figure 56.

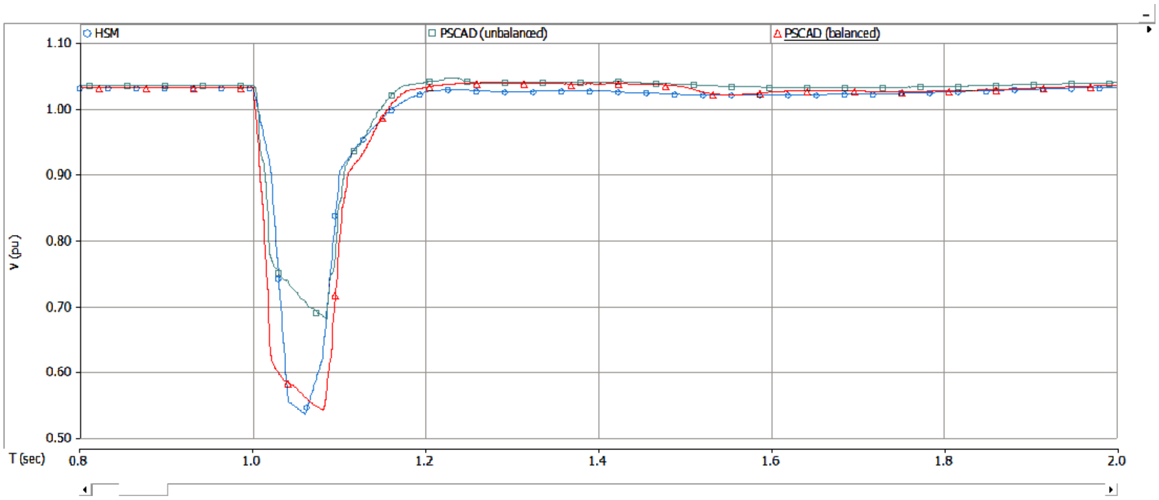


Figure 56: Torrens Island A 275 kV voltage (unbalanced fault)

As shown in Figure 56, the residual voltage for the unbalanced fault is higher than the residual voltage of the equivalent balanced fault. This difference in voltage will likely result in different amounts of DER and CMLD tripping.

Figure 57 shows the reactive power in the Torrens Island A – Kilburn 275 kV circuit.

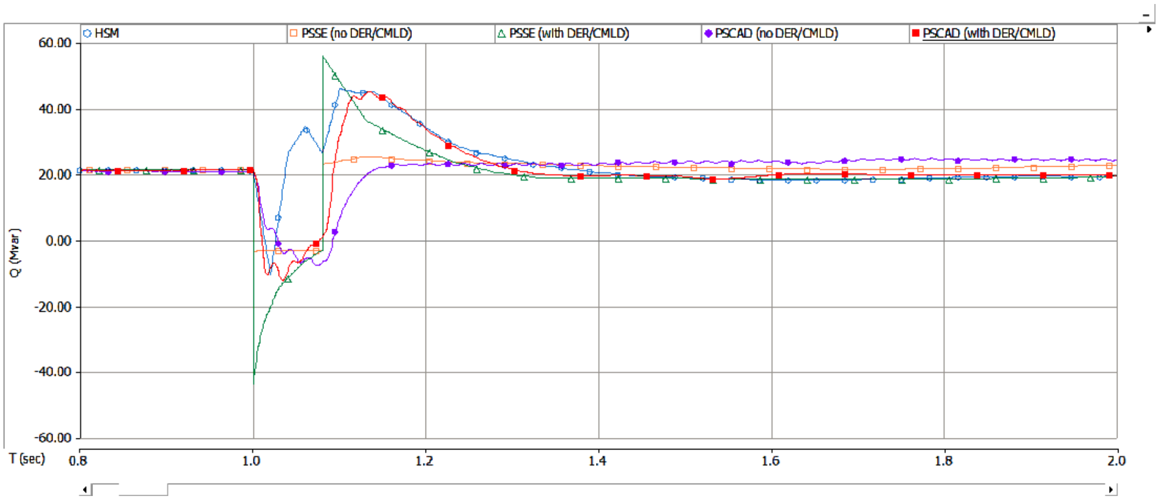


Figure 57: Torrens Island A – Kilburn 275 kV reactive power

As shown in Figure 57, the initial reactive power drop in the PSCAD™/EMTDC™ model closely matches the HSM data during the fault. When applying the same smoothing time constant to the PSS®E results, both the PSCAD™/EMTDC™ model and the PSS®E model show very similar results. After the fault is cleared, the PSCAD™/EMTDC™ model closely matches both the HSM data and the PSS®E model. This result is shown in Figure 58.

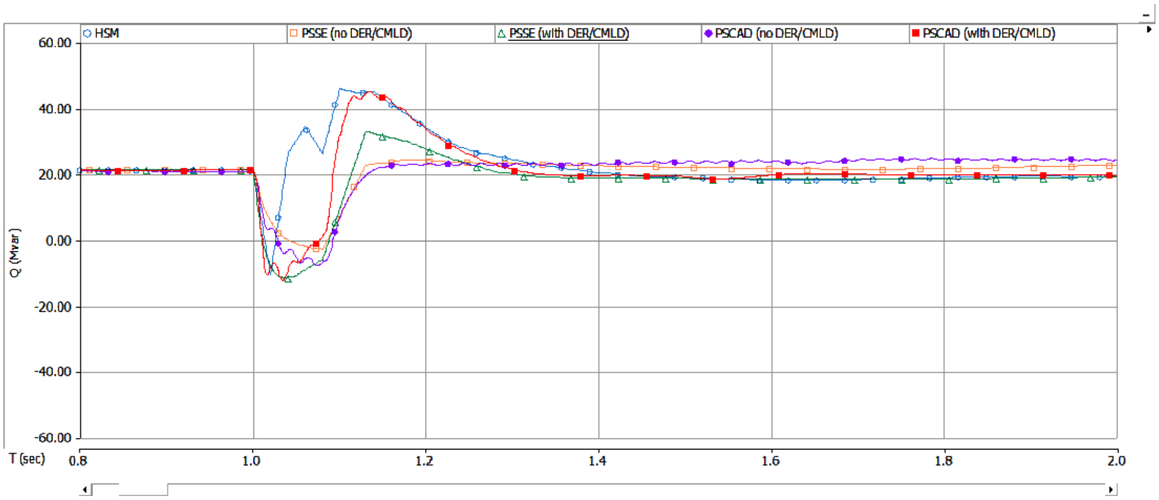


Figure 58: Torrens Island A – Kilburn 275 kV reactive power (PSS®E results smoothed)

5.3.3.2 CMLD/DER comparison

Figure 59 shows the total DER generation in SA for measurements from the PSCAD™/EMTDC™ model.

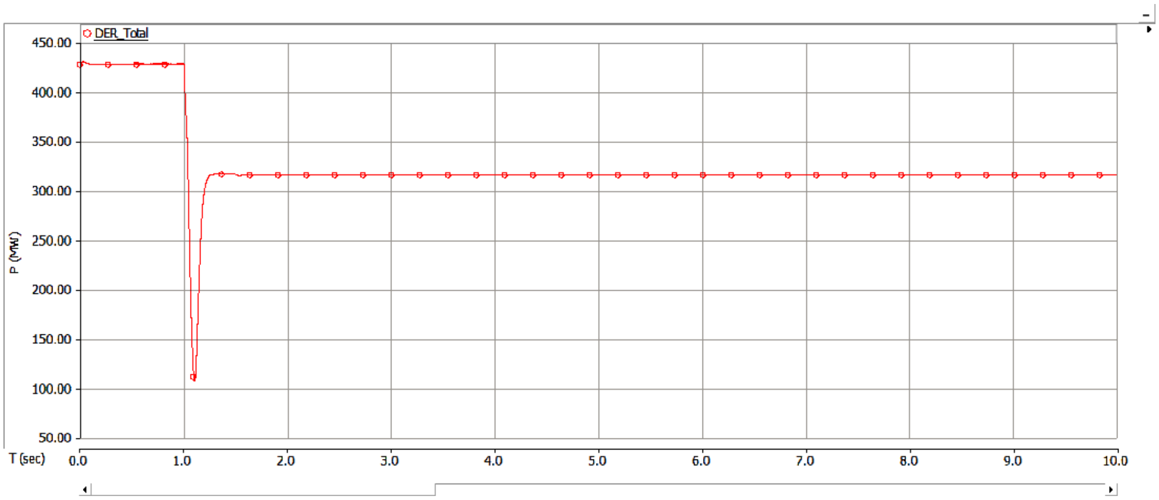


Figure 59: DER in SA

Figure 60 shows a comparison of the change in DER with phase-angle tripping enabled and disabled.

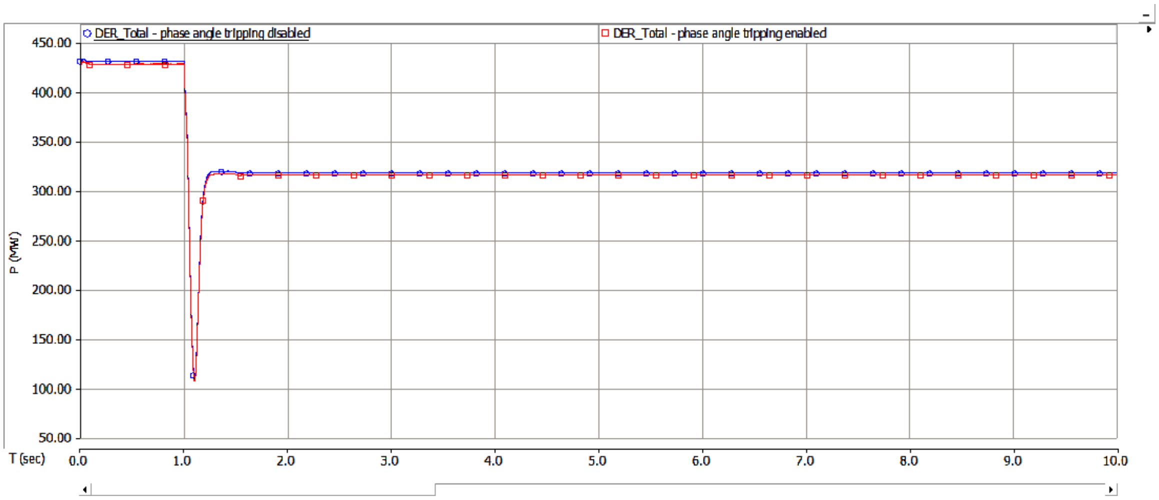


Figure 60: DER in SA (phase-angle tripping enabled and disabled)

As shown in Figure 60, no difference in the change of DER was observed.

Figure 61 shows the CMLD load in SA for the PSCAD™/EMTDC™ model.

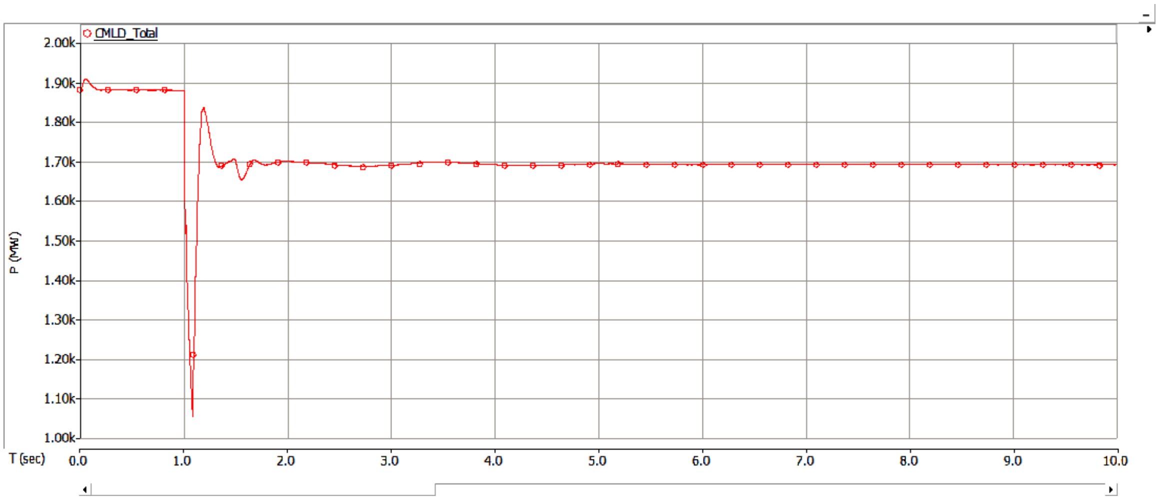


Figure 61: CMLD in SA

Figure 50 shows a comparison of the change in operational demand in SA with and without the CMLD and DER models.

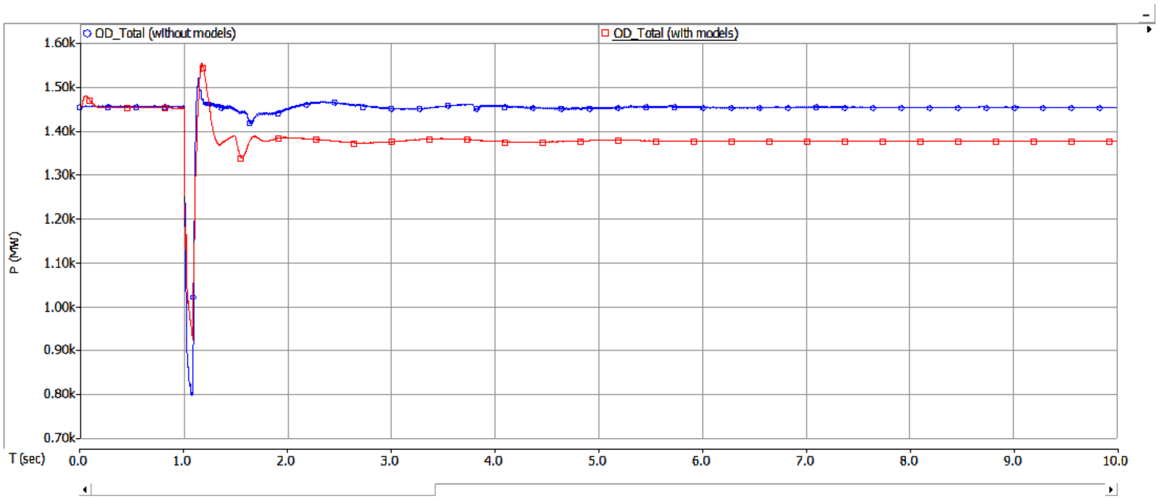


Figure 62: Operational demand in SA

The post-contingency steady states operational demand in SA drops by about 5% with DER and CMLD models compared to the simulation without DER and CMLD models.

Table 24 shows a comparison of the total CMLD load and DER change based on SCADA measurements, the PSS®E model and the PSCAD™/EMTDC™ model.

Table 24: DER/CMLD MW change comparison – March 12, 2021

Model	DER (MW)	CMLD (MW)	Operational Demand (MW)
Solar Analytics/SCADA Estimate	72	168	96
Estimated Range	49 – 103	91 – 199	42 – 96
PSS®E	95	206	111
PSCAD™/EMTDC™	113	188	75

As shown in Table 24,

- The PSCAD™/EMTDC™ model overestimates the change in DER by 41 MW (57%) and is outside the estimated range.
- The PSCAD™/EMTDC™ model overestimates the change in CMLD by 20 MW (12%) but is inside the estimated range.
- The PSCAD™/EMTDC™ model underestimates the change in operational demand by 21 MW (22%) but is inside the estimated range.

Figure 63 and Figure 64 show comparisons of total DER and CMLD loss for applying unbalanced faults and equivalent balanced faults.

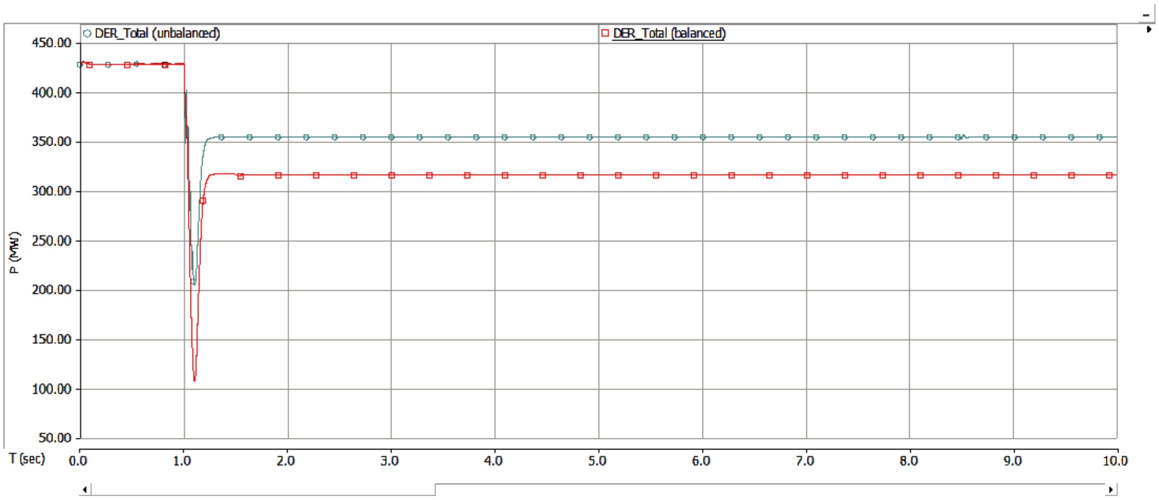


Figure 63: DER in SA (unbalanced and equivalent balanced faults)

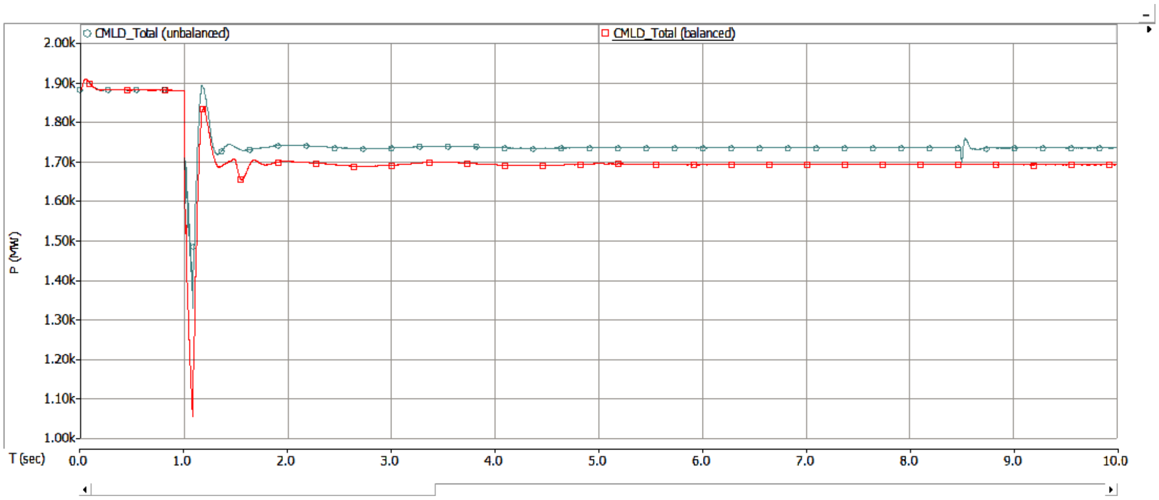


Figure 64: CMLD in SA (unbalanced and equivalent balanced faults)

As shown in Figure 63 and Figure 64, less DER and CMLD is tripped when applying the unbalanced fault, likely due to a higher residual voltage during the fault.

5.3.4 Conclusions

The conclusions for the March 12, 2021 case are shown in Table 25. Cells in green indicate a good match with the HSM data, yellow cells indicate a fair match with the HSM data, and orange indicates a poor match with HSM data.

Table 25: Assessment of model performance – March 12, 2021

Quantity	Characteristic	Match to HSM	Match to PSS®E	Comment
Voltages	Overshoot	Good	Good	Model closely matches HSM and PSS®E model.
	Recovery Rate	Good	Good	Model closely matches HSM and PSS®E model.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Active power	During dynamic state	Fair	Good	Model matches well with PSS®E model. Follows a similar trajectory to HSM data, but overestimates/underestimates flows during and after the fault, respectively.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
Reactive power	During dynamic state	Fair	Good	Model matches well with PSS®E model. Follows a similar trajectory to HSM data, but overestimates flows during and after the fault.
	Steady state post-disturbance	Good	Good	Model closely matches HSM and PSS®E model.
DER	DER Change	Fair	Good	PSCAD™/EMTDC™: 113 MW PSS®E: 95 MW Actual: 72 MW Model overestimates DER change by 41 MW (57%) and is outside the range.
CMLD	Load change	Good	Good	PSCAD™/EMTDC™: 188 MW PSS®E: 206 MW Actual: 168 MW Model overestimates CMLD change by 20 MW (12%) but is inside the range
Operational Demand	Net demand change	Good	Good	PSCAD™/EMTDC™: 75 MW PSS®E: 111 MW Actual: 96 MW Model underestimates OD change by 21 MW (22%) but is inside the range.

6 *Model validation: Frequency disturbances*

Two frequency disturbances were selected to be studied. A short description of these two events are shown in Table 26 and Table 27.

Table 26: Description of the event on August 25, 2018

Date and time	August 25, 2018, 13:11
Region	NEM
Description of the event	Both Queensland – New South Wales Interconnector (QNI) lines tripped, resulting in separation of the Queensland region from the rest of the NEM. This was followed by the separation of South Australia from the rest of the NEM, and under-frequency load shedding (UFLS) in New South Wales, Victoria, and Tasmania.

Table 27: Description of the event on January 31, 2020

Date and time	January 31, 2020, 13:24
Region	NEM
Description of the event	This event resulted in the non-credible loss of both the Moorabool – Mortlake (MLTS-MOPS) and the Moorabool – Haunted Gully (MLTS-HGTS) – Tarrone (HGTS-TRTS) 500 kV transmission lines, causing a separation of the Victoria and South Australia regions. Immediately after the incident, the Mortlake Power Station (MOPS) generating units and the APD aluminium smelter remained connected to the South Australia region but disconnected from the rest of Victoria. At the same time, both potlines at APD tripped, resulting in loss of load.

After consulting with AEMO and considering the cascading nature of these frequency disturbances, it was decided to model the following regions in PSCAD™/EMTDC™.

- August 25, 2018 - All four regions with Basslink modeled with a playback model, and
- January 31, 2020 - SA and VIC regions with VNI and Basslink modeled with playback models.

Initially, PSCAD™/EMTDC™ cases were developed for version 4.6.3, similar to the five voltage disturbance cases. However, an updated PSCAD™/EMTDC™ case for version 5.0.2 was available with AEMO. PSCAD™/EMTDC™ version 5.0 or later versions allow significant speed advantages and flexibility when running large cases such as the AEMO NEM case. Therefore, two frequency disturbance cases were imported to PSCAD™/EMTDC™ version 5.0.2 and all the detailed models were replaced with models copied from the version 5.0.2 AEMO base model.

Initial simulation results obtained from PSCAD™/EMTDC were significantly different from the HMS data and the PSS®E results. In order to identify whether these differences were caused by an error in the DER and CMLD models, the simulations were repeated in PSS®E and PSCAD™/EMTDC with the CMLD models replaced with ZIP load models and DER models were modified[8] to behave as constant power sources.

---

[8] The transition time to enable the outer loop control was extended beyond the simulation time.

In both disturbances, PSS®E simulations show that the system managed to control the frequency deviations and maintain system stability whereas PSCAD™/EMTDC simulations show that the system did not manage to control the frequency deviations and hence was unable to maintain system stability. A comparison of the system frequency at several locations across the system is shown in Appendix A and Appendix B for the disturbance in the August 25, 2018 and January 31, 2020 cases, respectively. This clearly demonstrates that the PSS®E and PSCAD™/EMTDC models provide significantly different simulation results for severe frequency disturbances with cascaded tripping of network elements.

Upon further investigation, it was identified that there was a significant difference between the modeling of governors between the PSCAD™/EMTDC™ and PSS®E models for conventional (synchronous) machines. Table 28 shows the in-service units with and without a governor for the August 25, 2018 case.

Table 28: MVA totals for in-service units with and without governor models: August 25, 2018 case

No.	Status of the governor modeling for the conventional generator units	Sum of unit MVA
1	Units with governor models missing only in PSCAD™/EMTDC™	2826
2	Units with governor models missing only in PSS®E	7852
3	Units with matched governor models between PSS®E and PSCAD™/EMTDC™	7533
4	Units without governor models in PSS®E and PSCAD™/EMTDC™	5492
Total sum of MVA for in-service units		**23,703**

As shown in Table 28, a significant portion of the conventional generator units (roughly 10.6 GVA) has a mismatch in their governor modeling. Details of units with and without governors and other changes made to the PSCAD™/EMTDC™ case representing August 25, 2018 are presented in Appendix C. Appendix D presents similar details for the January 31, 2020 case.

AEMO carefully reviewed the mismatches in governor models between the PSCAD™/EMTDC™ and PSS®E models and decided that harmonizing the governor models is an important task that should be undertaken in the future. As such, the validation of DER and CMLD models using wide-area networks and historical events may be performed at a future date. DER and CMLD models developed for PSCAD™/EMTDC™ have already been compared and validated against corresponding PSS®E models using a Single Machine to Infinite Bus (SMIB) system [5].

7 Efficient application in large networks

Each CMLD model uses multiple detailed EMT models, and having hundreds of CMLD models in a large network will greatly increase the computational burden. A sensitivity study was performed to check how reducing the amount of CMLD models can decrease the computational burden, without significantly impacting the simulation results.

To determine which CMLD models to include and which to omit (i.e., leave as a ZIP load), a voltage dip analysis was performed to identify how the voltage dips throughout the network for a fault. An example of a voltage dip contour is shown in Figure 65.

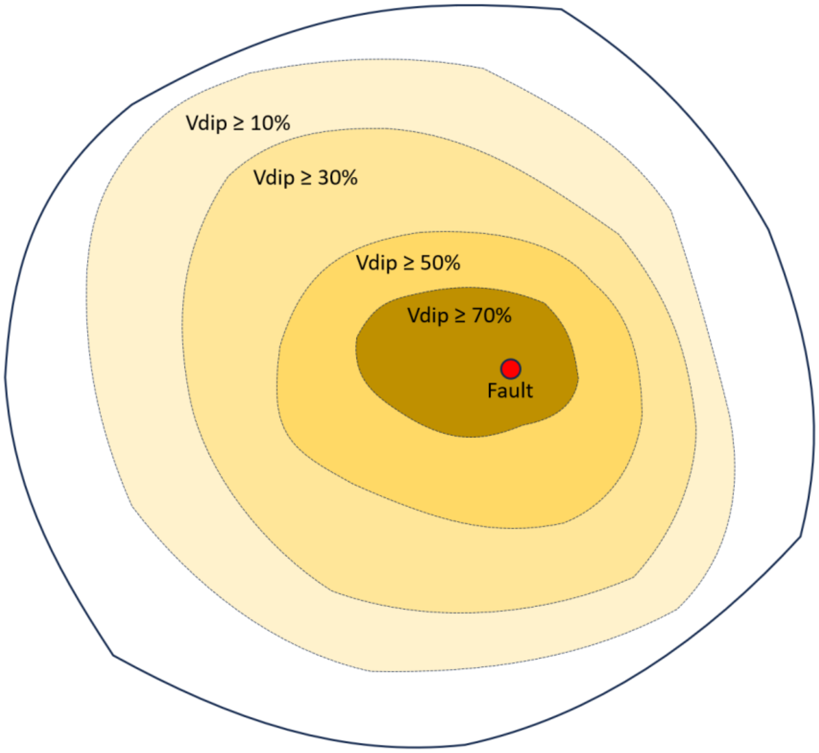


Figure 65: Area voltage dip contour example

As shown in Figure 65, the voltage depression near the fault will be the greatest (large voltage dip). The further away from the fault, the impact on the bus voltage is reduced (small voltage dip). Areas are then categorized based on the voltage dip and contours can be developed.

A three-phase fault was applied in the PSS®E model for the February 22, 2021 (QLD) case and the voltage at CMLD buses was measured to determine the voltage dip during the fault. The number of CMLD models and total active powers are determined for different voltage dip ranges and are summarized in Table 29.

Table 29: Voltage dip CMLD totals

Voltage Dip	Count	Power (MW)
Vdip ≥ 70%	87	3213.9
Vdip ≥ 50%	114	3840.7
Vdip ≥ 30%	130	4386.2
Vdip ≥ 10%	176	6552.9
Vdip ≥ 0%	249	7999.2

The list of buses (categorized by area) with CMLD load models are shown in Appendix E and the voltage dip contours are shown in Figure 66.

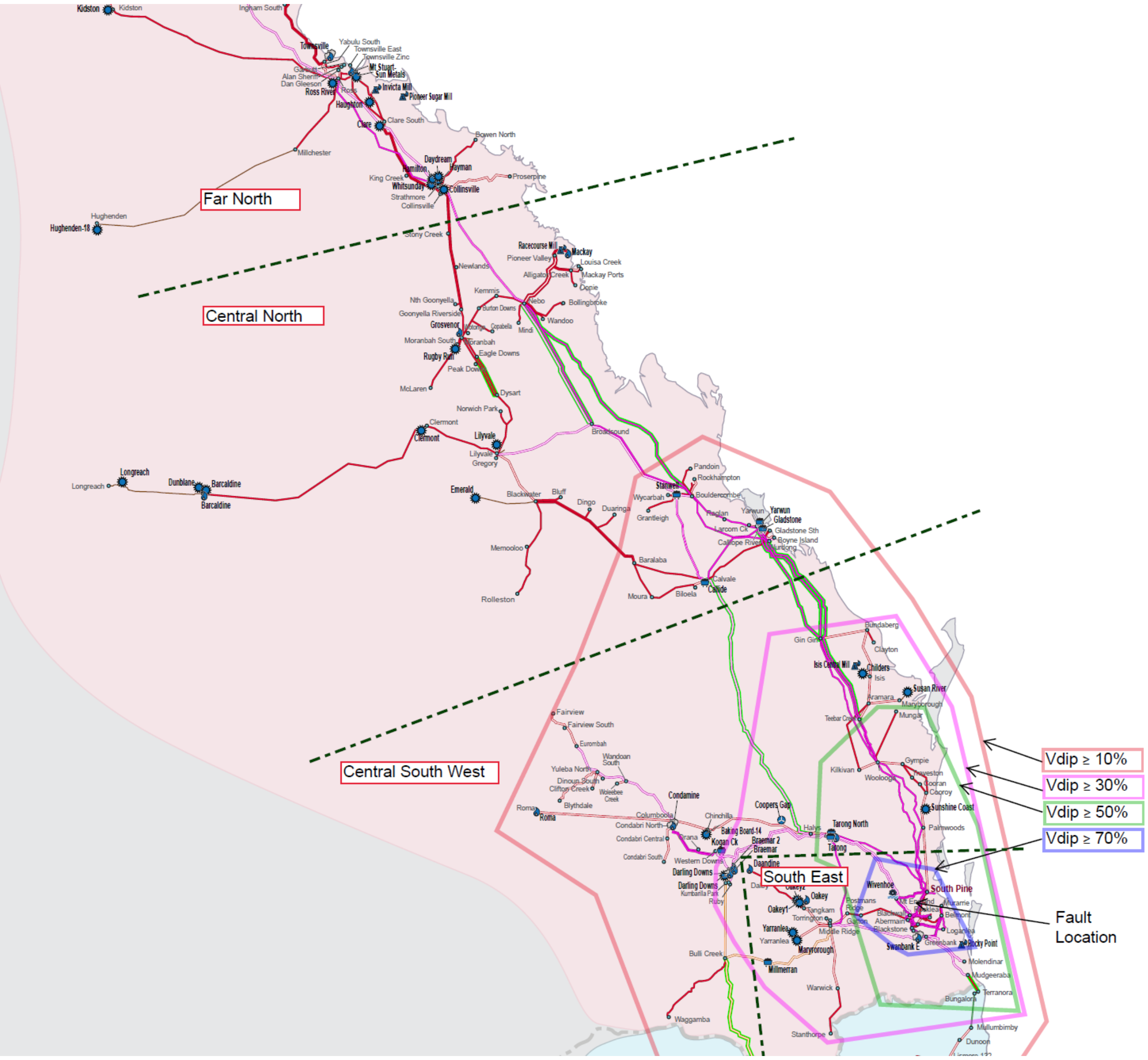


Figure 66: QLD voltage dip contour diagram

A series of PSCAD™/EMTDC™ simulations were performed, each including a different number of CMLD models based on the voltage dip. Six different simulations were selected as listed in Table 30.

Table 30: CMLD contour summary

Index	**Scenario Name**	**# of CMLD models**	**Description**
1	All Models	249	Includes all CMLD models in QLD network
2	V_{dip} > 10%	176	Includes models at buses where a voltage dip is 10% or greater
3	V_{dip} > 30%	130	Includes models at buses where a voltage dip is 30% or greater
4	V_{dip} > 50%	114	Includes models at buses where a voltage dip is 50% or greater
5	V_{dip} > 70%	87	Includes models at buses where a voltage dip is 70% or greater
6	No Models	0	No CMLD models are included

The total active power at all CMLD load locations was measured. Figure 3 shows the total CMLD active power in QLD (with the fault is applied at 20 sec).

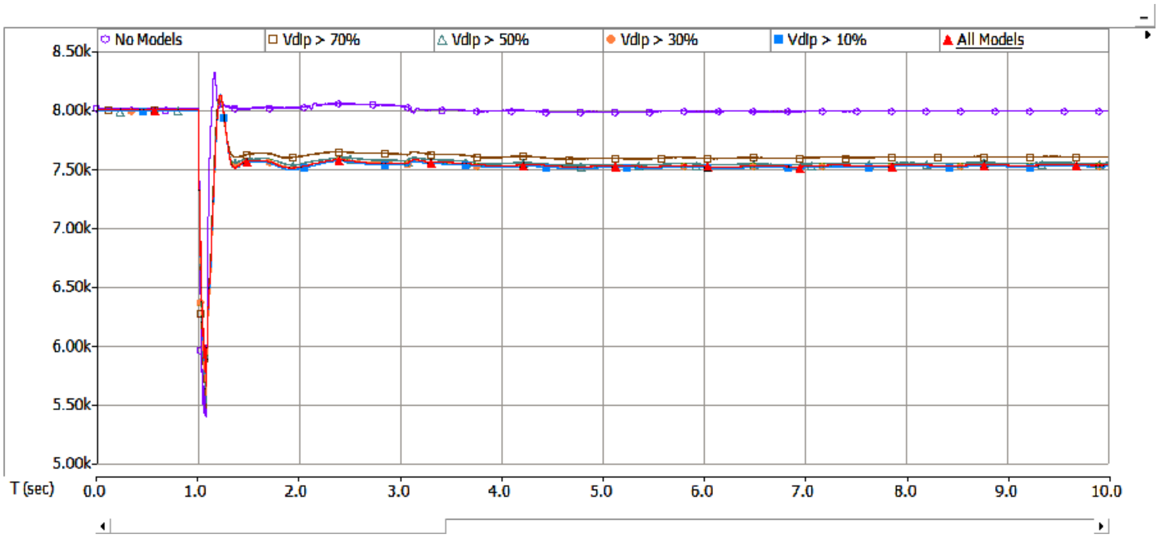


Figure 67: Total CMLD active power in QLD

The total CMLD tripping amount when different amounts of CMLD models are included is tabulated in Table 31 (approximate values are shown).

Table 31: CMLD contour summary

Included CMLD	# CMLD models	Total CMLD [MW]	Tripped Load [MW]
All Models	249	7999.2	470
$V_{dip} > 10\%$	176	6552.9	470
$V_{dip} > 30\%$	130	4386.2	470
$V_{dip} > 50\%$	114	3840.7	450
$V_{dip} > 70\%$	87	3213.9	400
No Models	0	0.0	15

The following conclusions are drawn from the above:

- With all models included, the total CMLD load tripping is about 470 MW. This is also the case for the "$V_{dip} > 10\%$" and "$V_{dip} > 30\%$" scenarios.
- For the "$V_{dip} > 50\%$" scenario, the total CMLD tripping is about 450 MW (20 MW difference from including all CMLD models).
- For the "$V_{dip} > 70\%$" scenario, the total CMLD tripping is about 400 MW (70 MW difference from including all CMLD models).
- When no CMLD models are included, a drop of about 15 MW was observed at CMLD locations (this can be attributed to the voltage dependency of the loads in the PSCAD™/EMTDC™ model).

From these results, if CMLD models are only included at locations with a voltage dip of 50% or greater, the total number of CMLD models included reduces by more than half (114 models instead of 249 models). This will reduce the computational burden while only having a small impact on the total MW tripped (450 MW instead of 470 MW).

Additional checks were made considering just three different levels of CMLD: all CMLD models, CMLD models at buses with voltage dip greater than 50% ("$V_{dip} > 50\%$"), and no CMLD models. The CMLD breakdown for each area in the QLD for the three scenarios is presented in Table 32.

Table 32: CMLD summary by area

Scenario	South East	Central South West	Central North	Far North
All Models	99 models (3310.1 MW)	56 models (1847.7 MW)	58 models (2180.4 MW)	36 models (660.9 MW)
$V_{dip} > 50\%$	98 models (3292.5 MW)	16 models (548.2 MW)	0 models	0 models
No models	0 models	0 models	0 models	0 models

Figure 68, Figure 69, Figure 70 and Figure 71 show the total CMLD active power for each area of QLD for the three selected scenarios (South East, Central South West, Central North and Far North, respectively).

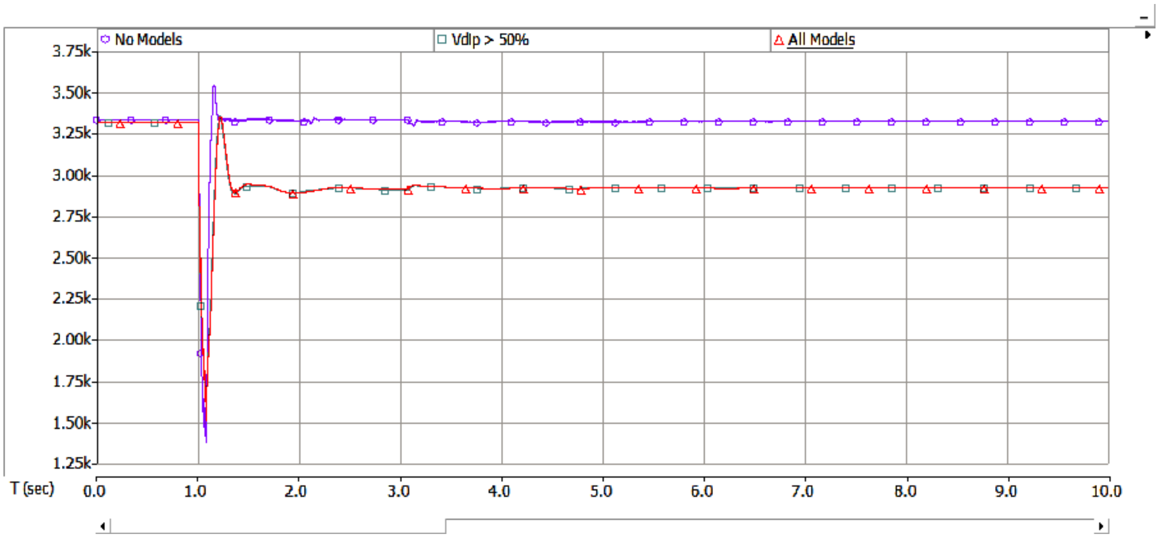


Figure 68: Total CMLD (South East area)

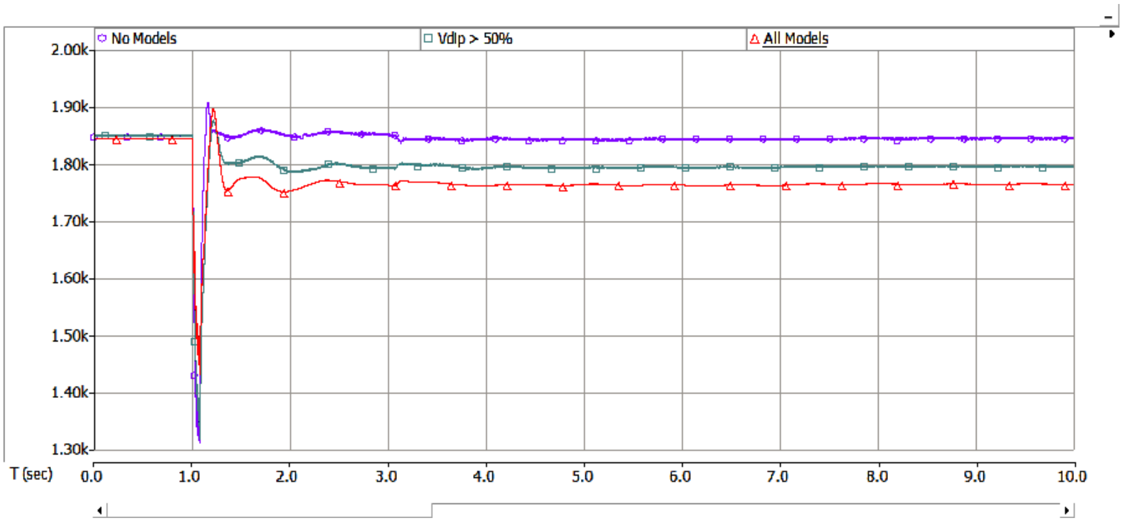


Figure 69: Total CMLD (Central South West area)

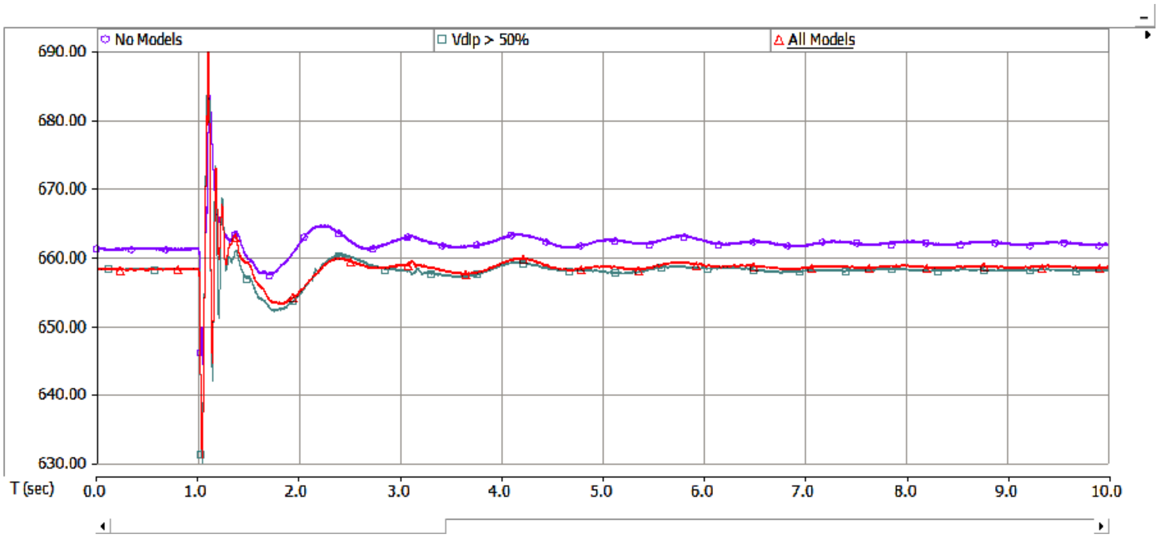


Figure 70: Total CMLD (Central North area)

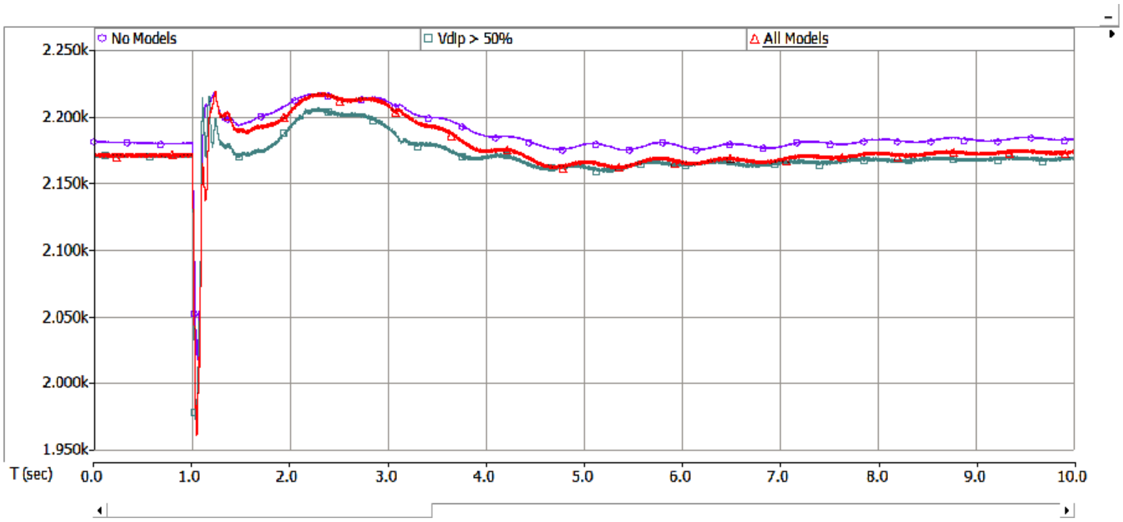


Figure 71: Total CMLD (Far North area)

Examining the CMLD MW tripping in the above figures, there is practically no change in the Central North and Far North areas. This is expected as Figure 66 (voltage dip contour diagram) shows that the impact of the fault on these two areas is very small (voltage dips less than 20%). The greatest amount of CMLD tripping occurs in the South East area. This area is closest to the fault and so there are large voltage dips observed in this area.

The voltages at the South Pine and Swanbank 275 kV buses are shown in Figure 72 and Figure 73.

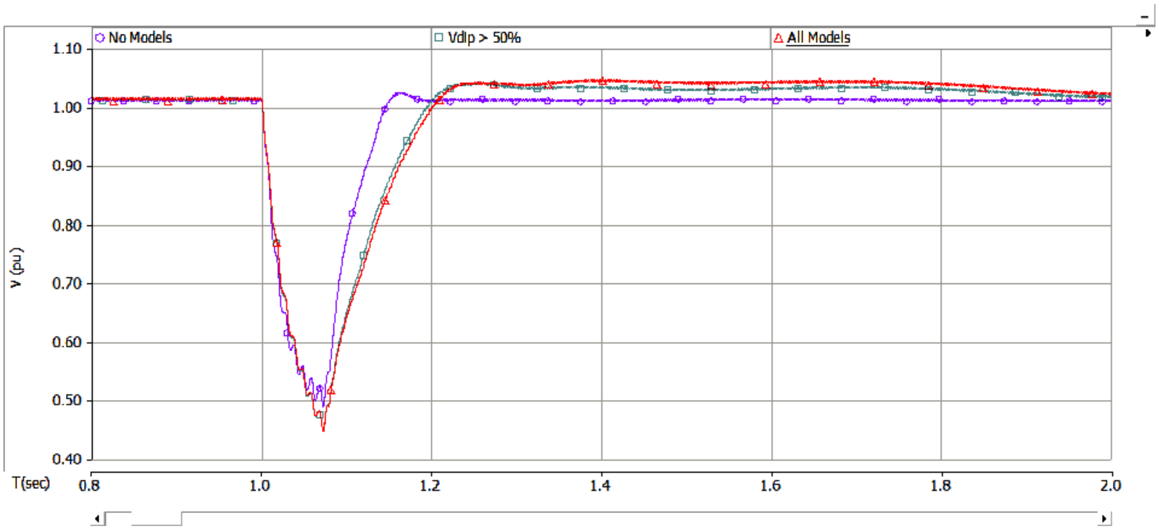


Figure 72: South Pine 275 kV voltage

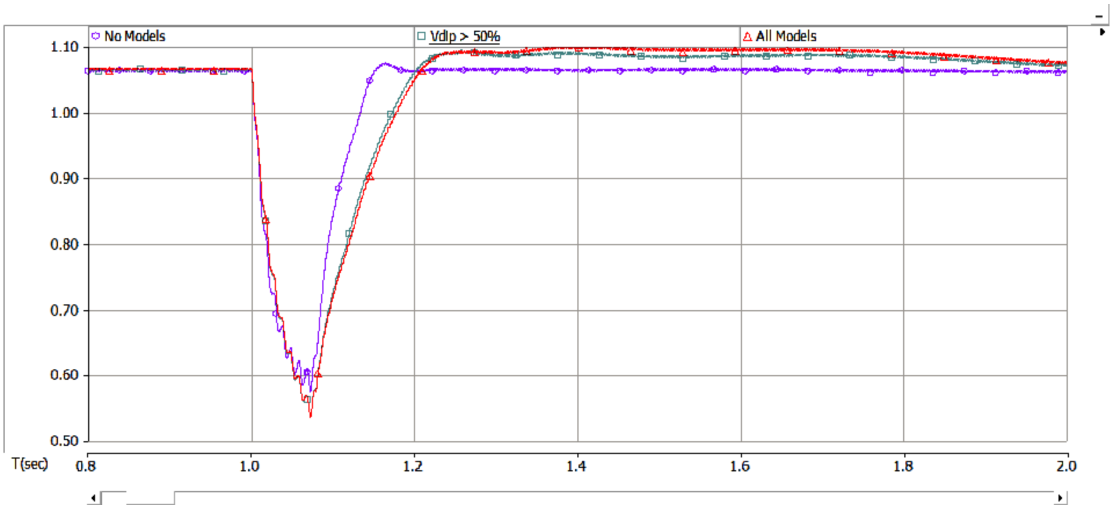


Figure 73: Swanbank 275 kV voltage

The active power for the South Pine 275/110 kV transformer and Swanbank-Greenbank 275 kV line are shown in Figure 74 and Figure 75.

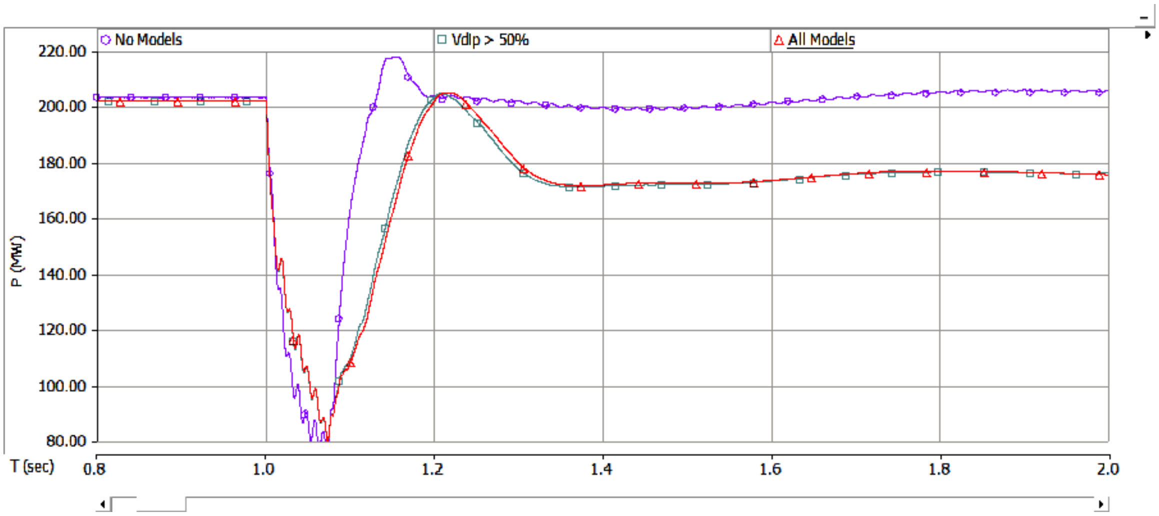


Figure 74: South Pine 275/110 kV transformer active power

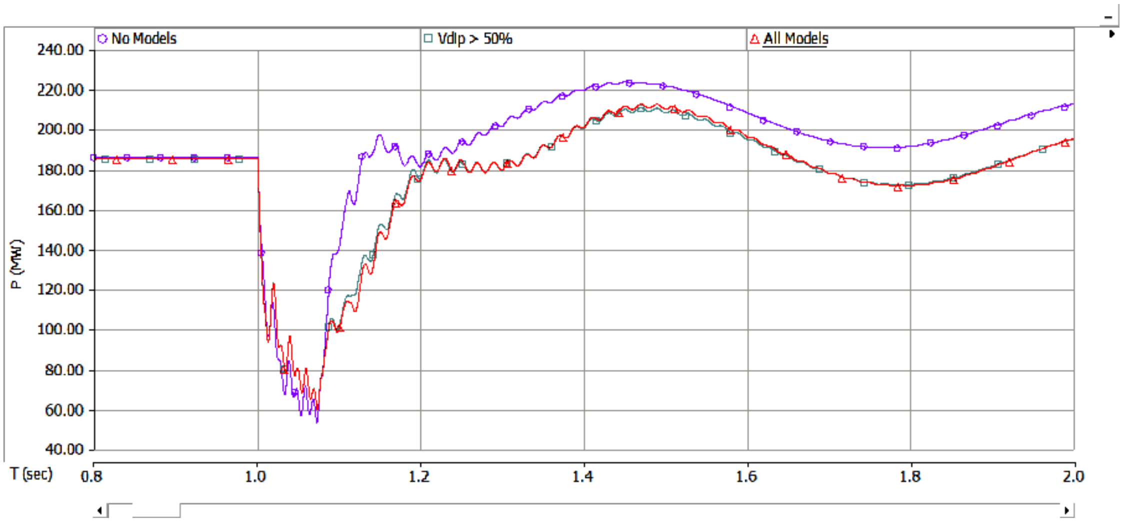


Figure 75: Swanbank - Greenbank 275 kV circuit 1 active power

The reactive power for the South Pine 275/110 kV transformer and Swanbank-Greenbank 275 kV line are shown in Figure 76 and Figure 77.

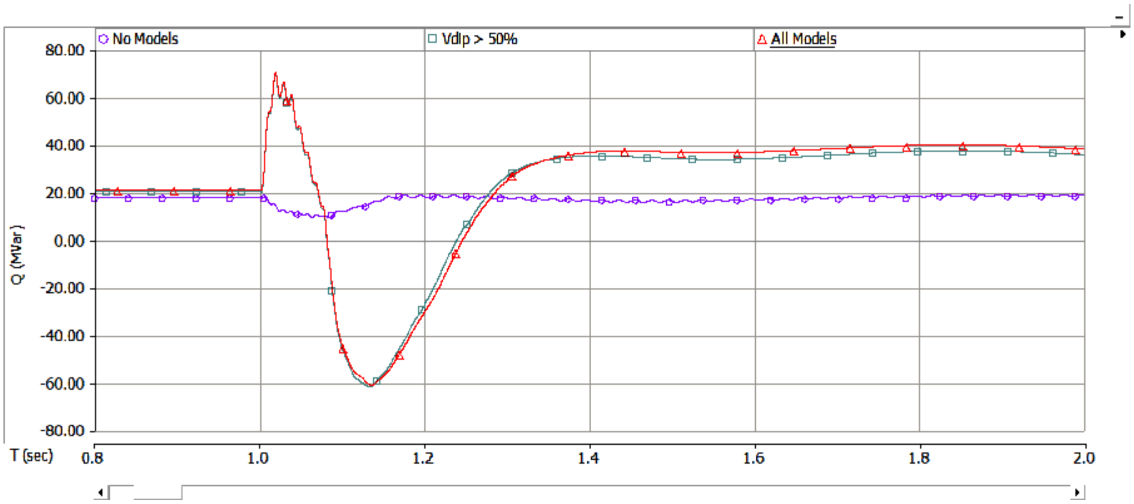


Figure 76: South Pine 275/110 kV transformer reactive power

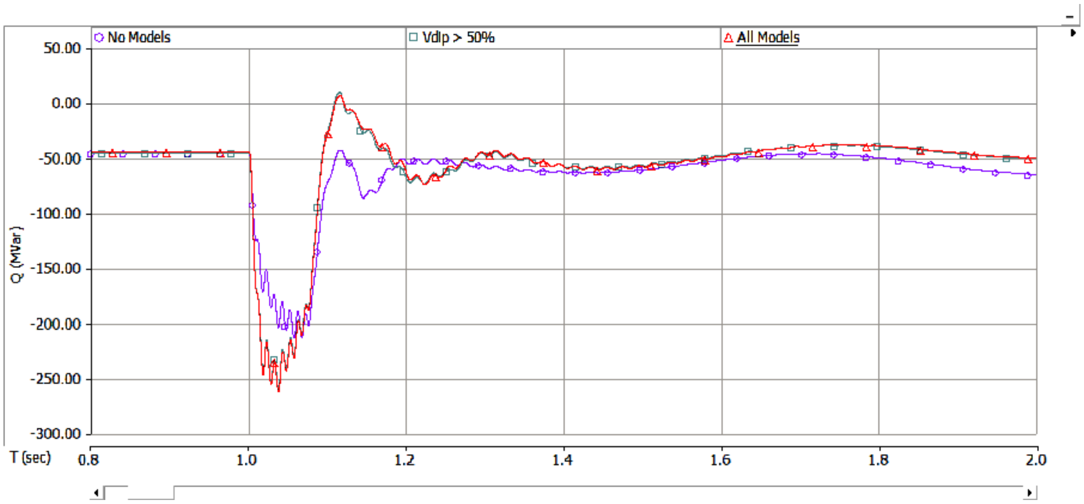


Figure 77: Swanbank - Greenbank 275 kV circuit 1 reactive power

These above figures demonstrate that the scenarios including all CMLD models and CMLD models at buses with voltage dips greater than 50% are nearly identical.

As shown in the above analysis, not all loads need to be modeled with the CMLD model to obtain the same dynamic response. By reducing the number of CMLD models, the computational burden can be reduced without compromising the results. It should be noted that every case is unique and the number of CMLD models to include or exclude will vary.

8 Conclusions

(A) Voltage disturbances

- A summary of the model performance for voltage disturbances is shown in Table 33. Cells in green indicate a good match with HSM data, yellow cells indicate a fair match with HSM data, and orange indicates a poor match with HSM data. A checkmark indicates a close match between the PSCAD™/EMTDC™ model and the PSS®E model.

Table 33: Voltage disturbances

Quantity	**Characteristic**	**No DER generation**		**With DER generation**		
		17/04/19	**22/02/21**	**03/03/17**	**18/01/18**	**12/03/21**
Voltages	Overshoot	🟨	🟩 ✓	🟩 ✓	🟩	🟩 ✓
	Recovery Rate	🟩 ✓	🟨	🟩 ✓	🟨	🟩 ✓
	Steady state post-disturbance	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓	🟩 ✓
Active power	During dynamic state	🟨 ✓	🟩 ✓	🟨 ✓	🟨	🟨 ✓
	Steady state post-disturbance	🟩 ✓	🟩 ✓	🟩 ✓	🟨	🟩 ✓
Reactive power	During dynamic state	🟨	🟨 ✓	-	🟨	🟨 ✓
	Steady state post-disturbance	🟩 ✓	🟩 ✓	-	🟩 ✓	🟩 ✓

- The PSCAD™/EMTDC™ model performances show a good match to the HSM data and the PSS®E model performances for voltage overshoot and recovery rate.

- The PSCAD™/EMTDC™ model performances show a close match to the HSM data and the PSS®E model performances in steady-state post-disturbance voltage, active power, and reactive power.

- The PSCAD™/EMTDC™ model closely matches the PSS®E model in all cases, except for the January 18, 2018 case.

- Table 34 shows the performance of the DER model. Cells in green are cases where the DER model is accurate within 15% of the actual DER loss, cells in yellow are cases where the DER loss is within 10% of the estimated range, and cells in orange are cases where the DER loss is outside the estimated range.

Table 34: DER model performance for voltage disturbances

Case	State	Actual DER loss (estimated range) (MW)	PSCAD™/EMTDC™ model DER loss (MW)	DER model percentage of observed	DER model difference
03/03/17	SA	130 (43 – 253)	189	145% Within estimated range	+59 MW
18/01/18	VIC	123 (57 – 218)	80	65% Within estimated range	-43 MW
12/03/21	SA	72 (49 – 103)	113	157% Marginally above estimated range	+41 MW

- Table 35 shows the performance of the CMLD load model. Cells in green are cases where the CMLD load model is accurate within 15% of the actual CMLD load loss, cells in yellow are cases where the CMLD load loss is within 10% of the estimated range, and cells in orange are cases where the CMLD load loss is outside the estimated range.

Table 35: CMLD load model performance for voltage disturbances

Case	State	Actual CMLD load loss (estimated range) (MW)	PSCAD™/EMTDC™ model CMLD load loss (MW)	CMLD load model percentage of observed	CMLD load model difference
17/04/19	SA	127 (110 – 132)	93	73% Outside estimated range	-34 MW
22/02/21	QLD	533 (420 – 584)	418	78% Marginally below estimated range	-115 MW
03/03/17	SA	409 (312 – 681)	300	73% Within estimated range	-109 MW
18/01/18	VIC	629 (507 – 851)	398	63% Outside estimated range	-231 MW
12/03/21	SA	168 (91 – 199)	188	112% Within estimated range	+20 MW

- Figure 78 shows the model performance considering the change in CMLD, DER, and overall operating demand (OD) for voltage disturbances. The bars represent the PSCAD™/EMTDC™ model performance (blue bars for CMLD loss, yellow bars for DER loss, and orange bars for operational demand change), the red markers represent SCADA/Solar Analytics data (target values), and the **black** lines represent the error bars (estimated range).

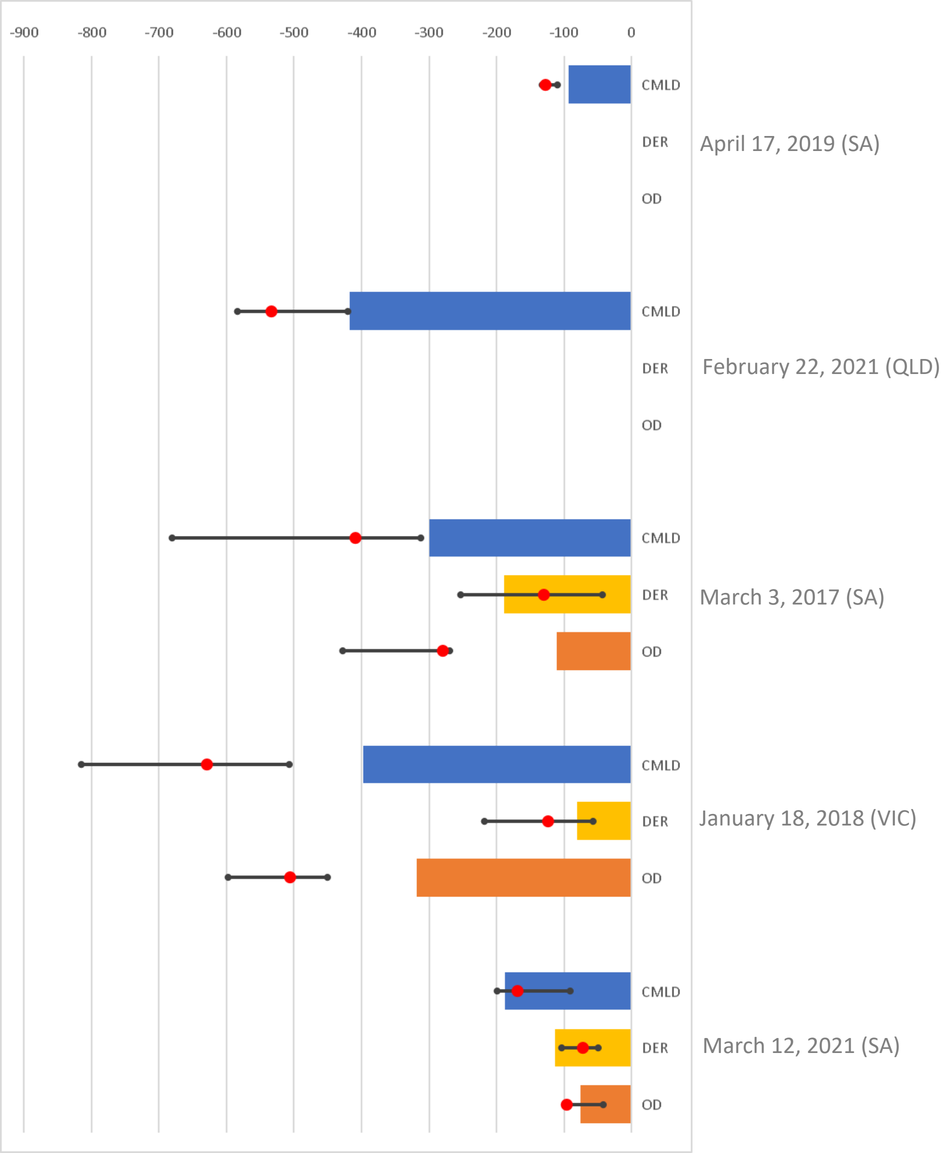


Figure 78: Voltage disturbances: model performance for load/DER loss (MW change)

- The change in CMLD is underestimated in the PSCAD™/EMTDC™ model for all cases except for the March 12, 2021 case. However, excluding the January 18, 2018 and April 17, 2019 cases, the change in CMLD load falls inside or just outside the estimated range.

- Excluding the January 18, 2018 case, the change in DER is overestimated in the PSCAD™/EMTDC™ model. However, the change in DER is inside or just outside the estimated range for all cases.

- Operating demand is underestimated in all cases. Only in the March 12, 2021 case does the operating demand fall in the estimated range.

In addition, the following observations and recommendations are made.

- Without DER/CMLD models, PSCAD™/EMTDC™ and PSS®E result does not match with HSM data for March 3, 2017 case. Post-contingency system is stable as shown by the HSM data. However, without DER/CMLD models, both PSCAD™/EMTDC™ and PSS®E simulation platforms show the post-contingency system cannot maintain stability.

- It Existing angle tripping parameters results deviate the simulation results from the HSM data. It is recommended to disable DER model phase angle tripping until the parameters are updated.

(B) **Frequency disturbances**

PSCAD™/EMTDC™ models were developed for the two "frequency disturbance" cases (August 25, 2018 and January 31, 2020). Before adding DER and CMLD models, the frequency observed throughout the system during and after the fault significantly differed between the PSS®E and PSCAD™/EMTDC™ models. After further investigation, it was found that the modeling of governors between the two software platforms was very different. After discussions with AEMO, the model validation for these two frequency disturbances were not performed due to the significant difference in governor modeling.

9 Future improvements

The following future developments have been identified to improve the performance and simulation speed.

(1) The feeder transformer in the CMLD model does not have an onload tap changer controls built into the model. Onload tap changer controls may be required for extended-term simulations.

(2) The CMLD model uses a single time step delay transmission line model as a variable scaling component in each of the three 3-phase induction motors. Variable scaling components are used to scale the motor component during the simulation to reflect the load shedding. The single time step delay transmission line model could introduce artificial reactive power injection at the terminals of the induction motors. Suitable tuning of parameters listed in 'advance settings' is required to minimize the artificial reactive power injection. By replacing the single time step delay transmission line model with a 'variable scaling component[9]', these slip calculation errors could be eliminated.

(3) The CMLD model has several components: three 3-phase induction motors (motors A, B, and C), a single-phase induction motor (motor D), an electrical load, a fixed load, and a feeder network including a step-down transformer and fixed shunt reactive power compensation. These components can be black boxed, as shown in Figure 79.

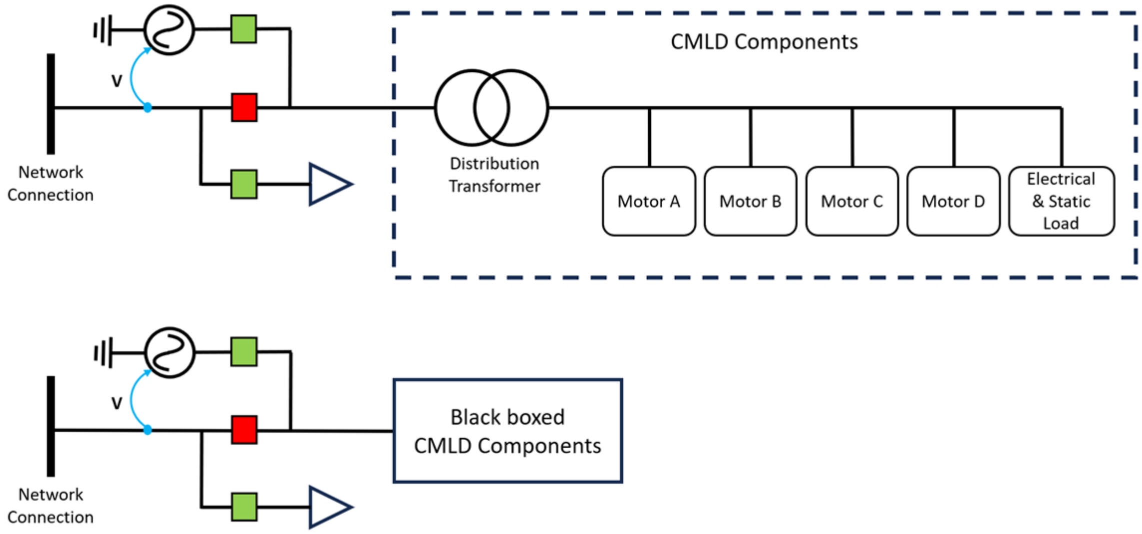


Figure 79: CMLD model black boxed components

Using the black boxed component, a switch will be incorporated in the model, allowing the user to select between existing exponential load model or the detailed CMLD model. This will allow the user to exclude CMLD models in situations where they are not required.

---

[9] A variable current scaling component may be included in a future release of PSCAD™/EMTDC™.

(4) Using the black boxed component, it will be possible to disable specific components of the CMLD model. Using the current CMLD model, all CMLD components are considered in the simulation, even if the parameters indicate they are not used to model the load. In the January 18, 2018 case (VIC), the zone 183 CMLD model uses only motor A, electronic load and static load components (the portions for motor B, C and D are set to 0%), as shown in Table 36.

Table 36: CMLD 183 (January 18, 2018 case) - load fractions

Component	Fraction
Motor A	10 %
Motor B	0 %
Motor C	0 %
Motor D	0 %
Electrical Load	15 %
Static Load	75 %

The black boxed component will be configured to allow for specific components of the CMLD model to be disabled (i.e. motors B, C and D) or enabled (i.e. motor A, Electrical and static loads) so that components that are not used to model the specific CMLD load are excluded in computations. This will decrease the computational burden of the simulation.

(5) Currently, some of the CMLD model components are modeled as time varying impedances and included as part of the G-Matrix. Thus, changes in the CMLD load will require modifications to the G-matrix and evaluate the inverse of the G-matrix. This increases the computational burden. If the CMLD model can be suitability simplified and interfaced to EMTDC as a current injection model, then the changes in CMLD load values will no longer result in an inversion of the G-Matrix.

(6) Future updates to the PSCAD™/EMTDC™ platform are expected to decrease the runtime of the AEMO network. The runtimes for the January 18, 2018 case (VIC, which includes both CMLD and DER models) and the February 22, 2021 case (QLD, which only includes CMLD models) are recorded in Table 37. These times are considering a 30 second simulation using PSCAD™/EMTDC™ V4.6.3.

Table 37: January 18, 2018 and February 22, 2021 case runtimes - PSCAD™/EMTDC™ V4.6.3

Model Scenario	Runtime for 30 second simulation [minutes]	
	18/01/18 – VIC, CMLD and DER models	**22/02/21 – QLD, CMLD models only**
No Models	80.5	71.0
All Models	250.6	184.6

The January 18, 2018 case includes both DER and CMLD models and was selected for update to PSCAD™/EMTDC™ V5.0.2. The runtime is re-evaluated in PSCAD™/EMTDC™ V5.0.2 and is presented in Table 38.

Table 38: January 18, 2018 case runtime - PSCAD V5.0.2

Model Scenario	Runtime for 30 second simulation [minutes]
	18/01/18 – VIC, CMLD and DER models
No Models	56.1
All Models	225.2

Table 38 shows that both runtimes with and without the DER and CMLD models are reduced when run in V5.0.2 compared with the V4.6.3 runtimes. Further reductions to the runtime of the AEMO network models will be investigated for future PSCAD™/EMTDC™ updates.

10 References

[1] "PSS®E models for load and distributed PV in the NEM: Model development and validation", AEMO, November 2022.
[2] NEM Mainland PSCAD Model, version 4.6.3, AEMO, April 2021.
[3] "Distributed Energy Resource (DER) PSCAD model User Guide", MHI, January, 2021.
[4] "Composite Load CMLDZNU2 PSCAD model User Guide", MHI, January, 2021.
[5] "Technical Note: Composite Load and Distributed PV Model Validation in PSCAD™/EMTDC™ using SMIB System", MHI, May 30, 2023.

Appendix A Simulation results - August 25, 2018

Frequency plots for the four mainland regions of the NEM are shown in Figure 80, Figure 81, Figure 82 and Figure 83.

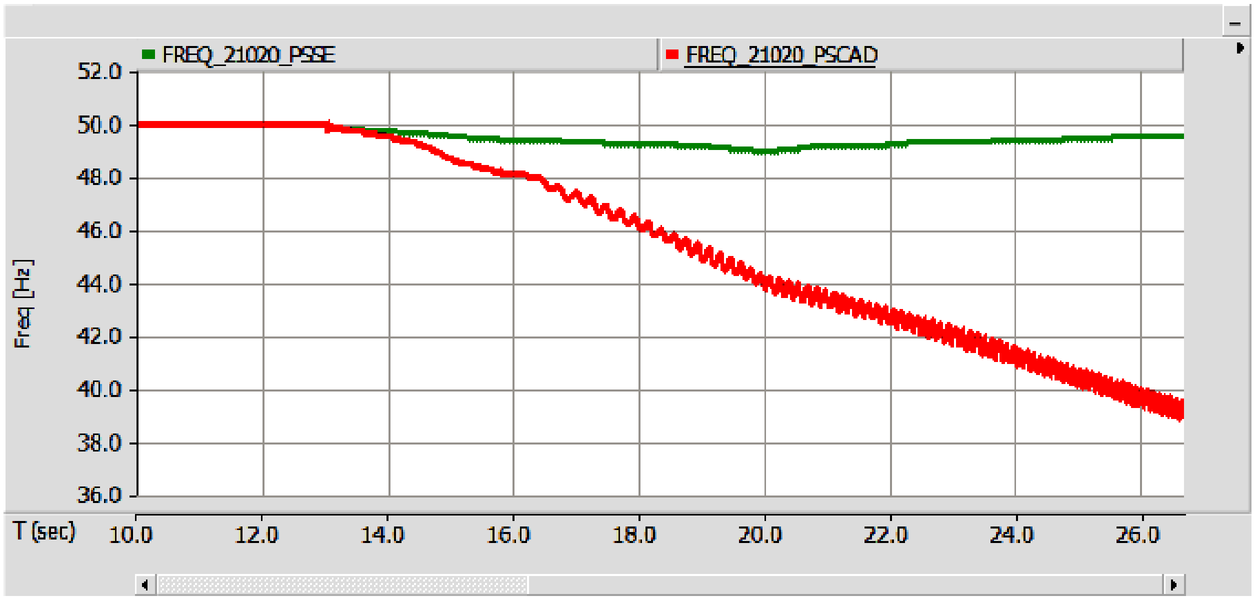


Figure 80: Frequency (NSW) comparison - PSS®E and PSCAD™/ EMTDC™

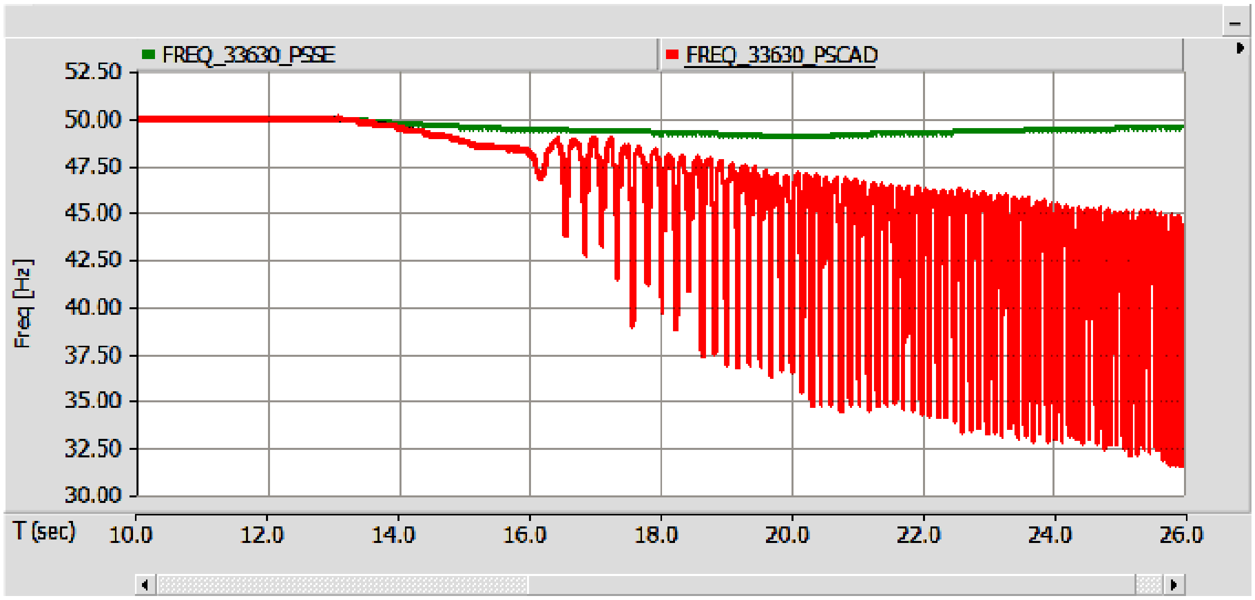


Figure 81: Frequency (VIC) comparison - PSS®E and PSCAD™/EMTDC™

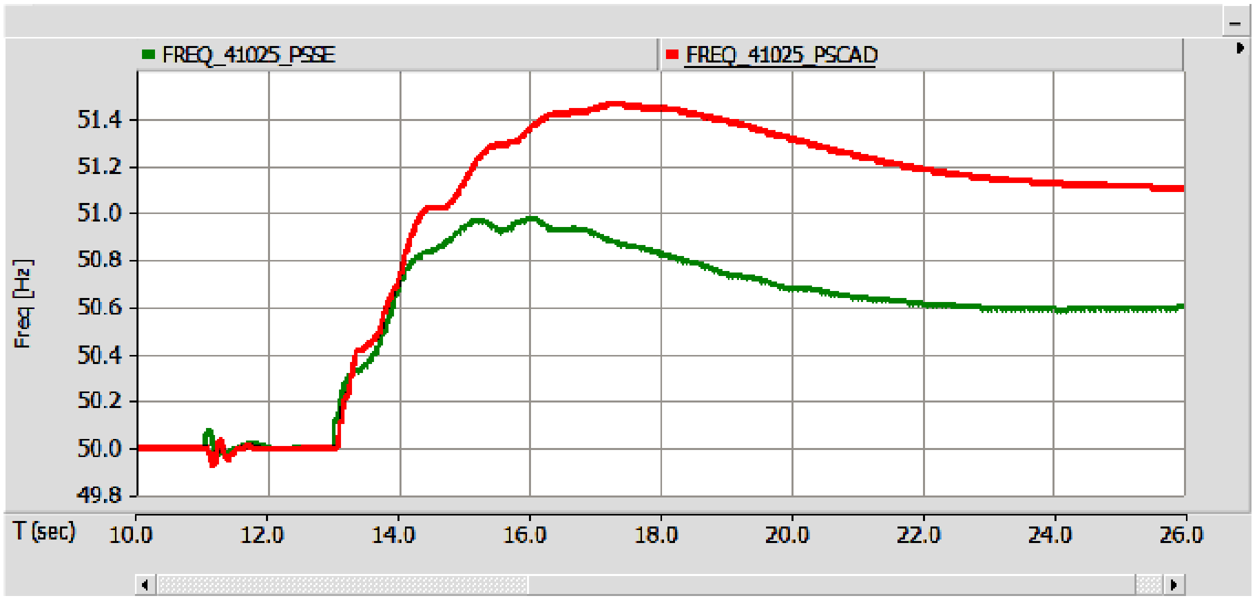


Figure 82: Frequency (QLD) comparison - PSS®E and PSCAD™/EMTDC™

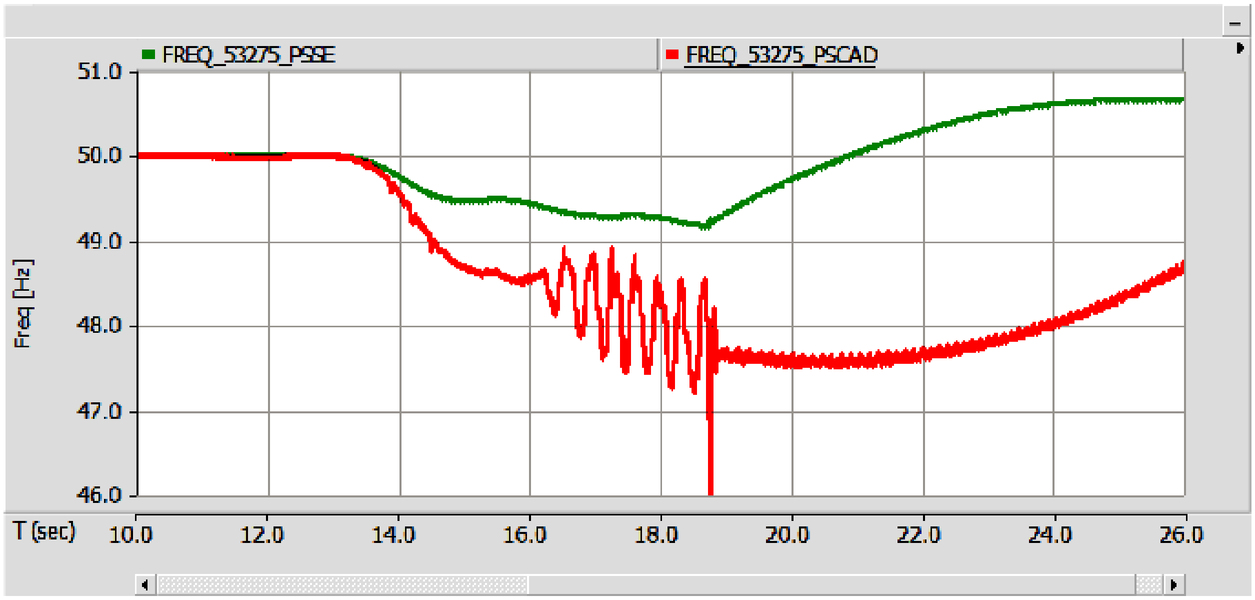


Figure 83: Frequency (SA) comparison - PSS®E and PSCAD™/EMTDC™

Appendix B Simulation results - January 31, 2020

Frequency plots for the two regions in this case (VIC and SA) are shown in Figure 84 and Figure 85.

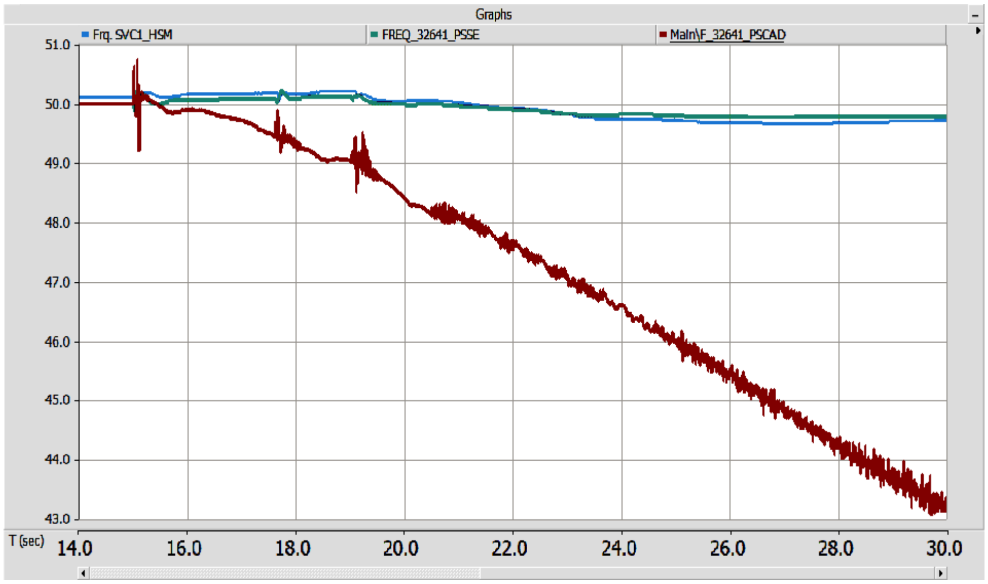


Figure 84: Frequency (Rowville) comparison - HSM, PSS®E and PSCAD™/EMTDC™

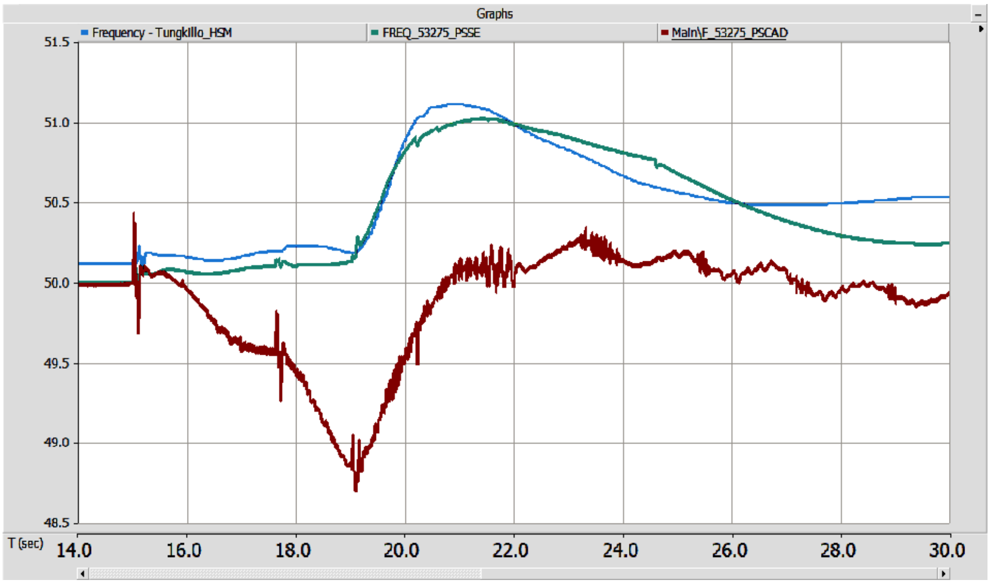


Figure 85: Frequency (Para) comparison - HSM, PSS®E and PSCAD™/EMTDC™

Appendix C Model differences and modifications - August 25, 2018

Table 39 shows the generators that had governor models in PSS®E but did not have governor models in PSCAD™/EMTDC™.

Table 39: Generators with governor models missing only in PSCAD™/EMTDC™

Region	Name	Bus and ID	Rated MVA	PSS®E GOV Model
QLD Central North	Gladstone U1	44071, ID 1	305.6	PSDGOV
	Gladstone U2	44072, ID 2	305.6	PSDGOV
	Gladstone U3	44741, ID 3	305.6	PSDGOV
	Gladstone U4	44742, ID 4	305.6	PSDGOV
	Gladstone U5	44075, ID 5	305.6	PSDGOV
	Gladstone U6	44076, ID 6	305.6	PSDGOV
	Callide B U1	44301, ID 1	391.0	PSDGOV
	Callide B U2	44302, ID 2	391.0	PSDGOV
SA Metro North	Pelican Point U18	50373, ID 18	210.0	PPSGOV
Total			**2825.6**	

Table 40 shows the generators that had governor models in PSCAD™/EMTDC™ but did not have governor models in PSS®E.

Table 40: Generators with governor models missing only in PSS®E

Region	Name	Bus and ID	Rated MVA	PSCAD™/EMTDC™ GOV Model
QLD Central South West	Kogan Creek	42521, ID 1	904.0	KOGOV
NSW North	Baywater U3	20103, ID 3	776.0	Toshiba GOV
	Baywater U4	20104, ID 4	776.0	Power Control
NSW Central	Mt Piper U1	20511, ID 1	776.0	Power Control
NSW South	Tumut 2 U7	20847, ID 7	90.8	T2 GOV
	Tumut 2 U8	20848, ID 8	90.8	T2 GOV
VIC South East	Loy Yang A U1	30441, ID 1	664.0	Gov Loy Yang A1, A3, A4
	Loy Yang A U2	30442, ID 2	588.0	Simple
	Loy Yang A U4	30444, ID 4	686.7	Gov Loy Yang A1, A3, A4
	Loy Yang B U1	30445, ID 1	592.0	Gov Loy Yang B1
	Loy Yang B U2	30446, ID 2	592.0	Gov Loy Yang B1
	Yallourn U1	30941, ID 1	434.0	Gov Loy Yang A1, A3, A4 (Bypassed)
	Yallourn U3	30943, ID 3	441.0	Gov Loy Yang A1, A3, A4
	Yallourn U4	30944, ID 4	441.0	Gov Loy Yang A1, A3, A4
Total			**7852.3**	

Table 41 shows the generators that had matching governor models between PSCAD™/EMTDC™ and PSS®E.

Table 41: Generators with matched governor models between PSS®E and PSCAD™/EMTDC™

Region	Name	Bus and ID	Rated MVA	PSSE GOV Model	PSCAD GOV Model
QLD Central South West	Tarong U1	44271, ID 1	391.0	TARGOV	Hitachi TARGOV Tarong
	Tarong U2	44272, ID 2	391.0	HITGOV	Hitachi TARGOV Tarong
	Tarong U3	44273, ID 3	391.0	HITGOV	Hitachi TARGOV Tarong
	Stanwell U1	46331, ID 1	391.0	PSDGOV	STAGOV
	Stanwell U2	46332, ID 2	391.0	STAGOV	STAGOV
	Stanwell U3	46333, ID 3	430.0	STAGOV	STAGOV
NSW Central	Eraring U1	20021, ID 1	776.0	ERRGOV	ESTGOV
	Eraring U2	20022, ID 2	833.0	ERRGOV	ESTGOV
	Eraring U3	20023, ID 3	833.0	ERRGOV	ESTGOV
	Eraring U4	20024, ID 4	833.0	ERRGOV	ESTGOV
NSW South	Tumut 1 U1	20841, ID 1	101.0	SHLT1GOVSTDW	T2 Gov
	Tumut 1 U4	20844, ID 4	101.0	SHLGOVSTD	T1 Gov
	Tumut 2 U5	20845, ID 5	90.8	SHLT1GOVSTDW	T2 Gov
SA Metro North	Pelican Point U11	50371, ID 11	210.0	PPGGOV2	GGov1
	Pelican Point U12	50372, ID 12	210.0	PPGGOV2	GGov1
	Torrens Island B U1	50385, ID 1	250.0	TGOV8	TGOV8
	Torrens Island B U2	50386, ID 2	250.0	TGOV8	TGOV8
	Torrens Island B U3	50387, ID 3	250.0	TGOV8	TGOV8
	Torrens Island B U4	50388, ID 4	250.0	TGOV8	TGOV8
	Osborne U1	50391, ID 1	160.0	UGGOV1	GGOV1
Total			**7532.8**		

Table 42: Generators without governor models in PSS®E and PSCAD™/EMTDC™

Region	Name	Bus and ID	Rated MVA	PSSE GOV Model	PSCAD GOV Model
	Tarong North	44541, ID 1	615.0	None	None
	Millmerran U1	49055, ID 1	535.0	None	MMRGOV (Bypassed)
QLD Central North	Yarwun U1	41997, ID 1	225.0	None	None
	Callide C U1	44503, ID 1	586.0	None	None
	Callide C U2	44504, ID 2	586.0	None	None
QLD Far North	Invicta Mill U1	44751, ID 1	46.2	None	None
	Kareeya U1	44761, ID 1	22.5	None	None
	Kareeya U2	44762, ID 2	22.5	None	None
	Kareeya U3	44763, ID 3	22.5	None	None
	Kareeya U4	44764, ID 4	22.5	None	None
	Mt Piper U2	20512, ID 2	776.0	None	None
	Values Point U6	20856, ID 6	776.0	None	None
NSW North	Liddell U2	20412, ID 2	588.0	None	None
	Liddell U4	20414, ID 4	588.0	None	None
	Osborne U2	50392, ID 2	81.0	None	None
Total			**5492.2**		

Table 43 shows the network modifications made in the PSCAD™/EMTDC™ case regarding detailed generator models.

Table 43: Network modifications – detailed model related

Region	Description
QLD - Far North	Mt. Emerald model (45845) switched off, represented as a small negative load in PSSE
SA - North	Hornsdale WF3 model (50213/53210) switched off, the dispatch of the remaining Hornsdale units was increased to compensate
NSW - Broken Hill	Silverton model (23040) switched off, nearby loads reduced to compensate
QLD - Central North	Switched off Whitsunday model (47841) and increased nearby Hamilton (44295) to compensate (not required in V5.0.2 model)
QLD - Far North	Switched off Sun Metal Model (41407), reduced nearby loads to compensate (not required in V5.0.2 model)

Table 44 shows the network modifications made in the PSCAD™/EMTDC™ case regarding generator models.

Table 44: Network modifications – generator modifications

Region	Description
QLD - Central South West	Switch off two generators that do not have generator models (41005, ID 3/41007, ID 2), nearby loads (42170, ID 1/42340, ID 1) switched off to compensate
QLD - Far North	Kareeya Unit 5 (44765) switched off because there is no generator model, Kareeya units 1-4 increased to compensate
	Negative load at 2307 (-8.8 MW) switched off, nearby load (43190) was reduced to compensate
QLD - South East	Negative load at 1308 (-13.7 MW) switched off, nearby loads (41080, 43325, 47900) were reduced to compensate
	Negative load at 28931 (-24.4 MW) switched off, nearby loads (23936, 25963, 28962) were reduced to compensate
	switched off small negative loads in QLD - South East (<1MW)
QLD - Central North	Negative load at 40725 (-21.3 MW) switched off, nearby loads (40715, 45155) were reduced to compensate
	Source at 40320 (0 MW) replaced with fixed capacitor matching MVAR
NSW - South	Generator at B2BLW (20375) [36.1 MW] represented using standard generator model
	Negative load at 1514 (-8.1 MW) switched off, nearby loads (26738) were reduced to compensate
	switched off small negative loads in NSW - South (<1MW)
NSW - Central	Negative load at 2178 (-13.7 MW) switched off, nearby loads (25397) were reduced to compensate
NSW - Lismore	Negative load at 28870 (-3.3 MW) switched off, nearby loads (29980) were reduced to compensate
VIC - South West	switched off small negative loads in VIC - South West (<3MW)
VIC - South East	switched off small negative loads in VIC - South East (<1MW)
SA - Metro North	switched off small negative loads in SA - Metro North (<1MW)

Table 45 shows additional network modifications made in the PSCAD™/EMTDC™ case.

Table 45: Network Modifications – Miscellaneous

Region	Description
QLD - Central South West	Increase the Pmax value of Millerran unit (49055, ID 1) to 450 MW
NSW - Central	Increase the Pmax value of Millerran unit (20023, ID 3) to 700 MW

Appendix D Model differences and modifications - January 31, 2020

Most large generators have models in both PSS®E and PSCAD™/EMTDC™, but some governor models were missing in PSS®E and some governor models were missing in PSCAD™/EMTDC™. Table 46 lists the mismatch capacity of generator models in PSS®E and PSCAD™/EMTDC™.

Table 46: Capacity of mismatched generator governors in PSS®E and PSCAD™/EMTDC™

Governor	Region	PSS®E (MVA)	PSCAD™/EMTDC™ (MVA)
With governor models	SA	2022	1945
	VIC	1030	8298
	SA+VIC	3052	10,243
Without governor models	SA	246	323
	VIC	7856	588
	SA+VIC	8102	911

Some small generators have models in PSS®E but did not have models in PSCAD™/EMTDC™ (shown in Table 47). These generators were represented by generic generator models in PSCAD™/EMTDC™.

Table 47: Generators that have models in PSS®E but did not have models in PSCAD™/EMTDC™

Region	Bus Number	Bus Name	Mbase (MVA)	PSS®E		
				Generator	Exciter	Governor
SA_South	50904	LAD	46.2	GENROU	IEEEX2	-
	50905	LAD	46.2	GENROU	IEEEX2	-
VIC_Metro	30421	LNG	186.0	GENROU	ESST4B	-
	30422	LNG	186.0	GENROU	ESST4B	-
	30841	SOM	49.3	GENROU	ZEXSOM	-
	30842	SOM	62.3	GENROU	ZEXSOM	-
	30843	SOM	43.0	GENROU	ZEXSOM	-
	30844	SOM	43.0	GENROU	ZEXSOM	-
VIC_North	20751	HPS	27.8	GENSAL	SEXS	-
	20691	GPS	42.5	GENSAL	ALSTAV	-
	20692	GPS	42.5	GENSAL	ALSTAV	-
	30861	WKP	34.4	GENSAL	ZUNITP	-
VIC_SouthEast	30524	BAP	48.0	GENROU	ZEXBPS	-
	30525	BAP	48.0	GENROU	ZEXBPS	-

Some generators were modeled as a negative load in PSS®E (shown in Table 48). These generators were represented by generic generator models in PSCAD™/EMTDC™.

Table 48: Generators modeled as a negative load in P®SSE

Region	Bus Number	Bus Name	Mbase (MVA)
SA_MetroNorth	2415 - 2426	Barkers Inlet	263.4

Some small WF, SF and BESS have custom models in PSS®E but did not have models in PSCAD™/EMTDC™ (shown in Table 49). These models were represented by generic WF models in PSCAD™/EMTDC™.

Table 49: WF, SF and BESS which have custom models in PSS®E but do not have models in PSCAD™/EMTDC™

Region	Bus Number	Bus Name	Mbase (MVA)
VIC_SouthWest	30141	YAL	28.7
	38563	OAK	7.5
	30560	OAK	48.3
	30531	MTN	20.7
	30595	CNN	45.1
	30596	CNS	59.5
	30593	CBW	22.6
	30599	CWG	20.5
	30031	BUA	N/A
	30032	BUA	N/A
Vic_SouthEast	36393	BHW	59.5
	36395	BHW	47.2

A comparison of generators with different governor models is shown in Table 50.

Table 50: Different governor models in PSS®E and PSCAD™/EMTDC™

Region	Bus Name	PSS®E	PSCAD™/EMTDC™
SA_MetroNorth	5PEL_G11 15.750	PPGOV2	GGOV1
	5PEL_G12 15.750	PPGOV2	GGOV1
	5PEL_G18 15.750	PPSGOV	-
	5QPS_G2 11.000	QUARGOV	-
	5QPS_G25 15.000	-	GGOV1
VIOC_SouthWest	3MRT_G1 20.000	SGT502	GGOV1
	3MRT_G2 20.000	SGT502	GGOV1
VIC_North	3MK_B_G1 13.800	WEHGOV	Eildon Gov
	3MK_B_G2 13.800	WEHGOV	Eildon Gov
	3DPS_G1 15.500	-	DPD Gov+Turbine Waterway
	3MUR_G11 17.000	-	MURGov1

Region	Bus Name	PSS®E	PSCAD™/EMTDC™
	3MUR_G12 17.000	-	MURGov1
	3MUR_G14 17.000	-	MURGov1
	3MUR_G10 15.000	-	T1 Gov
	3MUR_G1 15.000	-	T1 Gov
	3MUR_G2 15.000	-	T1 Gov
	3MUR_G3 15.000	-	T1 Gov
	3MUR_G4 15.000	-	T1 Gov
	3MUR_G5 15.000	-	T1 Gov
	3MUR_G6 15.000	-	T1 Gov
	3MUR_G7 15.000	-	T1 Gov
	3MUR_G8 15.000	-	T1 Gov
	3MUR_G9 15.000	-	T1 Gov
	3MKP_G1 11.500	-	MKPS Hydro Gov + Hydro Tur 1
	3MKP_G1 11.500	-	MKPS Hydro Gov + Hydro Tur 1
	3MKP_G1 11.500	-	MKPS Hydro Gov + Hydro Tur 1
	3MKP_G1 11.500	-	MKPS Hydro Gov + Hydro Tur 1
	3MKP_G1 11.500	-	MKPS Hydro Gov + Hydro Tur 1
	3MKP_G1 11.500	-	MKPS Hydro Gov + Hydro Tur 1
	3LYA_G1 21.000	-	GOV Loy YANG A1, A3, A4
	3LYA_G3 21.000	-	GOV Loy YANG A1, A3, A4
	3LYA_G4 21.000	-	GOV Loy YANG A1, A3, A4
	3LYB_G1 20.000	-	GOV Loy Yang B1
	3LYB_G2 20.000	-	GOV Loy Yang B1
	3YPS_G1 20.000	-	GOV Loy YANG A1, A3, A4
	3YPS_G2 20.000	-	GOV Loy YANG A1, A3, A4
	3YPS_G3 20.000	-	GOV Loy YANG A1, A3, A4
	3YPS_G4 20.000	-	GOV Loy YANG A1, A3, A4
VIC_Metro	3NEW_G1 24.000	-	Newport Gov Alstom

Appendix E QLD loads modeled based on contours

Table 51 shows the CMLD buses voltage dip for the February 22, 2021 case.

Table 51: CMLD buses voltage dip

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
South East	403030	4ASHWST__33A33.000	1	40	53.4	3.1	80	100-80%
	407830	4LOCROS__33A33.000	1	40	42.8	9.5	81	100-80%
	408020	4REDBPL__11A11.000	1	40	10.8	1.2	80	100-80%
	408631	4RACEVW__33B33.000	1	40	67.4	11.6	80	100-80%
	413630	4ABERMA__33A33.000	1	40	53.3	12.2	82	100-80%
	437040	4KELVIN_110A110.00	1	49	6.0	-2.7	81	100-80%
	441640	4ROKLEA_110A110.00	1	49	33.3	7.4	81	100-80%
	443832	4GOODNA__33C33.000	1	40	97.4	4.6	80	100-80%
	449041	4QR_WUL_110B110.00	1	49	6.7	-1.0	82	100-80%
	479630	4STAFRD__33A33.000	1	40	109.3	15.2	80	100-80%
	408021	4REDBPL__11B11.000	2	40	7.1	0.7	80	100-80%
	414242	4NEWTEN_110C110.00	2	40	1.8	-2.3	81	100-80%
	413633	4ABERMA__33D33.000	3	40	13.8	3.0	82	100-80%
	402430	4RUNCRN__33A33.000	1	40	51.9	3.8	79	80-70%
	407330	4_DOBOY__33A33.000	1	40	97.8	18.1	76	80-70%
	407520	4NERANG__11A11.000	1	40	18.3	1.1	75	80-70%
	408121	4CADESC__11B11.000	1	40	21.8	1.2	73	80-70%
	410840	4BEENLH_110A110.00	1	40	23.3	2.4	78	80-70%
	412840	4ROBINA_110A110.00	1	40	6.1	-6.2	77	80-70%
	416020	4SUMNER__11A11.000	1	40	12.8	0.3	79	80-70%
	416130	4ALGEST__33A33.000	1	40	55.4	11.4	79	80-70%
	416225	4BUNDBA__11F11.000	1	40	12.2	3.3	78	80-70%
	418731	4RICHLD__33B33.000	1	40	87.5	15.8	79	80-70%
	424040	4YATALA_110A110.00	1	49	34.0	10.4	78	80-70%
	435040	4GRIFIN_110A110.00	1	49	46.7	5.4	79	80-70%
	440030	4MOLDNR__33A33.000	1	40	89.8	11.5	77	80-70%
	440430	4MUDGRB__33A33.000	1	40	14.6	0.9	77	80-70%
	442240	4LGNLEA_110A110.00	1	40	74.8	11.9	79	80-70%
	447030	4MYRTLE__33A33.000	1	40	20.0	3.8	79	80-70%
	453020	4NSPRNG__11A11.000	1	40	9.0	1.3	78	80-70%
	469041	4VRSITY_110B110.00	1	49	11.2	1.3	77	80-70%
	470220	4MAKERS__11A11.000	1	40	33.2	6.8	79	80-70%
	476121	4_ANNST__11B11.000	1	40	7.8	15.1	78	80-70%
	476320	4BRDBCH__11A11.000	1	40	16.4	-0.1	75	80-70%
	476730	4BRENDL__33A33.000	1	40	128.8	25.1	78	80-70%

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
	476830	4BROWNS__33A33.000	1	40	79.7	16.3	77	80-70%
	476920	4BURLEE__11A11.000	1	40	20.2	2.6	75	80-70%
	477120	4CHRLOT__11A11.000	1	40	21.4	3.1	77	80-70%
	477230	4CLVLND__33A33.000	1	40	117.5	12.8	77	80-70%
	477330	4COOMRA__33A33.000	1	40	72.3	4.2	76	80-70%
	477730	4HAYSIN__33A33.000	1	40	113.1	9.3	77	80-70%
	477830	4__IBIS__33A33.000	1	40	1.3	-2.0	78	80-70%
	478421	4MCLACS__11B11.000	1	40	19.8	2.4	76	80-70%
	478530	4MEANDH__33A33.000	1	40	25.9	8.1	78	80-70%
	478640	4_SSMMC_110A110.00	1	49	20.9	0.9	77	80-70%
	478720	4MILTON__11A11.000	1	40	9.5	1.4	79	80-70%
	478945	4NEWSTD_110F110.00	1	49	5.6	-1.5	79	80-70%
	479230	4NUDGEE__33A33.000	1	40	118.0	9.7	77	80-70%
	479321	4STHPRT__11B11.000	1	40	15.3	1.6	76	80-70%
	479531	4SANDGT__33B33.000	1	40	63.8	8.6	78	80-70%
	479920	4SURFPD__11A11.000	1	40	12.3	2.5	76	80-70%
	480142	4VICPRK_110C110.00	1	40	26.1	1.4	79	80-70%
	480330	4BELMON__33A33.000	1	40	86.0	7.1	78	80-70%
	480421	4WSTEND__11B11.000	1	40	20.1	4.6	79	80-70%
	480621	4WELGRD__11B11.000	1	40	19.7	2.8	75	80-70%
	407523	4NERANG__11D11.000	2	40	17.8	2.3	75	80-70%
	412821	4ROBINA__11B11.000	2	40	11.0	3.8	76	80-70%
	416021	4SUMNER__11B11.000	2	40	13.5	0.9	79	80-70%
	453023	4NSPRNG__11D11.000	2	40	6.8	1.7	76	80-70%
	469040	4VRSITY_110A110.00	2	49	11.1	2.0	77	80-70%
	476321	4BRDBCH__11B11.000	2	40	14.7	3.9	76	80-70%
	476921	4BURLEE__11B11.000	2	40	18.2	2.1	75	80-70%
	478721	4MILTON__11B11.000	2	40	13.9	-1.6	79	80-70%
	479320	4STHPRT__11A11.000	2	40	18.1	2.6	75	80-70%
	479921	4SURFPD__11B11.000	2	40	14.9	3.0	76	80-70%
	480420	4WSTEND__11A11.000	2	40	25.3	2.3	78	80-70%
	408120	4CADESC__11A11.000	3	40	17.8	0.1	74	80-70%
	414230	4NEWTEN__33A33.000	3	40	132.3	19.0	79	80-70%
	416224	4BUNDBA__11E11.000	3	40	12.2	3.3	78	80-70%
	442230	4LGNLEA__33A33.000	3	40	71.5	20.3	78	80-70%
	453021	4NSPRNG__11B11.000	3	40	6.8	1.7	76	80-70%
	476930	4BURLEE__33A33.000	3	40	72.6	7.8	76	80-70%
	478130	4LYTTBS__33A33.000	3	40	54.9	5.0	78	80-70%
	478420	4MCLACS__11A11.000	3	40	15.4	2.1	77	80-70%
	479322	4STHPRT__11C11.000	3	40	15.6	2.4	76	80-70%
	480130	4VICPRK__33A33.000	3	40	33.6	2.6	79	80-70%

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
	480620	4WELGRD__11A11.000	3	40	22.7	4.0	75	80-70%
	410831	4BEENLH__33B33.000	4	40	85.5	8.3	77	80-70%
	412820	4ROBINA__11A11.000	4	40	11.0	3.8	76	80-70%
	440021	4MOLDNR__11B11.000	4	40	28.7	3.6	72	80-70%
	453022	4NSPRNG__11C11.000	4	40	9.0	1.3	78	80-70%
	476120	4_ANNST__11A11.000	4	40	11.2	15.0	78	80-70%
	477121	4CHRLOT__11B11.000	4	40	20.8	2.8	77	80-70%
	479922	4SURFPD__11C11.000	4	40	10.2	7.6	76	80-70%
	478134	4LYTTBS__33E33.000	5	40	38.8	3.7	77	80-70%
	401030	4YRNLEA__33A33.000	1	40	13.5	2.2	51	70-50%
	402930	4POSTRG__33A33.000	1	40	11.5	0.0	51	70-50%
	404343	4SOUTHT_110D110.00	1	40	8.2	-2.3	51	70-50%
	405830	4WARWCK__33A33.000	1	40	15.4	1.4	51	70-50%
	406030	4STNTHP__33A33.000	1	40	8.3	-3.2	52	70-50%
	411641	4TORING_110A110.00	1	49	28.3	2.0	51	70-50%
	416720	4KERNEY__11A11.000	1	40	12.3	2.9	51	70-50%
	418931	4OAKEYT__33B33.000	1	40	15.1	3.6	50	70-50%
	445501	4SWNEPS___G121.000	1	44	13.5	0.0	57	70-50%
	477430	4GATOBS__33A33.000	1	40	20.4	3.6	51	70-50%
	405231	4SLADVA__33A33.000	2	98	4.3	0.9	51	70-50%
	411642	4TORING_110B110.00	2	49	27.4	3.3	51	70-50%
	404330	4SOUTHT__33A33.000	3	40	33.5	0.4	51	70-50%
	400231	4_DALBY__33B33.000	1	40	17.6	7.1	46	50-30%
Central South West	476631	4BEERWH__33B33.000	1	40	32.7	3.6	72	80-70%
	401134	4CABLTR__33E33.000	2	40	100.5	12.4	73	80-70%
	400830	4GYMPIE__33A33.000	1	40	43.5	6.8	58	70-50%
	401230	4KILKVN__66A66.000	1	49	11.4	2.3	55	70-50%
	401330	4CHINCL__33A33.000	1	40	12.4	0.4	52	70-50%
	401630	4NAMBOR__33A33.000	1	40	47.9	-5.1	66	70-50%
	403340	4_SSCOR_132A132.00	1	49	2.7	-0.9	63	70-50%
	407040	4COOROY_132A132.00	1	49	73.7	6.7	64	70-50%
	440940	4PALMWD_132A132.00	1	49	164.3	10.8	68	70-50%
	441831	4TARONG__66B66.000	1	49	4.2	3.7	52	70-50%
	441832	4TARONG__66C66.000	2	49	6.3	3.4	52	70-50%
	400820	4GYMPIE__11A11.000	3	40	9.4	1.4	58	70-50%
	441833	4TARONG__66D66.000	3	49	15.3	1.3	52	70-50%
	400821	4GYMPIE__11B11.000	4	40	8.9	0.9	58	70-50%
	441830	4TARONG__66A66.000	4	49	8.7	1.1	52	70-50%
	442720	4TRNGPS___6A6.6000	12	40	6.5	6.3	52	70-50%
	405930	4MARYBH__66A66.000	1	49	26.3	6.2	43	50-30%
	413130	4__ISIS__66A66.000	1	49	35.5	1.4	39	50-30%

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
	413231	4ISISRV__66B66.000	1	1	6.8	0.4	38	50-30%
	416640	4GRANIT_132A132.00	1	49	3.9	2.0	37	50-30%
	442380	4_HALYS_275A275.00	1	49	8.0	2.7	48	50-30%
	442701	4TRNGPS___G120.000	1	40	27.6	14.1	35	50-30%
	445401	4TARNOR___G120.500	1	44	32.7	17.5	32	50-30%
	447546	4KUMBAR_132G132.00	1	224	150.9	19.7	31	50-30%
	460340	4BULICR_132A132.00	1	49	13.9	-8.4	30	50-30%
	466530	4TORQUY__66A66.000	1	1	23.7	0.3	43	50-30%
	470030	4PIALBA__66A66.000	1	1	31.0	0.8	43	50-30%
	402030	4BUNDBG__66A66.000	2	49	89.3	4.0	40	50-30%
	442702	4TRNGPS___G220.000	2	40	27.7	14.0	35	50-30%
	442703	4TRNGPS___G320.000	3	40	25.2	19.6	35	50-30%
	442704	4TRNGPS___G420.000	4	40	25.3	19.6	35	50-30%
	408241	4EUROMB_132B132.00	1	224	43.1	12.0	28	30-20%
	416440	4CONDAB_132A132.00	1	224	29.5	5.2	26	30-20%
	419440	4COLMBA_132A132.00	1	49	10.3	0.2	26	30-20%
	421740	4CONDBR_132A132.00	1	224	47.8	7.7	26	30-20%
	421840	4COND_S_132A132.00	1	224	44.0	7.7	26	30-20%
	421941	4WOLEBE_132B132.00	1	224	135.3	9.7	28	30-20%
	422440	4DINOUN_132A132.00	1	49	65.7	10.2	28	30-20%
	422540	4CLIFOR_132A132.00	1	49	45.2	5.6	28	30-20%
	422741	4FVWTEE_132B132.00	1	224	10.9	4.4	28	30-20%
	423440	4BELVUW_132A132.00	1	224	52.2	15.0	26	30-20%
	428240	4BLYTHD_132A132.00	1	49	43.3	8.4	28	30-20%
	448142	4__FVWS_132C132.00	1	224	26.5	7.7	28	30-20%
	448320	4APLING__22A22.000	1	224	21.1	-0.5	29	30-20%
	460501	4MILMER___G119.000	1	44	26.6	19.4	24	30-20%
	444721	4BRAEPS__15B15.750	2	44	2.0	1.0	22	30-20%
	448321	4APLING__22B22.000	2	224	21.0	-3.4	29	30-20%
	460502	4MILMER___G219.000	2	44	27.2	19.8	24	30-20%
	408308	4ROMAPS___G810.500	8	44	1.3	0.0	28	30-20%
	408440	4__ROMA_132A132.00	10	224	38.4	-7.2	27	30-20%
	444801	4BRM2PS___G115.750	1	44	2.0	0.9	18	20-10%
	445222	4KOGNCK__21B21.000	1	44	61.4	14.5	18	20-10%
	447105	4DDWNPS__G1A15.000	1	44	5.0	0.0	18	20-10%
	444802	4BRM2PS___G215.750	2	44	2.0	0.8	18	20-10%
	447106	4DDWNPS__G2A15.000	2	44	4.9	0.0	17	20-10%
	447107	4DDWNPS__G3A15.000	3	44	4.9	0.0	18	20-10%
Central North	401930	4GLDSTH__66A66.000	1	49	30.0	10.8	15	20-10%
	402120	4QLDALU__11A11.000	1	104	46.0	35.6	15	20-10%
	402330	4ROCKHA__66A66.000	1	49	70.8	11.0	10	20-10%

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
	402630	4BILOEL__66A66.000	1	49	28.0	-2.6	12	20-10%
	402730	4_MOURA__66A66.000	1	154	52.4	15.5	10	20-10%
	406130	4PNDOIN__66A66.000	1	49	32.8	-0.3	10	20-10%
	407430	4GLDNTH__66A66.000	1	49	25.9	-5.1	15	20-10%
	412730	4EGANHL__66A66.000	1	49	44.5	1.8	10	20-10%
	413030	4BOATCK__66A66.000	1	114	29.5	6.5	12	20-10%
	415320	4QALUMN__11A11.000	1	40	29.1	10.7	15	20-10%
	422240	4WIGIGS_132A132.00	1	49	4.2	-0.9	15	20-10%
	440840	4_BOYNE_132A132.00	1	194	434.8	250.7	16	20-10%
	442442	4CALVLE_132D132.00	1	1	2.8	-0.2	12	20-10%
	447380	4RAGLAN_275A275.00	1	49	1.3	-3.1	14	20-10%
	478201	4GLADPS___G115.750	1	44	13.2	9.9	11	20-10%
	419940	4_YARWN_132A132.00	2	114	82.5	17.6	13	20-10%
	440841	4_BOYNE_132B132.00	2	194	413.5	216.9	16	20-10%
	478202	4GLADPS___G215.750	2	44	14.2	8.3	11	20-10%
	478204	4GLADPS___G415.750	4	44	13.5	9.5	10	20-10%
	478205	4GLADPS___G515.750	5	44	13.1	10.2	11	20-10%
	478206	4GLADPS___G615.750	6	44	13.0	10.2	11	20-10%
	400730	4__MDSS__66A66.000	1	98	9.7	-0.9	4	10-0%
	403201	4BLKWTR___S1132.00	1	49	1.9	0.0	3	10-0%
	403430	4MORANB__66A66.000	1	49	19.4	5.9	0	10-0%
	403530	4DYSART__66A66.000	1	49	39.5	9.3	0	10-0%
	403932	4PROSER__66C66.000	1	49	16.9	2.9	1	10-0%
	404201	4DUARNG___S1132.00	1	49	1.2	-1.1	2	10-0%
	406530	4ALLIGC__33A33.000	1	40	34.9	3.2	1	10-0%
	406731	4KEMMIS__66B66.000	1	154	9.8	1.1	2	10-0%
	406930	4NEWLND__66A66.000	1	154	17.0	4.6	1	10-0%
	407130	4CLRMNT__66A66.000	1	49	9.3	8.4	4	10-0%
	407230	4BARCAL__66A66.000	1	49	15.7	-4.2	5	10-0%
	409940	4GRANTL_132A132.00	1	49	18.7	0.0	8	10-0%
	410701	4COPBEL__S1 132.00	1	49	15.2	-6.5	1	10-0%
	411240	4MTMCLR_132A132.00	1	49	2.1	-8.1	-1	10-0%
	414131	4PIONER__66B66.000	1	49	42.1	2.2	2	10-0%
	417630	4LOUISA__33A33.000	1	40	25.8	6.8	1	10-0%
	418140	4BOWENN_132A132.00	1	49	18.1	3.2	1	10-0%
	419840	4BROADL_132A132.00	1	49	35.0	9.1	0	10-0%
	420940	4_BLUFF___S1132.00	1	49	2.2	-1.5	2	10-0%
	421101	4WYCARB___S1132.00	1	49	9.4	0.7	6	10-0%
	421240	4GOONYE_132A132.00	1	154	31.4	16.3	0	10-0%
	422301	4WOTONG___S1132.00	1	49	4.2	-13.7	0	10-0%
	426340	4ROLSTO_132A132.00	1	49	13.7	-2.3	4	10-0%

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
	437531	4EMRALD__66B66.000	1	49	26.2	-2.9	4	10-0%
	441530	4LILYVL__66A66.000	1	154	53.4	52.7	4	10-0%
	443001	4CALLDB___G120.000	1	44	24.3	13.7	8	10-0%
	444120	4STWLAX___6A6.6000	1	40	2.3	-0.6	7	10-0%
	444207	4STWLPS__20C20.000	1	44	22.5	17.1	7	10-0%
	445001	4CALLIC___G119.500	1	44	20.6	21.0	9	10-0%
	403230	4BLKWTR__66A66.000	2	154	79.9	12.6	4	10-0%
	403834	4MACKAY__33E33.000	2	44	60.6	4.2	2	10-0%
	403931	4PROSER__66B66.000	2	49	15.9	2.0	1	10-0%
	406730	4KEMMIS__66A66.000	2	154	6.9	5.3	2	10-0%
	437230	4COLLNS__33A33.000	2	40	14.4	4.4	1	10-0%
	445002	4CALLIC___G219.500	2	44	19.9	21.6	9	10-0%
	444206	4STWLPS__20B20.000	3	44	22.5	17.1	8	10-0%
	444205	4STWLPS__20A20.000	4	44	22.4	17.1	8	10-0%
Far North	404638	4GARBUT__66I66.000	1	49	28.6	9.3	1	10-0%
	404820	4_TULLY__22A22.000	1	40	15.1	-3.4	0	10-0%
	405020	4INNSFL__22A22.000	1	40	18.6	0.8	0	10-0%
	405120	4CAIRNS__22A22.000	1	40	29.6	-1.5	0	10-0%
	405320	4KAMRGA__22A22.000	1	40	34.3	-4.9	0	10-0%
	405401	4BARRON___G111.000	1	44	1.2	0.0	0	10-0%
	405530	4TURKIN__66A66.000	1	49	43.3	-5.5	0	10-0%
	407740	4KIDSTN_132A132.00	1	49	5.0	-0.9	1	10-0%
	409020	4CRNCTY__22A22.000	1	40	28.4	4.9	0	10-0%
	409230	4DNGLSN__66A66.000	1	49	39.9	-3.3	1	10-0%
	409320	4CARNSN__22A22.000	1	40	31.0	11.5	0	10-0%
	409532	4MILCHS__66C66.000	1	49	8.7	3.9	1	10-0%
	412920	4EDMOTN__22A22.000	1	40	28.8	-1.6	0	10-0%
	413420	4CARDWL__22A22.000	1	40	2.4	1.3	0	10-0%
	414030	4TOWNZK__33A33.000	1	184	112.0	36.9	1	10-0%
	414401	4TNVLPS__GT111.000	1	44	5.9	0.0	1	10-0%
	414402	4TNVLPS__ST110.500	1	44	3.0	0.0	1	10-0%
	415020	4ALANSH__11A11.000	1	40	22.5	1.7	1	10-0%
	415932	4LAKLND__66C66.000	1	1	3.9	-0.7	0	10-0%
	417140	4ELARSH_132A132.00	1	49	3.1	-1.4	0	10-0%
	418531	4CAPERV__66B66.000	1	1	3.1	-5.0	1	10-0%
	419333	4CLARST__66D66.000	1	49	11.6	4.7	1	10-0%
	431530	4__HUGH__66A66.000	1	49	9.3	-3.0	2	10-0%
	488430	4AITKEN__66A66.000	1	49	14.0	2.3	1	10-0%
	490340	4CRAGLI_132A132.00	1	49	8.2	-1.1	0	10-0%
	490630	4_BOHLE__66A66.000	1	49	17.2	-0.3	1	10-0%
	490730	4BLACKR__66A66.000	1	49	22.4	6.5	1	10-0%

Area	Bus Number	Bus Name	Id	Zone Num	Pload (MW)	Qload (Mvar)	DIF (%)	Contour Values
	491130	4CRANBK__66A66.000	1	49	12.4	0.3	1	10-0%
	491330	4HERMIT__66A66.000	1	49	16.7	6.8	1	10-0%
	491631	4NEILSM__66B66.000	1	49	4.1	-1.8	1	10-0%
	491730	4RASMSS__66A66.000	1	49	15.1	1.7	1	10-0%
	492130	4TVPORT__66A66.000	1	49	16.0	4.4	1	10-0%
	492731	4STUART__66B66.000	1	49	35.2	6.8	1	10-0%
	495030	4WDSK_T__66A66.000	1	1	4.8	1.4	1	10-0%
	405402	4BARRON___G211.000	2	44	1.2	0.0	0	10-0%
	491630	4NEILSM__66A66.000	2	49	4.1	0.2	1	10-0%