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Review of
AEMO's PSCAD Modelling of the
Power System in South Australia

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Executive Summary

This report reviews AEMO's PSCAD modelling of the power system in South Australia. AEMO has developed an integrated PSCAD model of the SA power system to improve its ability to assess system security with rapidly increasing amounts of non-synchronous generation. The model presently includes synchronous generation, wind farms, and the Battery Energy Storage System (BESS) at Hornsdale, with transmission and distribution networks represented down to the 66 kV level. The model is to be extended to include more accurate aggregated models of loads, distributed energy resources such as rooftop PV generation, and BESS embedded in the distribution system as they will be connected in increasing quantities to the power system.

The review first describes the general issues associated with increasing penetration of non-synchronous generation, and then describes the rationale behind AEMO's development of PSCAD models. The report then describes AEMO's use of the integrated PSCAD model of the SA system to develop a criteria for system strength in SA.

As the reviewer, I have formed the following opinions on AEMO's development of the PSCAD models which are used to assess and maintain power system security in the SA region :

PSCAD Models for Wind Farms

The PSCAD models for the wind farms are sufficiently accurate for assessing the stability of the SA power system. Note that AEMO has assumed that the models are a faithful representation of the actual controls as currently implemented in the physical plant. Whenever changes are made to the originally commissioned controls, the owner of the wind farms will need to provide updates to the models used by AEMO.

Validation of Models for Wind Farms and Synchronous Generators

AEMO has validated the PSCAD models for wind farms and synchronous generators by benchmarking against 'R2' registered data from generator post-connection tests, and previous major system disturbances such as the SA Black System Event of 28 September 2016, and SA-VIC Separation Event of 1 December 2016.

PSC's experience with inverter control systems suggests that benchmarking against R2 tests and the occasional measurements from system disturbances may fail to identify the behaviour of the inverters over the full range of disturbances to which they might be exposed. PSC has observed a tendency amongst some inverter manufacturers to primarily focus on the response to the specific faults tabled in AEMO's 'Dynamic Model Acceptance Guideline', however this approach may not reveal unexpected responses to other disturbances due to the highly non-linear control systems employed in inverters. Given the increasing number of inverter connected non-synchronous generators in SA, I recommend that all PSCAD models of non-synchronous generators are tested thoroughly by all parties for their response to a wider variation in disturbance scenarios which will allow assessment of other possible phenomena such as adverse control interactions between multiple non-synchronous plant.

Models for Protection Relays

AEMO's PSCAD models include accurate representations of protection functions. It will be important to keep these models up to date, when Generators and ElectraNet notify AEMO of any protection changes, specifically any protections that will trip a generator due to external disturbances on the system (such as voltage or frequency fluctuations, or the multiple voltage dip protection associated with the black system event of 28 September 2016).

Integrated PSCAD Model for SA

AEMO's integrated PSCAD model of the SA system is well suited to help develop overall system strength requirements in SA. As the penetration of distributed energy resources increases, it will be important for AEMO to continue to develop detailed load models (particularly in the metro region), and aggregated models for rooftop PV generation and future embedded behind-the-meter BESS.

Criteria for Overall System Strength in SA

AEMO have developed a criteria for overall system strength in SA which is based on a well founded methodology and a detailed and validated PSCAD model of the SA power system. AEMO recognize that work on the SA system strength criteria needs to be extended to cover network outages, islanded conditions when separated from VIC, performance of distance protection relays, and the effect of loads and rooftop PV generation.

1. Introduction

The SA power system is hosting a rapidly increasing amount of non-synchronous generation, mostly in the form of transmission connected wind generation and rooftop photo-voltaic (PV) generation. Both types of non-synchronous generation are connecting to the power system via power electronic converters. This non-synchronous generation is displacing existing synchronous generation, and is changing the fundamental characteristic behaviour of the power system.

AEMO has historically modelled the power system using RMS-type models which have been sufficiently accurate for synchronous generation but are inadequate for modelling large amounts of non-synchronous generation with power electronic converters, particularly when investigating extreme system events where power system operating states could vary significantly. As a result, AEMO has recently improved the accuracy of their modelling by developing a model of the SA power system using a detailed electromagnetic transient (EMT) simulation tool (PSCAD) to represent the instantaneous voltages and currents in the three phase network.

As a quality check on the PSCAD model, AEMO has contracted Ranil de Silva from Power Systems Consultants (PSC) to review the model and the processes to develop the model. This report presents the findings of the review of AEMO's PSCAD model of the SA power system.

2. Scope of Work

PSC's scope of work for reviewing AEMO's PSCAD modelling of the SA power system included:

1) The overall process applied to the PSCAD model development, simulation, and analysis.
2) The development of site specific PSCAD wind farm models based on PSS/E model parameters submitted by proponents and information in AEMO possession (such as Releasable User Guide and data sheets), including :
    a. Waterloo wind farm (Vestas)
    b. Hallett wind farm (Suzlon)
    c. Snowtown 2 wind farm (Siemens)
3) The approach taken for validation of wind farm models using measured data from SA-VIC separation events.
4) The modelling of critical protection relays including the loss of synchronism relay on the Heywood Interconnector, and over-voltage protection on wind farms.
5) The development of system strength requirements in SA.

3. Background to Non-Synchronous Generation in SA

Historically, the power system in SA (and the rest of the world) has been largely supplied by synchronous generators. These generators have provided rotating inertia and 'system strength'. The stored rotational energy associated with the inertia helps to stabilize the system frequency as the load fluctuates. A high system strength provides a stable system voltage in both magnitude and phase. The machine rotors also tend to stay synchronized with other rotors in the system. These characteristics are naturally inherent in synchronous generators, even in the absence of any control system.

Non-synchronous generation such as wind generation and PV generation typically connect to the system via inverters. Unlike synchronous machines, these inverters are entirely dependent on their control systems to deliver power to the system.

The rapidly increasing amount of non-synchronous wind and PV generation in SA is displacing synchronous generation (specifically fossil fuelled synchronous generation which is more expensive to run than PV or wind farms). This non-synchronous generation is based on 'Grid-Following Inverters' (Appendix 2) which rely on a stable grid voltage as a reference to enable stable operation, and typically contribute little to system inertia or system strength. By comparison, 'Grid-Forming Inverters' provide their own voltage reference and are used to create stable system voltages for microgrids, however more development is needed to enable grid-forming inverters to be used in the wider power system.

The displacement of synchronous generation by non-synchronous generation based on grid following inverters is resulting in a gradual decline in the inertia and strength of the SA power system. In turn, the weakening system strength tends to de-stabilize the grid-following inverters. This effectively puts a limit on the amount of grid-following inverters that can be hosted in the SA system without further support from synchronous generators.

4. AEMO Model Development

4.1. The Need for More Accurate Models in SA

AEMO has historically modelled the SA power system, and the rest of the NEM power system, using RMS-type models in the PSS/E power system simulation software. The simplified RMS-type representation of the system allows the models to be run in a reasonable timeframe on the current generation of desktop or laptop computers (a typical simulation run covers several tens of seconds).

The RMS-type models have previously provided a sufficiently accurate representation of the SA system when dominated by synchronous generation, but are inadequate for modelling large amounts of non-synchronous generation with power electronic converters. The inadequacy stems from the fast acting and complex controls used in non-synchronous generation, and the complex behavior of non-synchronous generation when connected to a weak system with poor voltage regulation and distorted voltage waveforms (in contrast, synchronous generation tends to exhibit a much less complex and much more predictable behavior).

Accurate modelling of non-synchronous generation in weak systems requires that the instantaneous voltage and current waveforms in all three phases are represented in the model. AEMO has selected the electromagnetic transient simulation tool PSCAD/EMTDC ('PSCAD') for this purpose. PSCAD has been commonly used by manufacturers, researchers, and utilities for power systems analysis for a number of decades, and has been well validated against real systems.

The primary disadvantage of electromagnetic transient simulation tools compared with RMS-type software is that the detailed modelling representation is associated with a much greater computational burden than the simplified RMS-type model. Consequently, electromagnetic transient simulations have historically been limited to localized parts of the power system, with remote regions represented by simplified equivalents.

4.2. Events Leading to Development of a PSCAD Model for SA

AEMO's development of PSCAD models for the SA power system has been spurred on by a number of recent system events that have highlighted the need for more accurate modelling of the system. Figure 1 shows how a series of system events led to the development of PSCAD models and a set of rule changes and guidelines to help cope with the increasing amount of non-synchronous generation.

On 1 November 2015, the Heywood interconnector tripped resulting in the separation of the SA and VIC systems. Wind generation was very low at the time, and there was no PV generation as the incident took place in the night. AEMO used measurements from this event to assess the accuracy of PSS/E synchronous generator models in SA [1]. AEMO found that the exciter models were accurate but observed significant inaccuracies in the governor models for Northern Power Station (now retired), the gas turbine component of Pelican Point CCGT's, and Torrens Island. The governor models were subsequently modified to improve the accuracy of the PSS/E simulation.

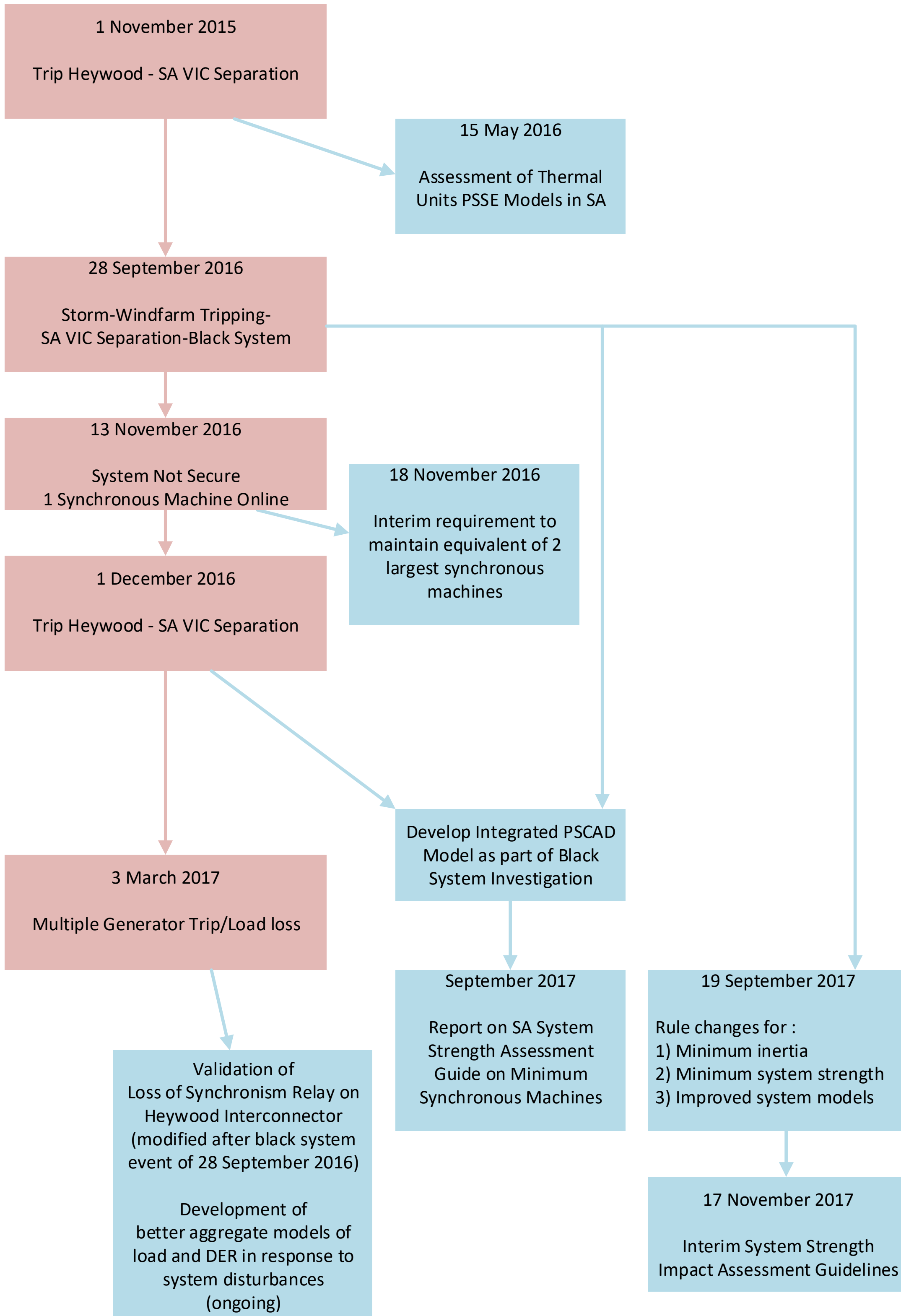
On 28 September 2016, a black system event occurred in SA [2]. Multiple tornadoes in SA tripped multiple 275 kV transmission circuits, and resulted in multiple faults in quick succession. The series of voltage dips from the faults triggered protection on several wind farms to runback about 456 MW of wind generation. The reduction in wind farm output was compensated by an increase in power imported from VIC via the Heywood interconnector, however the Heywood import reached a level that tripped the interconnector on loss of synchronism protection. The net loss of power infeed from the wind farms and import from VIC resulted in the SA frequency falling so fast that load shedding schemes were unable to arrest the fall, resulting in a black system in SA. AEMO began development of the integrated PSCAD model of SA to help analyse the black system event and the investigation report led to a number of recommendations including consideration of the ability of wind farms to ride through faults in weak systems, revision of settings on the Heywood Interconnector Loss of Synchronism protection, incorporation of adequate system strength into planning criteria, and investigation of requirements for the minimum generation dispatch to preserve stability.

On 13 November 2016, a 'system non-secure' event occurred when the SA power system was operating with only one synchronous generator in service [3]. AEMO's analysis suggested that if the sole synchronous generator had tripped then the system strength would have fallen to a level where wind farms might trip, protection might not operate properly, and voltage fluctuations would become excessive. AEMO engineers rapidly conducted PSS/E studies to come up with a rough estimate of the minimum amount of synchronous generation necessary to maintain a secure system. The studies suggested an interim requirement for at least two Torrens Island units (or equivalent) to be online. AEMO recognized that a more definitive requirement would require much more detailed modelling of the system.

On 1 December 2016, the tripping of circuits in VIC connected to the Heywood Interconnector resulted in the separation of the SA and VIC systems [4]. The loss of infeed from VIC resulted in the SA frequency falling until arrested by about 230 MW of load shedding. High speed recorders on synchronous generators and wind farms in SA provided measurements to AEMO engineers which were used to help validate the PSCAD models then under development.

On 3 March 2017, a CVT failure in the Torrens Island 275 kV switchyard resulted in three separate faults which tripped five synchronous generators in Adelaide with a combined generation loss of about 610 MW [5]. Wind farms in SA rode through the event, and the Heywood Interconnector did not trip, suggesting that improvements to wind farm protection and the Heywood Interconnector Loss of Synchronism protection after the 28 September 2016 black system event had been successful. Under-frequency load shedding did not operate, however AEMO observed an initial 400 MW drop in demand in SA, followed by a rapid 150 MW increase. AEMO believes that this 150 MW increase in demand was due to rooftop PV generation disconnecting in response to the faults. AEMO are currently trying to improve their understanding of demand response, and rooftop PV response to system faults in order to develop aggregated models of these type of behind the meter devices, as they could have a significant effect on the behaviour of the overall system.

Figure 1. System Events and Model Development



4.3. Development of Wind Farm Models

AEMO represents wind farms as aggregated collections of turbines to reduce the computational burden associated with modelling individual turbines. High speed recorders are used to verify that the net output of the wind farm during a system fault is reasonably representative of the aggregated behavior of individual turbines. At a minimum, recorders are installed at least at the wind turbine closest to the collector bus, the turbine furthest from the collector bus, and on the main transformer connection to the system.

AEMO's PSCAD wind farm models for SA can presently be classified into four categories :

1) Most wind farms are represented by black-box PSCAD models with detailed representation of vendor-specific control systems. Where necessary, site specific control parameters have been derived by AEMO from proponent supplied PSS/E models, confidential transfer function block diagrams and model source codes, Releasable User Guides, and data sheets in AEMO's possession. This is to ensure that the PSCAD models reflect the most accurate model parameters including any tuning applied to the PSS/E model at the R2 stage. Note that control systems and parameters for the majority of these models are not taken from actual wind turbine control codes. However, AEMO used actual measured responses from these wind farms to ensure they are sufficiently accurate.

   Due to the commercially sensitive nature of black-box PSCAD models, it is a common practice to make a very limited number of control parameters available for changes by the user, with all other model parameters hard-coded in the black-box model, and not visible to the user.

2) Six wind farms using Suzlon S88 turbines are represented by a PSCAD model jointly developed by the Manitoba Hydro Research Centre and AEMO, based on inspection of the PSS/E model code, transfer function block diagram, and other information provided by respective generators. The AMSC 'DVAR' STATCOM's installed at these wind farms are represented by PSCAD models received from AMSC directly. AEMO then re-parameterized control parameters from proponent supplied PSS/E models, Releasable User Guides, and data sheets in AEMO's possession.

3) Five wind farms, Hornsdale Stages 1 to 3, and Snowtown 2 (comprising Snowtown South and North wind farms), all using Siemens wind turbines, are represented by PSCAD site specific black-box models supplied by the respective proponent. The control systems and parameters in the black-box have been taken from the actual wind turbine control code and are therefore

assumed to be a highly accurate representation of the actual generating system.

4) Two wind farms utilizing Type 1 turbines (induction generators without power electronics interface) are currently utilising simplified models. AEMO intends to improve the accuracy of these models if other generation is proposed to connect in their vicinity :
   a. The 30 MW Starfish Hill wind farm is embedded in the distribution network and modelled as a simple high impedance voltage source.
   b. The 91 MW Wattle Point wind farm is modelled by a detailed PSCAD model of Vestas V82 wind turbines, however with generic models of wind farm STATCOMs.

During the course of this review, AEMO engineers demonstrated the process of how AEMO derived site specific parameters for Waterloo wind farm (Vestas turbines) and Snowtown 2 wind farm (Siemens turbines). For both of these wind farms, the PSS/E model parameters had a one-to-one correspondence to the PSCAD model parameters which facilitated the verification of the respective PSCAD models.

Some of the wind farms include AMSC 'DVAR' STATCOM's to provide dynamic voltage support and are represented in PSCAD by a black-box model provided by the manufacturer. The controls in the black box have been taken from the actual STATCOM control code and are therefore a highly accurate representation of the actual generators as confirmed by comparison of measured and simulated response.

In the reviewer's opinion, the PSCAD models for the wind farms are sufficiently accurate for assessing the stability of the SA power system. However, it should be noted that AEMO has assumed that the models will remain a faithful representation of the actual controls after commissioning. It is recommended that whenever changes are made to the controls, the owner of the wind farms will need to provide updates to the models used by AEMO. In addition, the simplified wind turbine models for Starfish Hill, and STATCOM's at Wattle Point, will need to be improved if other generation is proposed to connect in their vicinity. Note that these simplified models have a negligible impact on accuracy of results associated with SA system strength investigations. The requirement for improved information on models is supported by a rule change from the Australian Energy Market Commission [6].

4.4. Validation of Wind Farm and Synchronous Generator Models

AEMO validates models for wind farms and synchronous generators by using test results from initial commissioning or after upgrades, or from measurements made during major system disturbances.

Generator owners provide AEMO with modelling data to allow AEMO to plan and assess the security of the system. 'R1' registered data includes models based on design prior to connection, and 'R2' registered data includes models that have been validated against post-connection system tests.

During this review, AEMO provided examples of R2 model validation tests for:

1) Snowtown Stage 2 wind farm, 90 turbines modelled as 3 aggregated turbines (Voltage reference step change, power factor reference step change, and main transformer tap change).
2) Dry Creek Unit 3 AVR and Governor upgrade (Voltage reference step change, under-excitation limiter test, over-excitation limiter test, and governor speed test).
3) Torrens Island Unit A1 AVR upgrade (Voltage reference step change, under-excitation limiter test, and over-excitation limiter test).

In addition to R2 tests, AEMO requires that all recent and upcoming non-synchronous generation be permanently fitted with high speed recorders to measure their performance during system disturbances. This is further supplemented by high-speed data obtained from numerous locations within the transmission network sourced from network owner, ElectraNet.

1) The SA – VIC separation on 1 November 2015 was used to validate and correct PSS/E models for synchronous generators. AEMO converted these PSS/E models to PSCAD models.
2) The SA black system event on 28 September 2016 was used to validate PSCAD models for wind farms and synchronous generators, and highlighted the lack of modelling protection functions that tripped some wind turbines after multiple system faults.
3) The SA – VIC separation event of 1 December 2016 was used to validate PSCAD models for wind farms and synchronous generators.
4) The SA generator trip event of 3 March 2017 helped to continue validation of PSCAD models for wind farms and synchronous generators, and highlighted the need for improved modelling of loads and rooftop PV generation.

In the reviewer's opinion, AEMO is making good use of R2 test data, and ongoing measurements from system disturbances to validate the PSCAD models for wind farms and synchronous generators.

However, PSC's experience with inverter control systems suggests that benchmarking against R2 tests and the occasional measurements from system disturbances may not identify the behaviour of the inverters over the full range of disturbances to which they might be exposed. PSC has observed a tendency amongst some inverter manufacturers to primarily focus on the response to the specific faults tabled in AEMO's 'Dynamic Model Acceptance Guideline' [7], however this approach may not reveal unexpected responses to other disturbances due to the highly non-linear control systems employed in inverters. Given the increasing number of inverter connected non-synchronous generators in SA, I recommend that all PSCAD models of non-synchronous generators are tested thoroughly by all parties for their response to a wider variation in disturbance scenarios:

1) Variations in frequency
2) Variations in fault type (phase-ground, phase-phase, 2-phase-ground, and 3-phase)
3) Variations in fault duration
4) Variations in fault residual voltage
5) Variations in system strength and X/R ratio
6) Variations in harmonics and negative sequence distortion in the system voltage
7) Voltage disturbances due energization of local transformers

It is noted that items 1) - 5) are already described in AEMO's 'Dynamic Model Acceptance Guideline'. However, considering that EMT-type models are provided as black-box models, it is recommended that these models are tested at the boundaries of operation, as well as outside the intended operating range. This allows users to confirm that models can correctly simulate an unstable operating condition rather than providing stable response under all conditions and irrespective of network strength.

These variations should be simultaneous, and there may be benefit in randomizing the selection of disturbing variables to avoid focus on specific levels.

Note that these recommendations for testing response to wider variations in disturbances would not have changed the outcome of AEMO's system strength studies. However, a more comprehensive suite of testing is becoming more important considering increasing penetration of inverter connected generation, and to allow the ability to analyze power system response to extreme operating conditions including non-credible contingencies.

4.5. Development of Protection Relay Models

Protection relays are represented in AEMO's PSCAD model by either:

1) Inclusion of protection functions within the black-box PSCAD models provided by wind turbine manufacturers.
2) Models developed by AEMO, based on the Generator Performance Standards for specific generators, and publicly available vendor-specific relay information.

During this review, AEMO engineers went through the process of developing the following PSCAD models for specific protection relays:

1) The loss of synchronism relay on the Heywood Interconnector was developed based on a functional diagram of the SEL 421, ElectraNet's relay test results and discussions with ElectraNet's protection specialists. AEMO engineers translated this information into a PSCAD model which was then validated against measurements from the system black event of 28 September 2016, and subsequently against the generator trip event of 3 March 2017.

2) Out-of-step (pole-slip), loss-of-excitation, and reverse power relays for synchronous generators. For example, reverse power relays were modelled in PSCAD by AEMO engineers as simplified relays with reverse power levels and definite time delays, based on information provided by the generator owners and publicly available vendor-specific relay information.

3) Over-voltage and under-voltage relays for wind farms (where not already embedded within the vendor specific black-boxes), were modelled based on the over-voltage or under-voltage ride-through curve provided by the wind farm owners and information included in respective generator performance standards.

In the reviewer's opinion, AEMO's PSCAD models appear to include accurate representations of protection functions. It will be important to keep these models up to date, when AEMO is notified by Generators or ElectraNet that protection has been upgraded or settings have changed, specifically any protections that will trip a generator due to external disturbances on the system (such as voltage or frequency fluctuations, or the multiple voltage dip protection associated with the black system event of 28 September 2016).

4.6. Model Maintenance

AEMO's PSCAD models will need to be maintained to reflect any changes made to existing generating systems.

Accurate modelling by AEMO relies on co-operation from Generators and other Participants (NSP's) in terms of disclosure of up to date modeling, plant and protection information and notifying AEMO when changes are made to generating systems. There are already existing processes in the NER which place obligations on Generators to provide AEMO with details of changes to generating system modelling and settings. These obligations will be updated as part of the system strength and power system model guidelines rule changes, including requirements for Generators to perform full assessment of their proposals (new or altered) using detailed models (such as PSCAD) where connecting to weak parts of the network.

The full assessment using PSCAD models performed by the Generators and NSPs on a local connection by connection basis, in addition to the new power system model guidelines rule changes, will assist in maintaining the accuracy of AEMO's overall PSCAD model for SA.

4.7. Development of Integrated PSCAD Model for SA

AEMO has combined the PSCAD models of individual generators and the SA transmission network to create an integrated PSCAD model of the SA system. This is currently one of the largest PSCAD models of any power system in the world and requires up to 3 hours to simulate 20 seconds on a powerful computer. AEMO has confirmed that in collaboration with the Manitoba Hydro Research Centre, they have been adopting new simulation techniques which may only require one minute per one second worth of simulation for the entire model of the SA system.

The model is restricted to SA with connection to VIC represented as a simplified equivalent. Other states in the NEM may need to be added in the future as the penetration of non-synchronous generation becomes more widespread.

Transmission connected synchronous and wind generation is well represented. The most recent cases used for determining system strength requirements include the 100 MW BESS at Hornsdale wind farm. At this stage, no transmission or distribution connected solar farms exists in SA. Transmission connected industrial demand is represented as static loads with active power proportional to V and a 1.5% frequency droop, and reactive power proportional to V^3 .

The distribution system is modelled with static load represented in the same way as the transmission connected load. Synchronous generators are well modelled (note that deeply embedded synchronous generators are not represented as they contribute little toward the overall strength of the SA system). There is a simplified representation for distribution connected wind generation, and rooftop PV and distribution BESS is not represented.

AEMO's current analysis accounts for system strength requirements under credible contingency conditions. Additional system strength requirements may apply to cater for secure operation of the SA power system when subject to non-credible contingencies such as during islanding conditions, or major loss of load and distributed energy resources such as rooftop PV.

AEMO recognizes that development of detailed load models (particularly in the metro region) and aggregate models for the rapidly growing of rooftop PV and distribution BESS will be needed in the near future [8] to accurately investigate non-credible contingency conditions. However these models will be challenging to develop:

1) Load characteristics change through the day and with season.
2) Adjustable Speed Drives for motors (ASD) can have complex control characteristics, similar to inverters.
3) Direct connected motors have a range of settings for contactor drop-off and restart.
4) Rooftop PV generation is difficult to aggregate into a model. AEMO has described how 100 rooftop PV inverters in the same area were monitored and all responded differently to a system fault, and the aggregate response differed significantly from the individual responses [8].

AEMO has been progressively refining the integrated SA PSCAD model for overall power system security and stability studies, although it might still be unrealistic for most developers to simulate the entire SA system in PSCAD. However, subject to public consultation, the Power System Model Guidelines to come into effect by 1 July 2018 will include a provision for Generators to be able to receive EMT-type models of other plant which will enable developers to create detailed localized network models (including neighboring non-synchronous plant near their proposed projects), where remote parts of the system could be represented as simplified equivalents.

In the reviewer's opinion, AEMO's integrated PSCAD model of the SA system is well suited to help develop overall system strength requirements in SA. It is important for AEMO to continue to develop more detailed load models and aggregated models for rooftop PV generation and future behind-the-meter BESS.

5. Development of Criteria for System Strength

AEMO recognized that the 18 November 2016 interim requirement to maintain system strength by ensuring at least two Torrens Island units (or equivalent) to be online needed to be investigated more thoroughly. The integrated PSCAD model for SA provided AEMO with the tool to refine the system strength criteria. (Note that at the time of the system strength study, the 100 MW BESS at Hornsdale wind farm was not operational and not included in the modelling).

AEMO developed system strength criteria which allowed determination of how many synchronous generators should be online in the Adelaide metropolitan area for up to 1,200 MW and 1,700 MW of non-synchronous generation [9]. Note that at the time of writing this report, AEMO was conducting further studies using the integrated PSCAD model to investigate whether the level of non-synchronous generation (1200 MW at the time of writing this report) could be increased while maintaining system security, including modelling the newly commissioned 100 MW of BESS at Hornsdale wind farm.

The integrated PSCAD model was used to confirm that the system is secure for a phase-phase-ground fault at the 275 kV connection point of online synchronous generators in the Adelaide metropolitan area. The criteria for stability was that synchronous and non-synchronous generation remained online, the Heywood Interconnector SA – VIC did not trip, and system voltages remained with the normal range.

AEMO recognize that work on the system strength criteria needs to be extended to cover network outages including separation from VIC, performance of distance protection relays, and the effect of loads and rooftop PV generation. Accounting for such aspects may result in additional system strength requirements. On-going power system studies are required to precisely determine the requirements.

In the reviewer's opinion, AEMO have developed a criteria for system strength which is based on a well founded methodology and a detailed and validated PSCAD model of the SA power system. Additionally, AEMO have expressed system strength requirements in terms of number of synchronous generators that must be online depending on the level of non-synchronous generation online which is reasonable in this reviewer's opinion.

References

1) 'PSS/E Model Assessment for 1 November 2015 SA System Separation Incident', AEMO Presentation, July 2016.

2) 'Black System South Australia 28 September 2016', AEMO, March 2017.

3) 'Power System not in a Secure Operating State in South Australia on 13 November 2016', AEMO, 6 April 2017.

4) 'Final Report – South Australia Separation Event, 1 December 2016', AEMO, 28 February 2017.

5) 'Fault at Torrens Island Switchyard and Loss of Multiple Generating Units on 3 March 2017', AEMO, 10 March 2017.

6) 'Rule Determination - National Electricity Amendment (Generating System Model Guidelines) Rule 2017', AEMC, 19 September 2017.

7) 'Dynamic Model Acceptance Guideline', AEMO, 28 June 2013.

8) 'Growing Impact of Load and Distributed Energy Resources on System Security During Major System Disturbances', AEMO, August 2017.

9) 'South Australia System Strength Assessment', AEMO, September 2017.

Appendix 1 Reviewer's Credentials

Ranil de Silva has 34 years of experience in the electrical power industry as an employee of Transpower New Zealand Ltd or its predecessors from 1983 to 1995, and then as a co-founder and Director of Engineering of Power Systems Consultants (PSC) from 1995 to the present. He gained his PhD in Electrical Engineering at the University of Canterbury in 1987.

PSC provides specialist consultancy services to the electricity industry in New Zealand, Australia, Asia, Europe, and North America and employs about 150 staff.

For the purpose of disclosure, PSC has carried out work and/or is currently carrying out work in Australia for AEMO, generating companies, TNSP's, and DNSP's.

Ranil's fields of special competence include :

- System studies including Load Flow, Short circuit, Stability, Fast Transient Analysis for AC and HVDC systems, and Insulation Coordination
- Investigation, Specification, Design, Factory Testing, and Commissioning of HVDC Schemes
- Analysis of Electricity Market Systems
- Analysis for Electricity Regulators
- Analysis of Distributed Energy Resources
- Incident Investigation

Appendix 2 Grid-Following and Grid-Forming Inverters

The inverters of non-synchronous generators can be broadly classified into two different types; grid-following inverters and grid-forming inverters. A good summary of the current state-of-the-art for inverters is provided in the recent IEEE Power and Energy article 'Paving the Way' [1].

At present, most inverters connected to typical utility power systems are grid-following inverters (sometimes known as grid-tied inverters), and include rooftop PV inverters and wind turbine inverters. The control systems of these inverters rely on a stable grid voltage to provide a reference for their control system. A weak power system with poor voltage regulation can result in unstable inverter operation.

On the other hand, grid-forming inverters create their own voltage reference and do not need a reference from the system. The power electronics hardware of a grid-forming inverter is essentially the same as for a grid-following inverter, however the control systems are different. Grid-forming inverters have been used for several decades in uninterruptible power supplies, adjustable speed drives, and in microgrids. When used in uninterruptible power supplies and adjustable speed drives, the grid-forming inverters are the sole source of power to the load. In microgrids, one large grid-forming inverter (or synchronous machine), is typically used to provide a stable voltage reference for other grid-following inverters.

Operating multiple grid-forming inverters in parallel is an aspirational goal for microgrids and utility power systems. This could potentially lead to a system completely supplied by non-synchronous generation, or by any arbitrary mix of synchronous and non-synchronous generation. However, at present the combined operation of multiple grid-forming inverters still presents a research and development challenge to stop the inverters 'fighting' against each other. The most promising avenue for combined operation appears to lie with some form of droop control for voltage and frequency to allow the inverters to share the control of the system. The concept of a 'Virtual Synchronous Machine' has been proposed to control a grid-forming inverter in a way that it mimics the characteristics of a synchronous generator, including the provision of inertia and system strength.

[1] T. Ackermann et al, 'Paving the Way', IEEE Power and Energy, Vol. 15, No. 6, November/December 2017.