RENEWABLE ENERGY INTEGRATION IN SOUTH AUSTRALIA

JOINT AEMO AND ELECTRANET STUDY

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AEMO
AUSTRALIAN ENERGY MARKET OPERATOR
ElectraNet

IMPORTANT NOTICE

Purpose

The purpose of this report is to provide information about the secure operation of the South Australian power system under specific conditions.

This report is based on information available to the AEMO and ElectraNet as at 31 August 2014, although AEMO and ElectraNet have endeavoured to incorporate more recent information where practical.

Disclaimer

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CONTENTS

EXECUTIVE SUMMARY 2

1. INTRODUCTION 4

1.1 AEMO and ElectraNet 4

2. BACKGROUND 4

2.1 NEM-installed renewable generation capacity 4
2.2 SA connection to the NEM 7

3. DISCUSSION AND RECOMMENDATIONS 7

3.1 Operation with low levels of synchronous generation online 8
3.2 System separation 11
3.3 Conditions when AEMO can manage SA separation from the NEM 13
3.4 Conditions when AEMO cannot manage SA separation from the NEM 15

TABLES

Table 1 Supply mix in SA 5

FIGURES

Figure 1 Renewable generation in the NEM 5
Figure 2 Synchronous generating units online in SA between Nov 2012 and Nov 2013 6
Figure 3 Reactive margin at selected SA busses 9
Figure 4 SA frequency following separation at 250 MW import, with and without further tripping of PV 18

EXECUTIVE SUMMARY

In recent years wind and solar photovoltaic (PV) energy generation has increased as a proportion of the total generation mix across all National Electricity Market (NEM) regions. This has been driven largely by climate change policies aimed at reducing carbon emissions in Australia, and advances in technology making alternative energy sources more cost-effective.

South Australia (SA) has the highest wind and PV generator penetration of any NEM region. At present, SA has about 1,470 MW of installed wind generation and 540 MW of PV generation. This represents about 50% and 17% of total installed wind and PV capacity in the NEM respectively.

In terms of residential rooftop PV installations, SA leads the NEM with a penetration rate of almost one in four (25%) of all rooftops. Under favourable market and policy scenarios, it is projected that at least 1,000 MW of wind and 500 MW of PV capacity will be added in SA by 2020.

While these developments benefit SA and the NEM, having a high proportion of wind and PV generation can present a risk for SA if the Heywood Interconnector link to Victoria is disconnected at a time when all local conventional synchronous generators are offline. This occurs as wind and PV generators, by themselves, are not able to provide the required controls to ensure system security.

While the probability of this risk is low[1], the potential consequence is a state-wide power outage with severe economic and possible health and safety impacts.

Given this, SA is a relevant case study for assessing the secure operation of the power system with a high concentration of non-synchronous wind and PV generation.

This joint study has been undertaken by the Australian Energy Market Operator (AEMO), as the independent market and system operator responsible for NEM system security and reliability, and SA transmission network service provider (TNSP) ElectraNet, to fulfil its planning and operational responsibilities.

The study investigates the impact of non-synchronous wind and PV generation on the SA power network and analyses:

- Operation of the SA power system with low levels of thermal synchronous generation online.
- Power system frequency control in SA, particularly under conditions when the SA power system is or could become separated from the NEM.

It concludes that the SA power system can operate securely and reliably with a high percentage of wind and PV generation, including in situations where wind generation comprises more than 100% of SA demand, as long as one of the following two key factors apply:

a) The Heywood Interconnector linking SA and Victoria is operational.
b) Sufficient synchronous generation is connected and operating on the SA power system.

Specifically, the SA power system can operate securely when the Heywood Interconnector double-circuit alternating current (AC) lines are connected, or at least one key conventional synchronous generator (e.g., Northern Power Station, Pelican Point, or Torrens Island) is online.

A very low probability but worst-case high-impact scenario is a state-wide power outage should the Heywood Interconnector AC lines be disconnected for any reason when no synchronous generator is online.

The Northern, Pelican Point, and Torrens Island generators provide the required frequency control and regulation to maintain the SA power system in a secure operational state. They also provide power system inertia, and contribute to the management of voltage limits.

Changing market factors could see less synchronous generation operating in SA, affecting the SA power system's ability to maintain required power system control in the future. These factors include:

[1] Concurrent disconnection of the Heywood Interconnector and no local conventional synchronous generation online is considered a non-credible contingency in the NEM.

- Rising gas prices, which affect the financial viability of gas-powered generation.
- Increasing PV generation in SA, which can displace synchronous generation.
- Increasing wind generation in SA, which can displace synchronous generation.
- Increased SA access to Victorian brown coal generation following the Heywood Interconnector upgrade from 460 MW to 650 MW in 2016. This can increase the post-contingency shock on the SA power system following loss of the interconnector.
- Declining electricity consumption from the grid.
- SA has the highest wholesale energy prices in the NEM, making it attractive for interstate generation and new generation development.

Next steps

As a result of this study, AEMO and ElectraNet are further investigating options to provide both short-term and longer-term solutions to support higher levels of wind and PV generation in SA, and to mitigate the risk and impact of a state-wide power outage in the unlikely event that SA becomes disconnected from the NEM.

Short-term response

Over the next six months, AEMO will improve its own systems and processes to:

- Monitor and respond to low inertia conditions in SA by limiting interconnector flows.
- Implement rate of change of frequency constraints in SA to maintain them within system protection limits.
- Enhance existing procedures to improve AEMO's ability to assess available system frequency control capability for planned outages of the Heywood Interconnector.

AEMO will also work with ElectraNet to introduce and coordinate an over frequency generation shedding (OFGS) scheme in SA. This will disconnect large-scale non-synchronous (i.e., wind or PV) generation in a coordinated fashion in response to an over frequency event.

AEMO and ElectraNet will continue to monitor the secure operation of the SA power system in view of the changing generation mix. Areas identified by AEMO and ElectraNet for further development are:

- A model of the PV response to changes in frequency to incorporate into OFGS implementation.
- Analysis of the potential inertial contribution from existing wind generation in SA.
- Improved modelling of PV in power system simulations to better understand its impact on power system operation.

Long-term response

In the longer term, AEMO and ElectraNet believe that energy sector policymakers, investors, and market participants will need to consider further enhancements to the operational processes and network infrastructure required to maintain power system security.

To support this, AEMO is working with ElectraNet to investigate the cost and effectiveness of the following remedial options:

- Arrangements to ensure minimum levels of synchronous generation remain online in SA.
- Development of new ancillary service markets, such as localised provision of inertia and frequency regulation.
- Network augmentation options such as high inertia synchronous condensers.
- Modifications to the controls of the Murraylink high voltage direct current (HVDC) Interconnector, enabling it to provide a rapid active power response in the event that SA is separated from the NEM.
- Changes to the National Electricity Rules (NER) to accommodate a protected events category, allowing AEMO to use the NEM-wide central dispatch process to mitigate against specified events presently considered to be non-credible.
- Limiting the output of non-synchronous generation as a last resort to protect against credible high-impact events.

1. INTRODUCTION

1.1 AEMO and ElectraNet

AEMO is the independent market operator responsible for system security and reliability in the NEM and gas markets. AEMO supports the industry in delivering a more integrated, secure, and cost-effective energy supply in the long-term interests of consumers.

AEMO operates the world's longest interconnected power system, covering a distance of around 5,000 kilometres from Port Douglas in Queensland to Port Lincoln in SA. More than $10 billion of electricity is traded annually in the NEM to meet the demand of more than eight million end-use consumers.

ElectraNet is the principal TNSP in South Australia and provides reliable transmission services to customers at lowest long-run cost. ElectraNet also has planning and operational responsibilities that support the overall secure and reliable operation of the SA power system.

2. BACKGROUND

New wind generation capacity and PV installations have grown in recent years to become a major part of new generation capacity in the NEM. This growth in renewable energy developments has been driven largely by climate change policy aimed at reducing carbon emissions in Australia.

AEMO and ElectraNet began joint studies in February 2014 to identify existing limits to secure SA power system operation with high levels of installed wind generation capacity and PV relative to SA electricity demand. The SA experience will help identify future limits that may be encountered in other NEM regions where wind and PV generation represents an increasing proportion of total generation capacity.

In 2012, AEMO completed a 100% Renewables Study for the former Department of Climate Change and Energy Efficiency. AEMO stated that in the context of a 100% renewable energy power system:

"There is unlikely to be a single technology that dominates; rather, reliance on a broad mix of generation technologies is likely to be required to meet the existing reliability standards. The study shows that generation plant is likely to be spread across all NEM regions. This diversity of generation and location is critical to maintaining the supply/demand equilibrium necessary for system security and reliability."

SA has ideal conditions for wind and PV generation. An abundance of these natural energy resources has led to high penetration levels of non-synchronous renewable generation technology (principally wind and rooftop PV) compared to demand in the SA power system. AEMO and ElectraNet have investigated the limits of operation for the SA power system in this evolving generation mix.

2.1 NEM-installed renewable generation capacity

SA has the highest installed capacity of wind generation and PV in the NEM as a percentage of regional demand. SA's NEM-installed and distribution-connected renewable generation capacity as at August 2014 is summarised in Figure 1.

Figure 1 Renewable generation in the NEM[2]

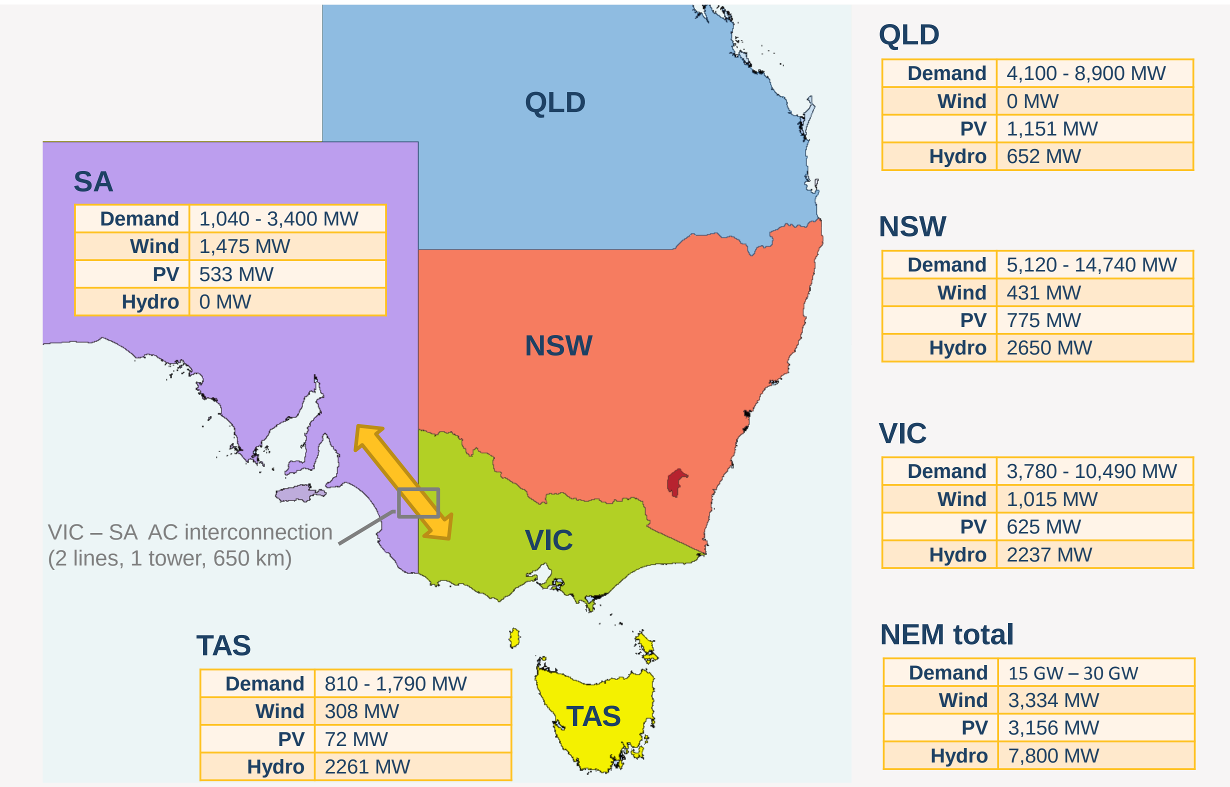


Table 1 summarises SA's supply mix from November 2012 to November 2013, showing both the annual average energy and extremes of the instantaneous supply mix.

Table 1 Supply mix in SA

Source	Total energy (TWh)	Percentage of SA demand (instantaneous)
Synchronous generation	8.10 (59.1%)	20% to 109%
Wind generation	3.76 (27.4%)	0% to 90%[3]
Imports (net)	1.84 (13.5%)	-36% to +58%
Total[4]	**13.70 (100%)**	

The installed capacity of renewable generation in SA consistently exceeds SA demand. When wind and sunlight are plentiful, SA experiences considerable penetration of wind generation and PV output. In 2014 AEMO observed the following:

- Total installed wind capacity in SA of 1,475 MW.
- In July 2014, 43% of SA's total energy was supplied by wind generation.
- On single days during September 2014, 75% of SA's energy was supplied by wind generation.
- At 4.15 am on 28 September 2014, 109% of SA demand was instantaneously supplied by wind.
- Maximum instantaneous SA wind generation on 3 July 2014 was 1,348 MW.

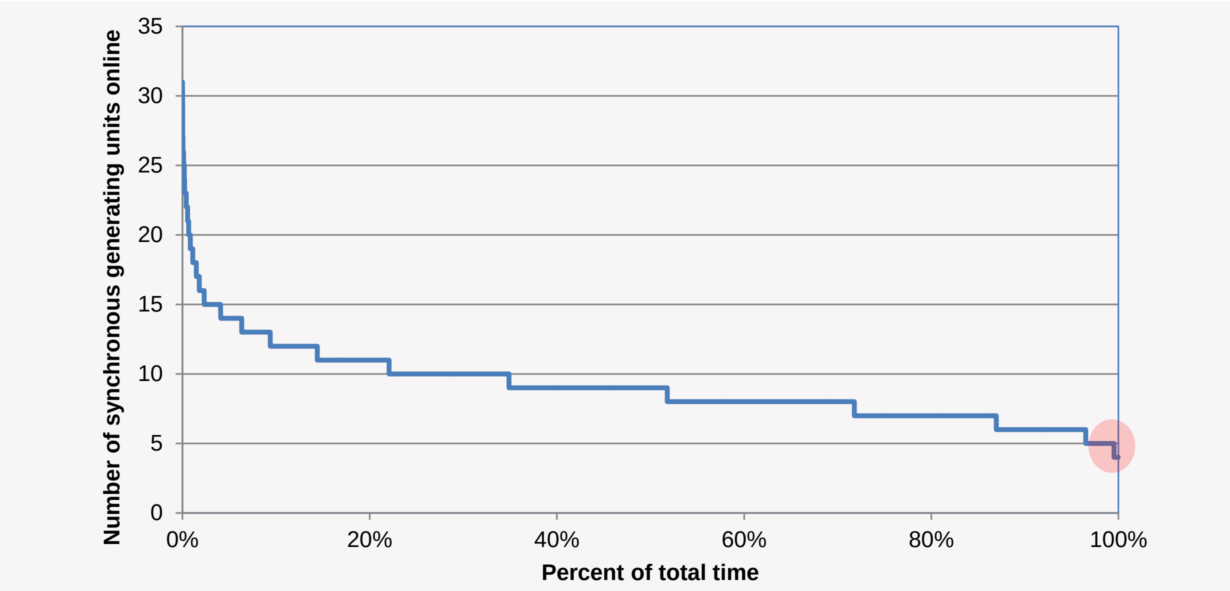
[2] As at August 2014. Source: AEMO Participant Registration and Exemption List, PV data. Available at: www.apvi.org.au. Viewed: 1 September 2014.
[3] The instantaneous percentage of demand in SA that was supplied by wind generation and imports combined varied from -9% to +80%.
[4] This is the total supplied through the shared transmission network. It excludes PV within distribution networks. 493 MW of PV with an assumed 15.7% annual capacity factor would produce 0.68 TWh, or 4.9% of the energy currently supplied through the shared transmission network.

SA wind generation has increased to a level where it can meet up to 151% of SA demand. This study focuses on the operational implications of high instantaneous supply scenarios to better understand the system security requirements of the SA power system in these conditions.

Increased wind participation displaces traditional synchronous generators from the market. Since 2012, the average number of synchronous generators in SA supplying energy to the NEM has declined.

Figure 2 shows the time distribution of the number of synchronous generating units online in SA between November 2012 and November 2013. It highlights periods of time with as few as four synchronous generating units online in SA.

Figure 2 Synchronous generating units online in SA between Nov 2012 and Nov 2013



Synchronous generators provide services to the power system such as inertia, frequency control capability, reactive support, and fault level for riding through power system disturbances. These support system security, and they reduce or disappear as synchronous generation is displaced from the power system by non-synchronous renewable generation.

Currently there are no processes or arrangements in place that would directly prevent the number of synchronous units online in SA from falling to zero in real time. Unit commitment decisions are the responsibility of plant operators, and are based on technical and economic factors not fully visible to outsiders.

Changing generation trends in SA have prompted AEMO and ElectraNet to investigate the following two questions regarding SA power system operation:

1. Can the SA power system operate securely with no synchronous generators online?
2. Can power system frequency in SA be maintained in conditions where SA:
   a) Becomes separated from the rest of the NEM (a non-credible contingency)?
   b) Is at risk of becoming separated from the rest of the NEM (a credible contingency)?

2.2 SA connection to the NEM

SA has two connections to the remainder of the NEM:

1. Heywood Interconnector: A double-circuit AC 275 kV transmission line linking the South East Terminal Station in SA to the Heywood Terminal Station in Victoria.
2. Murraylink Interconnector: A 220 MW HVDC link joining Red Cliffs in Victoria to Monash in SA.

2.2.1 The Heywood Interconnector

The overall AC interconnector between SA and Victoria via Heywood comprises two transmission line circuits running on single towers for a total distance of approximately 650 kilometres. If this interconnector fails, SA would be separated from the NEM, requiring the SA power system to control its own frequency.

Maximum power transfer capability between SA and Victoria is currently 460 MW on the Heywood AC Interconnector; this will be upgraded to 650 MW in 2016. The planned upgrade benefits both states, increasing power transfer capacity by 190 MW.

2.2.2 Murraylink

The Murraylink Interconnector provides up to an additional 220 MW of interconnection capability. However, being a direct current (DC) link, Murraylink is not able to contribute inertia or frequency control to the SA power system in its present form. Given this, Murraylink is not currently considered a source of SA system control.

3. DISCUSSION AND RECOMMENDATIONS

Conventional synchronous generation in SA provides the required frequency control and regulation to maintain secure operation of the SA power system. It currently contributes to fault level for ride-through of power system disturbances, fast-acting voltage control, inertia, and fast-acting frequency control capability when connected, irrespective of output levels.

Wind (in particular full converter-based turbines) and PV generation technologies are non-synchronous, and provide these services at a low level, or not at all. Reducing conventional synchronous generation in SA reduces frequency and voltage control capability, and increases the complexity of managing security of the SA power system.

Generation plant owners make decisions about generation commitment and operation based on commercial and technical factors not fully visible to outsiders. Decisions to commit generation into the power system are made by generators, not AEMO.

AEMO currently has no direct mechanism available to guarantee minimum levels of synchronous generation on the power system, other than by using its emergency direction powers. These powers are reserved for specific circumstances to mitigate risks to system security, reliability, or public safety.

AEMO's operational system and processes primarily focus on ensuring N-1 secure operation. This means the power system must be operated so that it will remain in a satisfactory operating state following the occurrence of the worst single credible contingency event.

AEMO and ElectraNet studied SA power system operation with low and zero levels of synchronous generation online. Two broad areas of system operation were considered:

1. The N-1 secure operation of the SA power system with normal system conditions and low to zero levels of synchronous generation.
2. Frequency control in SA following system separation, particularly under conditions of low synchronous generation online.

These studies focused on conditions of low demand in SA, and high imports from Victoria via the Heywood Interconnector. These conditions result in low levels of synchronous generation being connected, synchronised, and operating. AEMO and ElectraNet consider that the following circumstances, coupled with declining SA grid-supplied demand, will increase the likelihood of conditions of low synchronous generation occurring in SA:

- Increases in gas prices.
- Increased Heywood Interconnector capability in 2016.
- Increased installation of non-synchronous renewable generation.
- Declining electricity consumption from the SA grid.

3.1 Operation with low levels of synchronous generation online

The N-1 security of SA was assessed with low levels of synchronous generation online, considering three main areas of power system performance:

1. Voltage stability.
2. Transient stability.
3. Fault levels.

AEMO and ElectraNet did not assess power system damping or oscillatory stability. This aspect of power system performance will need to be investigated further.

3.1.1 Voltage stability

The ability to maintain stable power system voltages following probable events on the power system is reduced with low levels of synchronous generation. Synchronous generation is typically an important source of fast-acting reactive power support, particularly when it is located close to the demand centre, as it typically is in SA.

Voltage stability is typically defined in terms of the need to maintain a minimum reserve of reactive capability at key transmission busses.[5] If sufficient reactive capability is not available, there is a risk of widespread low voltage or voltage collapse conditions following transmission events, leading to large-scale supply disruption.

A key criteria for N-1 secure power system operation is that adequate reserves of reactive power, or reactive margins, are maintained following the single most critical transmission event. For SA, this is either the loss of a heavily-loaded transmission line, or trip of a conventional synchronous generator from high output.

Wind generation in SA provides material levels of reactive capability, both static and dynamic; however, this wind generation is remotely located and sources of reactive power are generally most effective when they are located close to demand supply points.

Voltage stability in SA is assisted by the presence of static reactive devices such as capacitor banks, and is particularly supported by the presence of fast-acting dynamic reactive devices such as Static VAr Compensators (SVCs). SA has four major SVCs[6], located at Para near the Adelaide demand centre, and in the South East, at the immediate receiving end of the Victorian interconnector at Heywood.

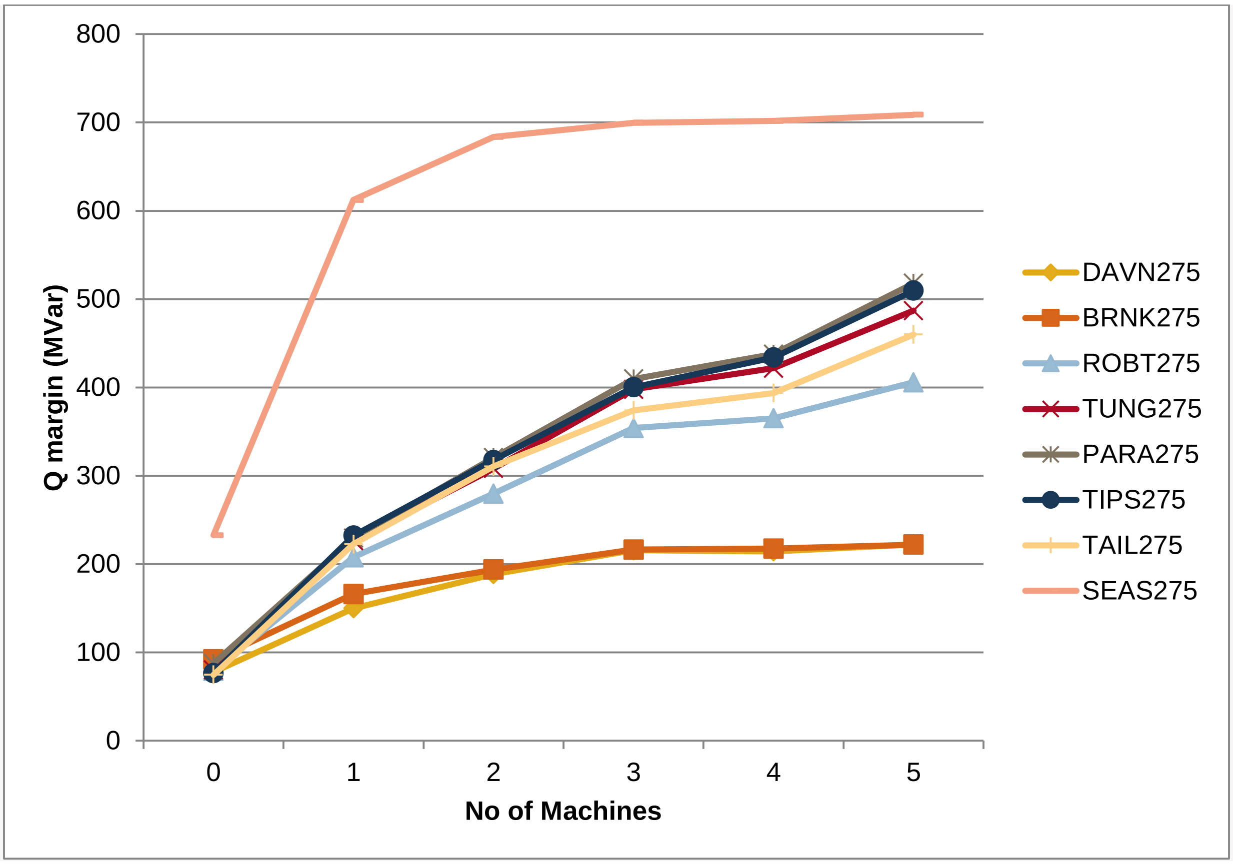
ElectraNet assessed the reactive reserves at a number of key transmission busses following critical transmission events for varying levels of synchronous generation online, including the case of zero synchronous generation. Various levels of Heywood Interconnector flow were considered, including the effect of the planned interconnector upgrade from 460 MW to 650 MW in 2016.

[5] A reactive reserve of 1% of the peak fault level at a given bus is required, typically around 100 MVAr.
[6] South East has two SVCs (-50/+80 MVAr), PARA has two SVCs (-70/+80 MVAr).

Figure 3 shows the results of a typical voltage stability study, outlining the calculated reactive margin at various points on the SA transmission network following a critical transmission contingency, under conditions of light SA load and high import into SA from Victoria.[7]

It shows that adequate (positive) reactive margins are maintained even with no synchronous generators in service, in a case where the Tungkillo capacitor bank is switched on.

Figure 3 Reactive margin at selected SA busses



Conclusion

Adequate reactive margins can be maintained down to zero synchronous machines online in SA if the Heywood Interconnector is intact and operational.

This is possible due to the reactive support provided by SVCs and transmission-connected capacitor banks in addition to the reactive support, both static and dynamic, provided by transmission-connected wind generation.

Careful operation of reactive plant, such as capacitor banks, is required with very low levels of synchronous generation online in order to ensure adequate levels of steady state control of network voltages and reactive margins are maintained.

Studies focused on the effects of transmission-connected wind generation. Distribution-connected PV generation is known to produce voltage control issues locally in distribution networks. PV does not play a significant role in transmission level voltage stability; however, careful coordination and control of reactive compensation is necessary to ensure this remains the case.

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[7] This study was undertaken for worst-case maximum import of 650 MW and SA demand of 1,400 MW with the Tungkillo capacitor bank switched on.

Recommendation

Where voltage stability limits are identified, they can be managed either through careful operation of existing reactive plant, through the use of constraint equations in the central dispatch, or possibly via network augmentation such as new reactive plant.

3.1.2 Transient stability

There is no single clear effect of reduced synchronous generation levels on the transient (or angular) stability of a general power system. Reduced power system inertia levels due to the displacement of synchronous generation can lower some existing transient stability limits; however, the opposite effect can also occur, depending on the mechanism of instability and the connection point of the synchronous generation that is displaced.

In the case of zero synchronous generation online, the power system moves closer to a distribution or reticulation network containing embedded power electronic devices, rather than being a classical power system dominated by the behaviour of rotating synchronous machines.

An assessment of the SA power system's ability to recover from and return to stable operation following a range of credible contingency events was performed. Various levels of synchronous generation down to zero machines were considered with an intact interconnector to Victoria via Heywood.

Conclusion

Power system stability following credible contingency events can be managed with zero synchronous machines online provided the interconnector at Heywood is connected. The SA power system is capable of returning to stable operation following single credible contingency events under these circumstances.

A notable contributor to this scenario is the SA requirement for wind generation to provide relatively high levels of dynamic reactive capability, under Essential Services Commission of South Australia (ESCOSA) wind generation licensing conditions. The dynamic reactive capabilities provided by wind generation are beneficial in assisting wind generation to ride through power system disturbances and return to stable operation.

To be certain this remains the case, AEMO will continue to monitor the performance of wind generation during actual disturbances. Agreed obligations under generator performance standards will continue to be enforced, particularly in relation to fault ride-through performance.

Note that no dynamic models of PV generation were used for this study. The challenge of how to best model PV in power system dynamic studies is presently an active area of international research. Given the high levels of PV generation currently installed in SA, and likely to be installed in future, AEMO and ElectraNet plan to incorporate dynamic PV generation models into future studies when available.

Recommendation

AEMO and ElectraNet are developing dynamic models of PV generation to support the ongoing accuracy and validity of power system studies in SA.

3.1.3 Low fault levels

The integration of high levels of non-synchronous generation reduces transmission system fault levels.

The fault current contribution of wind and PV generation is lower than synchronous generation. The ability of wind generation to successfully ride through power system disturbances and re-establish stable operation is more difficult under conditions of low power system fault levels.

AEMO and ElectraNet seek advice from wind turbine manufacturers during the connection process regarding minimum fault level requirements for their wind turbines. Reduced power system fault levels are most material for wind generation electrically connected close to synchronous generation, as the design of fault level requirements is based on the presence of the nearby synchronous generator. At more remote connection points, fault levels are determined principally by the high network impedance, and less so by the commitment patterns of remote synchronous generation.

The operating experience in SA has demonstrated that remotely located wind generation, which normally operates under low fault level conditions, is capable of successfully riding through power system disturbances as it has been specified and engineered to do so at the time of connection.

Conclusion

Existing wind generation connected to the SA power system is able to successfully ride through disturbances occurring as a result of single credible contingency events. This relies on an intact SA–Victoria interconnector at Heywood combined with the more stringent dynamic reactive capabilities required of wind generation under SA's licensing requirements.

Note that the introduction of series compensation in SA as part of the planned Heywood Interconnector upgrade in 2016 will reduce the network impedance of the interconnector, which will assist in increasing minimum network fault levels.

Reduced transmission network fault levels on PV generation is not considered to affect the SA transmission system. Fault levels at the low voltage connection points for PV systems are determined principally by distribution network impedances.

Low network fault levels in SA are not a barrier to operation with high levels of wind and PV generation provided the SA transmission network and the SA–Victoria interconnector at Heywood is intact.

Recommendation

AEMO will continue to monitor SA wind generation to ensure it has the ability to ride through typical power system disturbances.

3.2 System separation

In Section 3.1, AEMO and ElectraNet concluded that the management of voltage, power system stability, and power system operation at low fault levels in SA is manageable with no synchronous generation online, provided the Heywood Interconnector is operational.

For these areas of power system performance, secure operation of the power system is likely to be manageable even without the Heywood Interconnector operational. However, this is not the case for power system frequency control.

In the event of the interconnector becoming disconnected, maintaining SA power system frequency is critical. AEMO and ElectraNet conducted a number of studies to determine the limiting factors in managing frequency in a SA power system disconnected from the NEM. The following scenarios were modelled and the findings are explained below:

- Normal system conditions with no separation.
- Frequency control following SA separation from the NEM.
- Under frequency load shedding and system separation.
- Conditions when AEMO can manage SA separation from the NEM:
  - Frequency regulation and automatic generation control.
  - Inertia and rate of change of frequency.
- Conditions when AEMO cannot manage SA separation from the NEM:
  - Over frequency generator shedding.
  - Tripping of PV.

3.2.1 Normal system conditions with no separation

Under normal system conditions, short-term load-demand balancing and power system frequency control is managed by AEMO at the NEM level. For normal system conditions, where the full interconnector between Victoria and SA remains intact, frequency and short-term load-demand balancing in SA can be managed using generation located outside SA.

Changes in the SA generation mix will not affect SA frequency control under normal system conditions. Normal system conditions with a fully intact Heywood Interconnector (both lines) have historically been present at least 90–95% of the time. The remaining 5–10% is due to the forced or planned outage of one of the Heywood lines due to an incident or planned maintenance (while the other Heywood Interconnector circuit remains in service).

High variability in non-synchronous generation in SA presents challenges in managing flows within required limits on the Heywood Interconnector. This can occur when non-synchronous generation varies by large amounts over short timeframes, and the necessary balancing of the variation occurs via the interconnector.

Factors mitigating this issue include:

- The short five-minute dispatch cycle in the NEM, where the dispatch process can be adjusted every five minutes to offset any observed problems.
- Accurate forecasting of the change in the output of wind generation over the five-minute timeframe.
- Geographic diversity of non-synchronous generation which reduces the aggregate variability.

Variations in Heywood Interconnector flows are presently managed by using the central dispatch process to either automatically increase interconnector operating margins or to adjust interconnector dispatch targets to compensate large flow deviations.

Conclusion

The SA power system can be operated securely with any combination of synchronous or non-synchronous generation as long as the Heywood Interconnector is connected.

Recommendation

AEMO and ElectraNet will monitor the changing operational environment in SA to ensure the SA power system can be operated securely.

3.2.2 Frequency control following SA separation from the NEM

Following SA separation from the NEM, all necessary frequency control and short-term load-demand balancing services must be obtained from generation located within SA. Existing wind and PV generation in SA does not contribute to NEM frequency control arrangements.

Conclusion

Where SA has zero synchronous generation online, and is separated from the rest of the NEM, AEMO is unable to maintain frequency in the islanded SA power system. This would result in a state-wide power outage.

SA can separate due to the credible loss of the Heywood Interconnector (when one of the dual lines is already out of service and the remaining line is tripped), or due to a non-credible loss of the Heywood Interconnector (involving the loss of both lines simultaneously).

Under the NER, AEMO is only able to intervene in the central dispatch process to manage network limits when considering single credible contingency events. Separation of SA from the rest of the NEM is not considered to be a credible contingency event under normal system conditions. As a result, AEMO cannot intervene to manage network limits or performance issues that would arise following a non-credible system separation.

AEMO proposes a “protected events” category be introduced as a rule change in the NER. This would establish a framework across the NEM for AEMO to use the central dispatch process to mitigate against specified events listed in a protected events category where they are presently considered non-credible.

Recommendation

AEMO will investigate whether a protected events category in the NER would achieve the desired outcome of enabling AEMO to manage network limits in SA in the event of a non-credible loss of the Heywood Interconnector.

3.2.3 Under frequency load shedding and system separation

A key feature of the SA power system when considering frequency control is under frequency load shedding (UFLS).

As the Heywood Interconnector is relatively large in size compared to typical system demand in SA, loss of this interconnector can result in a large excess or deficit of supply following loss of interconnection. Where the interconnector is lost under conditions of import from Victoria into SA, it is understood and expected that some UFLS will occur in SA.

Under conditions where separation is considered credible, such as a planned outage of one of the two lines forming the interconnector, SA relies on UFLS to arrest the fall in frequency following separation. This differs from arrangements in other NEM regions, where contingency raise frequency control ancillary services (FCAS) are obtained when separation is considered credible; this arrests a decline in frequency without resorting to customer load shedding.

This reliance on load shedding in SA to manage single credible contingency events resulting in separation is an anomaly. It originates from a 2001 Electricity Supply Industry Planning Council (ESIPC) decision to specify a 47–52 hertz (Hz) frequency standard for SA separation events, rather than the 49–51 Hz band outlined in the frequency operating standards applied in other NEM regions.

The presence of UFLS in SA is also critical for managing non-credible contingency events such as the simultaneous loss of both Heywood Interconnector transmission lines. This is exacerbated by the planned 2016 Heywood Interconnector upgrade, which will increase the potential size of a non-credible contingency event from 460 MW to 650 MW.

Load shedding at levels approximately equal in size to the event was simulated for SA following the loss of interconnection on import from Victoria. This simulation used historically observed generation patterns and system conditions. Under conditions of low SA demand and high imports, a disconnection of more than half of SA demand is likely.

Conclusion

The response times of generator governors in SA are too slow to arrest the rapid decline in frequency of the SA power system following separation from Victoria. This is due to high levels of wind and PV generation, and results in reduced power system inertia and therefore frequency reducing more rapidly following separation. At least half of SA's demand would be shed in this scenario.

Recommendation

AEMO will investigate arrangements to ensure minimum levels of synchronous generation remain online in SA, which may include:

- Developing new ancillary service markets such as local provision of inertia and frequency regulation.
- Limiting the output of non-synchronous generation as a last resort to protect against credible high-impact events.

3.3 Conditions when AEMO can manage SA separation from the NEM

The interconnector between Victoria and SA is formed by two AC lines, which run over approximately 650 kilometres on a single tower. While simultaneous loss of both lines is not normally considered credible, planned outages or maintenance anywhere along these lines mean that SA separation will occur for a single credible contingency event. In this circumstance, separation is considered credible, allowing AEMO increased capability under the NER to limit the consequences of the event by preparing the SA power system to operate securely if the event was to occur.

A credible separation risk requires AEMO to have arrangements and processes in place to ensure the security of the SA power system following separation. Conditions of credible separation risk have historically existed for 5–10% of the time, normally due to planned maintenance or upgrades along the interconnector.

At present, when a credible separation risk is present, AEMO:

- Limits interconnector flow at Heywood to +/- 250 MW, a value broadly aligned with the historical maximum contingency size within the SA power system.

- Sources contingency lower FCAS from generation located within SA when SA is exporting and there is a credible risk of separation, to ensure that the 52 Hz upper frequency limit is not exceeded immediately after separation.

As the requirement for contingency lower FCAS varies with the contingency size set by interconnector flow levels, contingency lower FCAS requirements are co-optimised with Heywood Interconnector flow levels.

AEMO does not obtain contingency raise FCAS from generation located within SA when SA is importing, but relies on load shedding in SA via UFLS to manage frequency in SA immediately after separation.

As a result of the changing generation mix in SA, two new issues are emerging that require these arrangements to be improved where there is a credible risk of SA separation. They are:

- Frequency regulation and automatic generation control (AGC).
- Inertia and rate of change of frequency.

AEMO and ElectraNet have studied the requirement for frequency regulation, inertia, and rate of change of frequency parameters in preparing the SA power system for an event where the loss of the interconnector is considered credible.

3.3.1 Frequency regulation and automatic generation control

Following actual separation of the SA power system from the NEM, AEMO operators quickly act to establish a separate frequency control area for SA in AEMO's AGC system.

AGC is used to actively compensate for the small differences between instantaneous supply and demand that occur constantly, over timeframes shorter than the five-minute dispatch cycle. AGC is currently the critical central control system in the NEM responsible for short-term supply-demand balancing and for keeping power system frequency close to the required 50 Hz in timeframes shorter than the five-minute dispatch cycle. AGC acts by actively increasing and decreasing the output of a small number of generators under its control in response to small measured frequency deviations away from 50 Hz.

The generators selected for AGC frequency regulation in any given five-minute dispatch interval are determined using the real-time market for regulation FCAS services. Only generation that has voluntarily registered to participate in regulation FCAS markets can be used for this purpose, and currently only synchronous generators participate in this market.

Under normal system conditions, regulation FCAS services for mainland frequency control can be obtained from generation anywhere on the mainland, as frequency is common across the mainland. However, under conditions of system separation, regulation FCAS services must be obtained from local generation within the islanded frequency control area.

For AEMO's AGC system to control frequency in SA after separation from the NEM, it must have control over generators located in SA where output can be actively increased and decreased over short timeframes, to allow the active control of power system frequency to near 50 Hz. Current arrangements for managing a credible risk of SA separation do not ensure that generation with this capability is online in SA prior to separation, and rely on establishing a requirement for regulation FCAS in SA only after separation has actually occurred.

Three power stations in SA are registered to provide AEMO with regulation FCAS services[8], and only generators at these three stations can be placed under AGC control for frequency regulation. This means that regulating frequency in SA following separation currently relies on generation from at least one of these three being online during periods of potential separation risk, prior to actual separation occurring. Historically this requirement has always been satisfied without external intervention, but in the future it may not necessarily be the case.

Conclusion

In a scenario where Northern Power Station, Pelican Point Power Station, and Torrens Island Power Station are offline prior to separation, AEMO would have no way of regulating frequency in SA following separation from the

[8] Northern Power Station, Pelican Point Power Station, and Torrens Island Power Station.

NEM at Heywood. Studies have confirmed that widespread load shedding and tripping of generation in SA by protection schemes would occur.

Establishing a local regulation FCAS requirement in SA prior to a separation event occurring signals that generation capable of providing this service is required in SA. Other parties may register to provide AEMO with frequency regulation services, or other technologies capable of providing frequency regulation services may emerge in SA over time; however, at present the only method available for actively regulating frequency over short timeframes is through AGC and existing synchronous generation.

Regulation FCAS requirements in SA can only be obtained from a small number of providers. Procuring sufficient contingency lower FCAS in SA is presently challenging during periods when SA is considered at credible risk of separation.

Recommendation

Under credible separation conditions, AEMO is to ensure there is sufficient generation online in SA with the ability to actively control frequency, prior to actual separation occurring. AEMO will establish new arrangements for monitoring the availability of local regulation FCAS in SA, for use when there is a credible risk of separation.

3.3.2 Inertia and rate of change of frequency

In an electrical power system, inertia is defined as a measure of the mass of all the rotating generators connected to the power system. A power system is made up of many generators and motors connected together electrically (magnetically coupled) by the transmission and distribution systems. All generators connected together on the electrical system (synchronised) must spin at the same relative speed, or frequency. The rotating parts of synchronous generators or motors provide inertia to the power system. That is, a tendency to resist a change in motion, or a change in frequency. This maintains synchronisation.

Frequency in the power system is directly related to the rotating speed of the generating units: if the speed reduces, frequency reduces. High system inertia results in a slower, manageable rate of change in frequency. If the power system has low inertia, it will slow down or speed up very quickly, making it difficult to maintain frequency within acceptable limits.

The speed at which frequency changes immediately following separation will be determined solely by the inertia of online generation in SA. Changes of frequency at a rate greater than 1 Hz per second can trigger the operation of protection systems which detect high rates of change of frequency, in particular anti-islanding protection associated with wind generation, and trip-to-house-load relays at Northern Power Station.

Conclusion

If a non-credible separation event occurs concurrently with low or no synchronous generation in SA, a lack of power system inertia will cause a fast rate of change of frequency, potentially triggering protection systems that will disconnect SA generation.

Recommendation

When the risk of SA separation from the NEM is considered to be credible, AEMO will limit interconnector flows based on available system inertia, to limit the potential contingency size at separation. This will maintain the rate of change of frequency to within the limits of protection systems.

Where separation occurs due to a non-credible contingency event, AEMO is not able to prepare central dispatch to ensure that known system limits for rate of change of frequency are respected.

3.4 Conditions when AEMO cannot manage SA separation from the NEM

Sudden loss of the Heywood Interconnector from a previously normal system condition is historically very rare, and is considered to be a non-credible contingency. Loss of the interconnector in this way has occurred four times since 1999: once due to a bushfire, and three times due to the sudden loss of multiple generating units in SA.

The loss of the Heywood Interconnector with low to no synchronous generation online in SA was modelled. Under this condition, there is not enough inertia present in the SA power system for AEMO to maintain frequency in SA.

As a consequence SA would experience uncontrolled load shedding, generator tripping, and collapse of the power system. It is not possible to maintain power system security in SA under this scenario.

Conditions of zero synchronous generation have not been seen in SA to date. The lowest number of synchronous machines online in SA to date has been four machines.

The changing market environment could increase the likelihood of less synchronous generation being online. The following market environment changes may influence the future commitment of synchronous generators in SA:

- Increasing gas prices, making SA gas-powered generation relatively less economic.
- A planned increase in interconnector capability of almost 200 MW, allowing increased competition from low marginal cost interstate generation from Victoria.
- The highest wholesale market prices are in SA, making it attractive for interstate generation and new generation development.
- Further increases in both wind and PV generation in SA.
- Declining grid-supplied demand in SA.

As outlined previously, the sudden loss of both Heywood Interconnector AC lines is considered a non-credible event; as such, AEMO has limited options in preparing for the event under the present NER. Options include:

1. Under frequency load shedding (UFLS) schemes.
2. Over frequency generator shedding (OFSG) schemes.

These schemes enable the automatic rapid reduction of demand or generation in an attempt to arrest fast-moving frequency reductions or increases respectively. Emergency control schemes do not guarantee that the power system will survive all possible non-credible events, but do increase the chances of doing so, and at relatively low cost. With historical generation mixes these schemes have generally been effective in managing separation events, though the operation of such emergency control schemes can result in major supply disruptions.

The SA power system has an existing UFLS scheme in place, but does not have an OFGS scheme in place. UFLS schemes are discussed in further detail in Section 3.2.3; OFGS schemes are discussed in Section 3.4.1

Note: In the SA power system, with high levels of wind and PV generation and relatively low levels of synchronous generation, emergency control schemes may become less effective in managing severe events such as non-credible separation. Higher levels of load shedding may be required than previously, due to:

- Reduced levels of power system inertia.
- Rapid and larger changes in power system frequency.

Conclusion

Ensuring the SA power system survives and remains viable following all non-credible contingency events requires maintaining minimum levels of inertia within the SA power system to limit rapid frequency change. This allows sufficient time for emergency control schemes to operate correctly.

Recommendation

A solution to guard against the collapse of the SA power system following the non-credible separation of the Heywood Interconnector during times of low or no online synchronous generation within SA requires several changes to present operational processes and network infrastructure. AEMO is working with ElectraNet to investigate the following to determine their cost and effectiveness in addressing the problem:

- Arrangements to ensure minimum levels of synchronous generation remain online in SA.
- New ancillary service markets such as localised inertia and frequency regulation.
- Network augmentation options such as high inertia synchronous condensers.
- Modifications to the controls of the Murraylink HVDC Interconnector to allow Murraylink to provide an emergency active power response following separation.
- Changes to the NER to accommodate a protected events category.
- Limiting output of non-synchronous generation as a last resort to protect against credible high-impact events.

3.4.1 Over frequency generation shedding

UFLS would be triggered by sudden loss of interconnection when power transfer across the Heywood Interconnector was from Victoria to SA (net import to SA).

If power transfer across the interconnector was from SA to Victoria (net export from SA) when separation occurred, the SA power system would see a rise in frequency and generators would disconnect due to over frequency. An OFGS scheme would perform this function in a more coordinated manner and reduce the risk of more widespread loss of supply.

Conclusion

Over frequency conditions can occur following non-credible separation events during SA power export sufficient to result in the widespread and uncoordinated operation of generation over frequency protection in SA. Note that separation studies only considered separation of the Heywood Interconnector. A full OFGS design will also consider a small range of additional separation events occurring in Victoria, which result in parts of the Victorian power system remaining connected to an islanded SA region. An OFGS scheme design and operation will also include a small number of Victorian generators, in addition to those located in SA.

Technical discussions about establishing an OFGS for SA have been underway with ElectraNet since 2013; at present some further technical and regulatory matters around scheme design are yet to be agreed. Discussions with the operators of SA generation about the required changes to their protection systems to facilitate implementation of an OFGS have not yet commenced.

Recommendation

To mitigate this risk, an OFGS scheme is to be implemented for SA.

An OFGS scheme acts to automatically and rapidly disconnect selected generation in SA in a controlled and coordinated manner when certain abnormal high frequency conditions are detected.

The objective of an OFGS scheme in SA is to coordinate generator trips to maintain frequency operating standards for non-credible events. To do so, low inertia generation is shed as a priority in an attempt to maintain high inertia synchronous machines online to stabilise the power system. To implement an OFGS scheme, generation in SA will be required to modify the generator frequency protection settings currently identified as part of their generator performance standards.

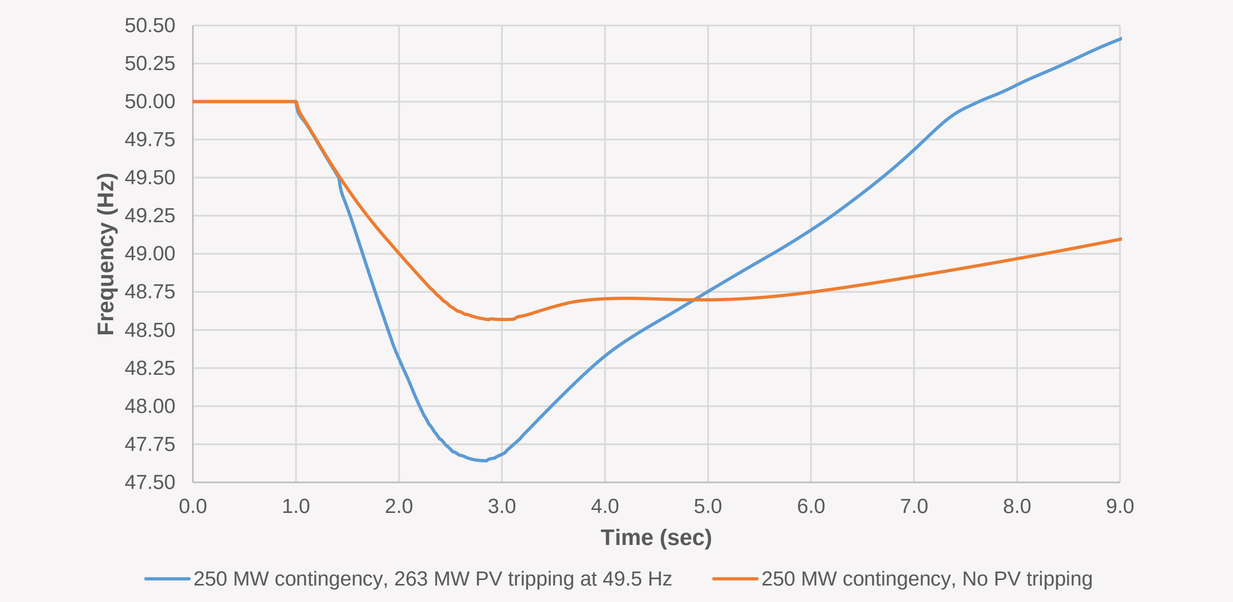
3.4.2 Tripping of PV

The sudden disconnection of large amounts of PV generation in response to a change in power system frequency has been identified as an important factor in power system disturbances internationally. In particular, the risk of tripping of large amounts of PV generation for conditions of under frequency could increase the size of an under frequency disturbance in SA, and increase the resulting under frequency load shedding.

Figure 4 compares the simulated frequency in SA for a particular scenario involving the loss of interconnection at 250 MW import into SA, with and without tripping of PV.[9] Note the much lower frequency resulting from the additional tripping of PV. In the simulation, the tripping of PV resulted in additional load shedding in SA approximately equal to the amount of disconnected PV generation. A new draft Australian standard for PV inverters has been completed. The new draft will mandate stricter standards for future installations.

[9] This simulation tripped 263 MW of PV, at 49.5 Hz, with zero delay. These are arbitrarily chosen values, but are arguably within the possible range of real outcomes based on the very limited information currently available about PV response to frequency disturbances.

Figure 4 SA frequency following separation at 250 MW import, with and without further tripping of PV



Conclusion

With more than 500 MW of PV currently installed in SA, there is potential for a large increase in the magnitude of contingency events where they result in material under frequency.

Recommendation

AEMO, ElectraNet, and Tasmanian TNSP TasNetworks will perform detailed studies of the response from distributed PV for changing frequency.