System Strength Challenges in Australia’s National Electricity Market

Subjects: Engineering, Electrical & Electronic
Contributor: Lynne YU

The national electricity market (NEM) of Australia is reforming via the rapid uptake of variable renewable energy (VRE) integration concurrent with the retirement of conventional synchronous generation. System strength has emerged as a prominent challenge and constraint to power system stability and ongoing grid connection of VRE such as solar and wind.

asynchronous machine | fault level | inverter-based resource | transition | system strength | weak grid

1. Introduction

As the world continues to fight the COVID-19 pandemic, countries have been promoting sustainable and eco-friendly targets as a global growth engine throughout the long-term climate recovery. In combination with carbon neutrality targets, Australia has outstanding access to variable renewable energy (VRE) resources such as solar and wind as well as large blocks of land, which has attracted a flow of domestic and foreign direct investment over the past decade [1]. In [2], projections indicate that renewable penetration will be over 90% over the next 20 years. However, the number of new committed utility-scale VRE projects has dramatically decreased from 2019, and proponents have been significantly impacted by connection and commissioning delays, operational curtailment, etc., due to transmission network constraints and uncertainty in the markets [3]. In parallel, authorities have been developing state-of-art solutions in system planning, infrastructure upgrades, augmentation, and regulatory reformation to keep pace with rapid transition challenges. It is crucial for the market participants to understand the overwhelming opportunities and limitations, technical capability, system constraints, and grid connection requirements and challenges to enable projects to be registered in the NEM.

1.1. The Australian Energy Market: Transition and Opportunities

In 2018, publication of the Finkel Review from the Australian Energy Market Commission (AEMC) reviewed the NEM transition and steered the way to a reliable, secure, and sustainable energy future [4]. Recent research from [5] indicates that the NEM has been transitioning to a market with increased prominence of non-dispatchable renewable generation attributed to a combination of factors including rising environmental awareness, carbon free initiatives, the economic viability of VRE, technology advancement, customer demand, and the withdrawal of fossil fuels. Another highlight from [5] demonstrates that states and territory governments have set out carbon neutral goals by 2050 regardless of the absence of a federal policy. It is undoubtedly the case that Australia’s energy market is on a highly transforming path.

AEMO has released the Integration System Plan (ISP) 2020 [6], mapping out technical solutions, actionable plans, and regulatory reforms to comfort network constraints and keep pace with transition. Coordinating with state government RE targets, the ISP illustrates a 20-year actionable roadmap along with insights to direct policy maker and market participants. It also establishes renewable energy “corridors” by deploying transmission infrastructure and augmentations to unlock more renewables and improve power system security and reliability.

1.2. Transition Barriers

According to the NEM Fact Sheet [6] Australia possesses the world’s longest geographical electricity transmission network, stretching at 5000 km along the east coast. Unlike other countries, the long and skinny topological network in the NEM is associated with increased engineering challenges, such as network bottlenecks, thermal capacity, system strength, power quality, protection coordination, operational stability and controllability, etc., as most of the IBR asynchronous generation is connected in rural areas remote from conventional thermal generators and load centers.

The power system has been presenting new technical challenges with the growing share of inverter-based resources (IBRs) such as solar farms, wind farms, and battery energy storage systems [7]. Coupled with ISP, the AEMO Renewable Integration Study (RIS) draws conclusions on key changes and concerns in the power system. It states that the NEM is transforming from centralised to decentralised in location, from firm conventional generation to VRE, and from electromechanical to power electronics asynchronous in techonology. In light of the supply and demand balance, uncertainty and variability, and frequency and inertia, system strength is a recently-emerging transmission level problem that is seen as the final barrier to the transition [8]. AEMO prioritizes voltage stability and system strength regulation as a major challenge in the NEM [9]. It observed additional challenges emerging to the grid in terms of system stability, where intensive works and reformation have been undertaken by authorities to deliver a secure and reliable power system and withstand unexpected events.

In view of large-scale renewable energy development practices, in particular system strength studies, the renewable farms are mostly away from urban areas. Instead, urban areas are regarded as load centres which draw electricity from the grid. This is precisely the issue, as most conventional and renewable generators are located in areas fairly far away from urban areas or load centres, introducing the system strength problem discussed here. In summary, system strength is more of a problem in large scale solar/wind/BESS farm projects, rather than in the distributed rooftop type of small renewables which mainly exist in urban areas. Distributed generation issues in urban areas are more related to voltage, power quality, inverter control, and/or distribution substation capacity issues.

1.3. Current Grid Connection Challenges

In practice, each project involves more connection challenges and takes a longer time than expected to complete, mainly due to the increased level of connection difficulties, as follows:

- Variations in processes and requirements from different network service providers (NSP)
- Variations in comprehension for the same National Electricity Rule clause from different people at NSPs/AEMO
- Variations in NSP-AEMO combination process, either sequential or parallel
- Potentially many rounds of due diligence studies
- Increased time requirements
- Connection process can be restarted due to new generator commitment
- Studies can be revised by new simulation models released by original equipment manufacturers

Power transmission in the NEM has not kept in pace with energy transformation, causing congestion and delays. It is observed that stakeholders are losing confidence as a result of the connection and commission process lagging, contributing to issues such as contracting risk, scheduling risk, financial risk, and unanticipated changes [9]. Furthermore, the pandemic situation has magnified uncertainty in power demand, pricing, logistics, construction processes, etc., slowing the transition.

2. System Strength

SS has emerged as a technical challenge confronting Australian power systems transforming to a low-carbon future.

2.1. System Strength Definition

The term “System Strength” has been emerging to describe a complex and a broad area of system and generator stability, normal and protection operability, power quality, and system economics. In fact, the definitions vary across jurisdictions and continue to evolve as the international power system community’s collective understanding of the phenomena involved continues to grow. Theoretically, SS is the strength or ability of the electric power system to maintain its voltage during and following the injection of reactive current [10]. A recent study carried out by [11] stated that SS describes the resiliency of the voltage waveform to disturbances. In [12], the voltage sensitivity of various SS application during and after a fault is demonstrated. Comparing a strong grid with a weak grid, a grid with high SS can experience fewer changes following the injection of reactive power. According to the CIGRE 671 technical brochure, SS is the change rate in the IBR terminal voltage relative to its current injection variations. AEMO describe SS as the ability of the power system to return to stable operating conditions both during steady state operation and following a disturbance. As the understanding of SS becomes more mature, it is used to describe the sensitivity of maintaining and controlling the voltage waveform at any given location in the power system, and the ability of facilities to operate in a stable manner such that the system as a whole is able to sustain and recover from disturbance.

2.2. Related Technical Terms

There are a range of measures of system strength, including short circuit ratio (SCR) and the ratio of reactance to resistance (X/R). In general, system strength is widely assessed by SCR or available fault current (AFC) [13]. SCR has been widely used to qualify the stability of the system. A simple method of calculating SCR is to calculate the three-phase fault level divided by plant rating:

$$SCR = \frac{3\ ph\ fault\ level\ \ (MVA)}{proposed\ plant\ rating\ \ (MVA)}$$

where the three-phase fault level is determined for zero contribution from other inverter-based equipment. However, all other IBR impact the effective SCR at POC as the strong interaction by power electronic interfaced devices. Studies from CIGRE TB 068 and TB 671 have proposed multi-infeed short circuit ratio (MISCR) and weighted short circuit ratio (WSCR), respectively, for evaluating the connected AC strength from a voltage stability perspective [14]. Other research from [15] on the underlying concept of generalized SCR (gSCR) better illustrates the effectiveness of equivalent SCR to evaluate the stiffness of system from homogeneous multiple IBRs to inhomogeneous multiple power electronic feed-in systems:

$$gSCR = \frac{S_{aci}}{S_i + \sum_{j=1,2,...n,j\neq i} gMIIF_{ij} \times S_j}$$

where $gMIIF_{ij} = \frac{Z_{ij}}{Z_{ii}} \times \frac{x_{Rj}}{x_{Ri}}$, S_{aci} represents the short circuit capacity of main bus.

Another interpretation from [14] explains that the qualification of SS is coordinated to the equivalent impedance seen from inverter terminals into the POC for voltage variations during all operation conditions. Indeed, challenges can arise when operating power systems with low system strength (SS). The connection of inverter-based generating units to the power system can impact some of these measures, requiring a share and eroding the fault level or SCR.

SS can also be related to AFC at a specified location in the power system, with higher fault current indicating higher system strength with greater ability to maintain the voltage waveform. This affects the stability and dynamics of generating control systems and the ability of the power system to both remain stable under normal conditions and returning to steady-state conditions following a disturbance.

2.3. Reason for System Strength

Historically, SS in the NEM has predominantly been provided as a byproduct when energy is produced by large synchronous generators, and was abundant in many parts of the network.

3. Weak Grid Manifestations and Test Results

As shown in **Figure 1** below, a practical grid connection study of a 100 MW AC solar farm located in South Australia has been modeled and conducted. The active power limitation is set to 100 MW at POC, and grid SCR is modeled with six SCR scenarios in the simulation. The plots of **Figure 2** and **Figure 3** are based on the various dynamic analysis tests to demonstrate the impact of SS on system stability.

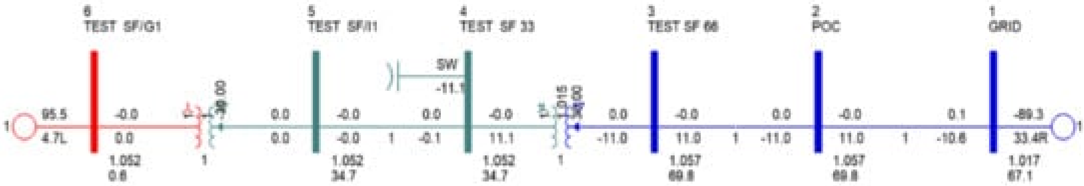

Figure 1. PSSE model of a Practical 100MW AC Solar Farm in South Australia.

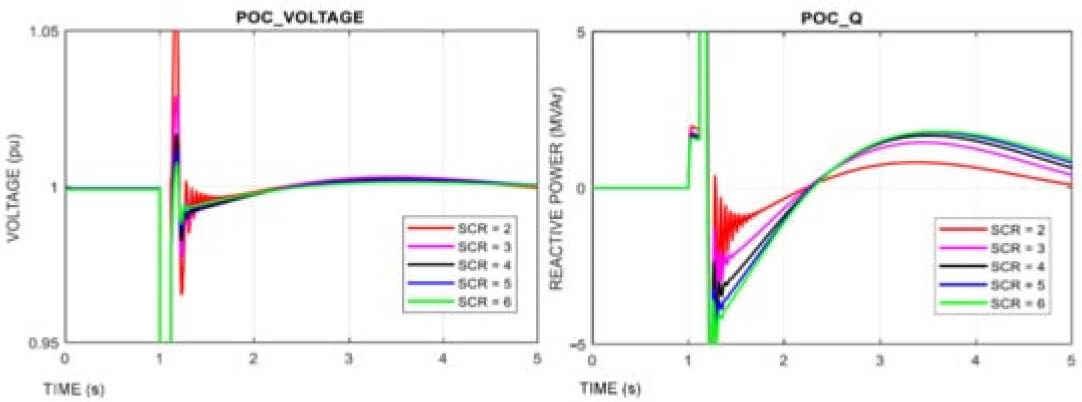

Figure 2. Result of Deep Fault Test: Voltage and Q response at POC.

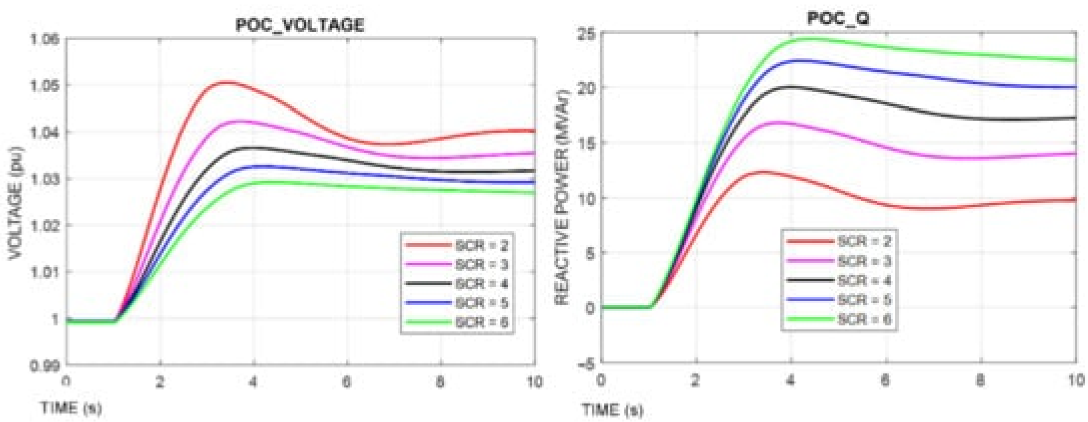

Figure 3. Result of 5% Voltage Step Test: Voltage and Q response at POC.

The plot of the Deep fault test indicates that oscillations can occur when applying the disturbance in the low SCR scenario, and that it takes longer for the weak grid to converge. In other words, these results illustrate that a reduction in SS reduces the controllability of the system, while the voltage responses grow more and more unstable after clearing the fault with reduced SCR values. Moreover, the dynamic state tests also demonstrate the capability of providing instantaneous reactive power injection for the power electronic device in response to any disturbance. Importantly, a fast response can translate into undamped voltage oscillations. Furthermore, it is noted that AEMO attempts to constrain and limit the number of VREs to ensure the security of system operation.

The plot of the 5% Voltage Step Test illustrates that a small amount of reactive power can lead to larger voltage changes in a weak grid, as well as that more reactive power is needed in order to adjust the terminal voltage in the low SCR scenario. **Table 1** summarizes the main issues associated with a weak grid.

Table 1. Summary of Main Issues Associated with Weak Grid [16].

Issue	Description
Inverter-based resource stability	IBR requires a minimum SS to remain stable and maintain continuous uninterrupted operation. Different types of converters use different strategies to match their output to the frequency of the system while maintaining voltage levels and power flows. In a weak system, this can lead to: • Disconnection of plant following credible faults in remote parts of the network • Adverse interactions with other IBG oscillations, as observed in practice in the NEM • Failure to provide sufficient active and reactive power support following fault clearance
Synchronous machine stability	Low SS can affect the ability of remote or small synchronous machines to operate correctly, resulting in their disconnection during credible contingencies.
Operation of protective equipment	Protective equipment within power systems works to clear faults on only the effected equipment, prevent damage to network assets, and mitigate risk to public safety. In weak systems: • Some protective equipment may have a higher likelihood of maloperation • Some protective equipment may fail to operate, resulting in uncleared faults and/or cascading tripping of transmission elements due to eventual clearance of the fault by out-of-zone protection, resulting in excessive disconnection of transmission lines and associated generation
Voltage management	Strong power systems exhibit better voltage control in response to small and large system disturbances. Weak systems are more susceptible to voltage

4. Australia Energy Market Operator. Final 2020 Integrated System Plan (ISP); AEMO: Sydney, Australian, 2020; pp. 32–40.

Historically, there have been several notable contingency events that led to the inadequate SS due to the arising challenge of the NEM [17]. The Australian Energy Market Commission (AEMC) has revised electricity rules more frequently since 2016 to ensure system security and stability.

4. System Strength Framework

As shown in **Table 2**, the newest framework as per Clause 5.20.C National Electricity Rules (NER V156) [18] requires that AEMO set fault level nodes and calculate minimum three-phase fault level amounts required at each of the nodes as a kind of proxy for SS provision across the NEM. According to [19], AEMO must publish an annual report regarding system strength requirements and including projections for SS amounts and any declared shortfall for the next five years. Correspondingly, local transmission network service providers (TNSP) or jurisdictional planning bodies are responsible for making and procuring available services to address the SS shortfall as directed by AEMO. TNSPs are required to provide SS service in each region and identify any fault level shortfall as part of the NTNDP. In addition, newly connected generators must remediate their own impact with a “do no harm” requirement for connecting to the network. If the connection of generators that demand system strength is the cause of some of these costs being incurred such generation should also share some costs of these services, as reflected in the system strength mitigation requirement (SSMR) [20]. The SS charges has been introduced to the SSMR to coordinate the mitigation option. The charges made up of the three factors shown below:

$$Total\ generator\ charge\ (\$) = SS\ price\left(\frac{\$}{MVA}\right) * SS\ locational\ factor * SS\ quantity\,(MVA)$$

where the first component, unit SS price, is fixed for a five-years interval; the second, SS locational factor, is related to the site-specific electrical distance at the POC, indexed with a five-year interval; and the last, SS quantity, represents the amount of SS service used by connection as fixed at the time of connection.

Table 2. System Strength Responsibilities under NER [17][21].

Participant	Obligation
Australia Energy Market Operator	Determine the level of SS required for existing generators to operate stably
Transmission Network Service Provider	Respond to a shortfall in SS within their network
Connecting Generator	Connecting generators must ‘do no harm’ to existing generators, loads, or network equipment. Remediate any ‘harm’ to existing levels of system strength
DNSP	Not considered yet
AER	Australia energy market regulator
AEMC	rule maker

5. AEMO. Renewable Integration Study (RIS) 2020. Available online: https://aemo.com.au/energy-systems/major-publications/renewable-integration-study-ris (accessed on 8 November 2020).
6. AEMO. Integrated System Plan 2020. Available online: https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp (accessed on 8 November 2020).
7. Upadhayay, N.; Nadarajah, M.; Ghosh, A. System Strength Enhancement with Synchronous Condensers for Power Systems with High Penetration of Renewable Energy Generators. In Proceedings of the 31st Australasian Universities Power Engineering Conference (AUPEC), Perth, Australia, 26–31 September 2021; pp. 1–5.
8. Peters, J.S. Control of Non-Synchronous Generating Plants to Improve Stability in Weak Grid Environments. Ph.D. Thesis, Monash University, Melbourne, Australia, 2018.
9. Vorrath, S. Grid Problems Now the Biggest Turnoff for Renewable Energy Investment in Australia. 2020. Available online: https://reneweconomy.com.au/grid-problems-now-the-biggest-turnoff-for-renewable-energy-investment-in-australia-73144/ (accessed on 8 November 2020).
10. Krishnayya, P.C.S.; Adapa, R.; Holm, M. IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities; Part I: AC/DC System Interaction Phenomena; CIGRE: Paris, France, 1997; pp. 1–216.
11. Xin, H.; Gan, D.; Ju, P. Generalized Short Circuit Ratio of Power Systems with Multiple Power Electronic Devices: Analysis for Various Renewable Power Generations. 2020. Available online: http://www.csee.org.cn/pic/u/cms/www/202103/26160215s7sc.pdf (accessed on 29 September 2021).
12. Hadavi, S.; Mansour, M.Z.; Bahrani, B. Optimal Allocation and Sizing of Synchronous Condensers in Weak Grids with Increased Penetration of Wind and Solar Farms. IEEE J. Emerg. Sel. Top. Circuits Syst. 2021, 11, 199–209.
1
1 rcuit 3282–
1 DC 480.
1 alia,

5. System Strength Planning

5.1. Setting Fault Level Nodes and Minimum Requirements

As previously stated, AEMO are responsible for investigating the ability of the system to provide adequate fault levels or sufficient resilience to changes in the voltage waveform, which traditionally has been provided by the injection of fault current from synchronous generators. With respect to selecting fault level nodes, there is a range of different ways that AEMO has identified to plan for system strength and resilience as the system changes.

First, AEMO has classified a variety of points in the network with different properties in order to measure the SS. As shown in **Table 3** [22], AEMO chooses at least one fault level node at each metropolitan load center considering the impact on high load concentrations, rooftop PV, and stabilizing reactive plant, etc. A synchronous generation centre which is contributing to fault levels as levels change in an area is considered an early warning of potential SS issues in a region. In addition, the penetration level of IBRs and electrically remote areas from SG are broadly evaluated for the scanning of SS requirements across a region by AEMO.

Table 3. Fault Level Selection.

Fault Level Nodes Selection Inputs	
Metropolitan Area	• Load centre • Rooftop PV, changing consumer mix • Impact on stabilising reactive plant
Synchronous Generation Centres	• Represent net fault levels from conventional synchronous generators • SG change level (decommissioning), potential area for SS issues
Synchronous Generation Centres	• Instability • Dilution of fault level for individual resources • Electrically remote from SG • Inherently weak grid area

5.2. Determining the Minimum Fault Levels

17. AEMO. Interim System Strength Impact Assessment Guidelines 2018. In System Strength Impact Assessment Guidelines; AEMO: Sydney, Australia, 2020; p. 43. Available online: https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/system-operations/system-security-market-frameworks-review/interim-system-strength-impact-assessment-guidelines-2018 (accessed on 13 November 2020).

18. The Australian Energy Market Commission. National Electricity Rules Version 156. Chapter 5: Network Connection, Planning and Expansion; The Australian Energy Market Commission: Sydney, Australia, 2020; pp. 598–608.

19. National Electricity Rules Change Proposal. 2020. Available online: https://www.aemc.gov.au/sites/default/files/documents/erc0300_rule_change_request_pending.pdf (accessed on 9 January 2021).

20. Huang, L.; Xin, H.; Wang, Z.; Zhang, L.; Wu, K.; Hu, J. Transient Stability Analysis and Control Design of Droop-Controlled Voltage Source Converters Considering Current Limitation. IEEE Trans. Smart Grid 2017, 10, 578–591.

21. AEMC. Efficient Management of System Strength on the Power System. 2021. Available online: https://www.aemc.gov.au/rule-changes/efficient-management-system-strength-power-system

Taking the selected nodes and projections for minimum synchronous machine (SM) combinations, AEMO then calculate the three-phase fault level at each of the nodes based on RMS analysis methods to evaluate the sufficiency of the fault level. If a shortfall is approaching, detailed EMT analysis including post-contingencies is conducted for full assessment; the success criteria include that IBRs remain online, SM returns to steady state after fault clearance, the region remains connected to the NEM, and transmission network voltage restores to normal operation band to withstand a protected or credible contingency event.

6. Remediation Approaches and Challenges

6.1. Synchronous Condenser

In terms of system strength remediation schemes, several studies have been carried out by consultants and different committees. The GHD knowledge sharing report from the ARENA funding program [23] compared various options that might be appropriate to tackle specific circumstances. The report concluded that adding synchronous condensers (Syn-con) is most likely to provide a solution at present. This approach has been well demonstrated in other jurisdictions, such as in Europe, to support higher levels of RE penetration. Syn-con represents a socialized, regulated network solution approach to ensure the diversity of SS solutions. However, despite concerning new technical challenges with integrating Syn-con, commercial risks for additional large capital expenditures may lead to investment risks. Furthermore, syn-con does not provide active power, and cannot address supply reliability requirements.

6.2. Converter Site-Specific Tuning and Grid Forming

A number of studies have investigated grid-forming inverters as an emerging technology that can provide SS as well as other dynamic grid voltage and frequency support [22] such as short circuit current and fault level contribution, which will be desirable in order to backfill the retirement of legacy SGs. In addition, appropriate site-specific tunings can enable regional network plants to operate in a stable manner. In particular, minimizing the incidence of inverter control system interaction under a reasonably diverse range of system operating conditions is a key desirable.

6.3. Synvhronous Machines

As the sources of SS, synchronous machines (SGs) with flexible fast start synchronous generation can deliver both system security and reliable service to the grid. One trade-off in offering fast start capability, particularly in gas-fired aeroderivative and reciprocating engine-based plants, is the typically lower inertia in these plants. Inertia in the range of 1–2 s can impact certain aspects of the fault ride-through performance characteristics of such plants. Another approach suggests SGs working in syn-con mode for SS provision. However, this solution is costly, and its economic efficiency needs to be carefully evaluated.

6.4. Distributed Energy Resources

Accordion to [24][25], distributed PV and virtual power plants have a supporting contribution to offer the overall network SS issue. This approach ensures that embedded generation has sufficient capability to ride through voltage faults and to not exacerbate primary dynamic stability issues on the transmission network. This points to the need for flexible dynamic DER technical standards related to medium-voltage and low-voltage network management and dynamic fault ride-through network support.

6.5. New Network Infrastructure

Lastly, new network infrastructure in particular can reduce network electrical impedance and provide N-1 coverage of any planned or unplanned outages of critical transmission assets. As mentioned in the previous study, AEMO released ISP in order to smooth the energy transition; however, most of the upgrades in infrastructure programs have to be undertaken for RIT-T testing, which leads to schedule risks for developers deploying green-field for potential projects.