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Review

An Overview of System Strength Challenges in Australia's National Electricity Market Grid

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Abstract: 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. In order to facilitate decarbonization pathways, Australia is the first country to evolve system strength and inertia frameworks and assessment methods to accommodate energy transition barriers, and other parts of the world are now beginning to follow the same approach. With the evolvement of the system strength framework as a new trending strategy to break the transition barriers raised by renewable energy project development and grid connection studies, this paper provides a high-level overview of system strength, covering such fundamental principles as its definition, attributes, and manifestations, as well as industry commentary, cutting-edge technologies and works currently underway for the delivery of a secure and reliable electricity system with the rapid integration of inverter-based resources (IBRs) in the NEM grid. The intent of this study is to provide a comprehensive reference on the engineering practices of the system strength challenge along with complementary technical, regulatory, and industry perspectives.

Keywords: asynchronous machine; fault level; inverter-based resource; transition; system strength; weak grid

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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 light of hundreds of countries pledging to achieve carbon neutrality, renewable energy (RE) development has been boosted from market-led private sector to policy-led public sector to transit to a net-zero carbon future [4]. 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 [5]. Recent research from [6] 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 [6] 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 [7], 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.

Referring to the views of ISP 2020, a phenomenal ~20 GW of existing fossil-fuel generation fleet in the NEM is expected to be decommissioned on reaching the end of design life by 2040. The retired capacity is projected to be replaced by more than 26 GW of additional VRE generation, based on ISP forecasts. However, despite the COVID-19 situation, clean energy investment is struggling as extensive issues emerging behind the ambitions. The complications and major barriers to VRE project development will be discussed in the following section.

1.2. Transition Barriers

According to the NEM Fact Sheet [7] 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 [8]. 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 [9]. AEMO prioritizes voltage stability and system strength regulation as a major challenge in the NEM [10]. 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.

Taken together, the facts presented in this section provide crucial insights into the primary awareness of system strength. In other words, this trend maps out that system stability issues need to be mitigated in order to ensure more resilient power systems and enable more VRE project to be registered in the NEM. A technical and detailed review is provided in section two.

1.3. Current Grid Connection Challenges

This paper is focused on an important factor in renewable energy project development grid connection requirement based on the system and regulatory environment of the Australian NEM. Grid connection studies are mandatory for new VRE generators to connect to the power system. Taking the management of system security and maintenance of the grid's reliability as priorities, RE project system design needs to align with the national electricity rules and meet the grid connection Automatic Access Standard or Minimum Access Standard in both steady and dynamic state assessment. AEMO and NSP undertake independent analysis for due diligence in the connection application. Having discussed the transmission network challenges in the previous section, AEMO published System Strength Impact Assessment Guidelines in 2018 for assessing the impact of proposed connection applications. The guidelines assumed an *SCR* below 3 p.u. at point of connection (POC), seen as a weak point triggering a full impact assessment and remediation [11].

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 [10]. Furthermore, the pandemic situation has magnified uncertainty in power demand, pricing, logistics, construction processes, etc., slowing the transition.

1.4. Key Contributions and Achievements

Based on recent renewable energy project development experiences and grid connection studies, this paper provides a high-level practical overview of system strength for NEM in the Australian grid. To the best of the authors' knowledge, this serves as the first such review attempt on system strength. The intent of this study is to provide a comprehensive reference on the engineering practices of the system strength challenges along with complementary technical, regulatory and industry perspectives. The main contributions of this paper include: (i) a comprehensive review of renewable energy development in Australia; (ii) the current status of and challenges faced by renewable energy projects in Australia; (iii) a detailed overview of power system strength as a key factor contributing to renewable energy grid connection practices in Australia; and (iv) a list of system strength evaluation and enhancement approaches summarized out of real renewable energy project grid connections in the Australian NEM. The paper aims to be a practical reference for engineers and renewable project developers in understanding the technical and financial risks associated with system strength in evaluating the feasibility of a renewable energy project's grid connection work, in the context of the Australian NEM. Although the review and analysis are based primarily on the Australian NEM, the findings and recommendations in this paper also provide both theoretical and technical guidance to other power grids internationally in terms of the transition towards renewable energy grids.

In this paper the definition, technical challenges, priority issues, impacting factors and requirements of SS are demonstrated in Section 2. Section 3 reviews SS frameworks that identify and evaluate regulatory reforms, obligations, and current assessing methods. SS planning from a planning perspective is discussed in Section 4. Technical approaches to system strength along with its attributes are summarized in Section 5, followed by emerging solutions to allocation of system strength shortages. Furthermore, Section 6 outlines concerns about the current regulatory and grid connection requirements for project development under the condition of low system strength. Finally, Section 7 concludes the paper and points out future research trends on this topic.

2. System Strength

SS has emerged as a technical challenge confronting Australian power systems transforming to a low-carbon future. Much attention has focused particularly on SS supplied primarily by rotational generation and maintaining power system stability [10]. This section presents a high-level review of the fundamental principles of SS, including explanation, driving force, influencing factors and manifestations.

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 [12]. A recent study carried out by [13] stated that SS describes the resiliency of the voltage waveform to disturbances. In [14], 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) [15]. *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:

$$SCR = \frac{3\ ph\ fault\ level\ (MVA)}{proposed\ plant\ rating\ (MVA)} \tag{1}$$

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 [16]. Other research from [17] 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:

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

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 [16] 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.

The provision of system strength is becoming more important given the rapid connection of large numbers of new, non-synchronous generation sources in transitioning to a low carbon future. As indicated in [18], voltage waveform stability is related to the waveform provision of synchronous machines, the stability of IBRs, and the rest of network stability management, with the two latter on the demand side approach. SS is an essential system service for electricity markets. It is necessary to support a secure and stable power system that can withstand voltage disturbances and unexpected events.

High penetration of asynchronous renewable integration and the unique topology of the Australian transmission network have created new challenges to power system stability, reliability, and controllability. To facilitate the transition underway, AEMC initiated the *Investigation into the system strength frameworks in the NEM* in March 2020; the corresponding regulatory reformation will be illustrated in Section 3.

3. Weak Grid Manifestations and Test Results

Previous studies have explored that the IBR is inherently different from rotational thermal generation. The characteristic negative damping manner of power converters leads to power system oscillation, and even to voltage collapse and power system cascading failure during contingency events. This section will illustrate the driving forces and results for the different SS which influence system performance by examining a case study.

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 by authors. 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 Figures 2 and 3 are based on the various dynamic analysis tests to demonstrate the impact of SS on system stability.

Comparing the performance when *SCR* equals 2, 3, 4, 5, 6 for the Deep Fault Test and 5% for the Voltage Step Test, the key outcomes of this simulation are as follows.

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.

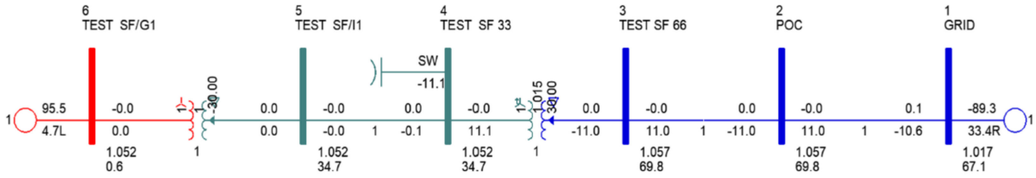

Figure 1. PSSE model of a Practical 100MW AC Solar Farm in South Australia.

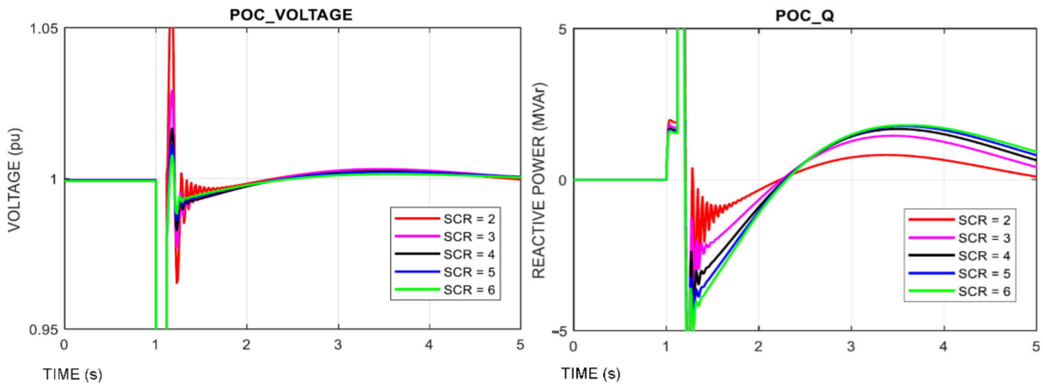

Figure 2. Result of Deep Fault Test: Voltage and Q response at POC.

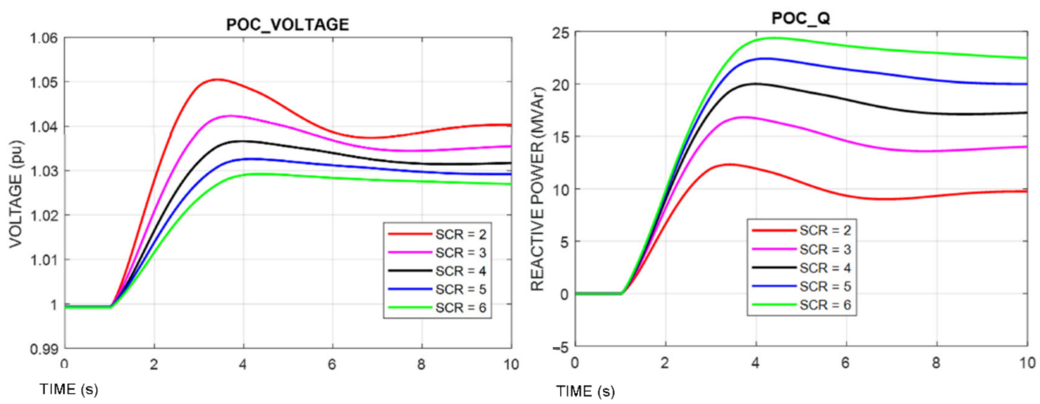

Figure 3. Result of 5% Voltage Step Test: Voltage and Q response at POC.

The plot of the 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.

Other observations from various VRE simulation studies include:

- All EMT models exhibit stable performance where the *SCR* is >3 at the *connection point*, and it is noted that the *SCR* at a generating unit's terminals will be lower than that of POC
- Reducing the *SCR* below 2 will increase the likelihood of power system instability;
- The linkage between the *SCR* and X/R ratio becomes more pronounced as the *SCR* ratio declines

- With *SCR* of >3, X/R ratio has a negligible impact
- It has been observed that some models exhibit stable response only for X/R ratios > 2 when operated under very low *SCR* conditions
- The *SCR* threshold during Preliminary Assessment can be set at 3, based on observed performance in EMT simulation studies of four large-scale transmission-connected wind farms and one large-scale transmission-connected solar farm [19].

Table 1. Summary of Main Issues Associated with Weak Grid [20].

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 instability or collapse.

Historically, there have been several noncredible contingency events that led to blackout or islanding due to the arising challenge of generation mixture in the NEM [19]. The Australian Energy Market Commission (AEMC) has revised electricity rules more frequently since 2016 to ensure system security and stability. The next section will summarize regulatory reforms addressing priority issues in the NEM.

4. System Strength Framework Review

To date, there has been shared responsibility between different participants under the current regulatory arrangements for addressing SS issues. In September 2017, the AEMC initiated changes to the national electricity rules (NER) to place SS obligations on AEMO, TNSPs and VRE generators in order to strengthen the power system [21].

As shown in Table 2, the newest framework as per Clause 5.20.C National Electricity Rules (NER V156) [22] 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 [23], 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) [24]. The SS charge has been introduced to the SSMR to coordinate the mitigation option. The charge is made up of the three factors shown below:

$$Total\ generator\ charge(\$) = SS\ price\left(\frac{\$}{MVA}\right) * SS\ locational\ factor * SS\ quantity(MVA) \tag{3}$$

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 [19,25].

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

Issues with Current Arrangement

AEMO's ISP 2020 has identified 35 Renewable Energy Zone (REZ) candidates and targeted grid augmentation to facilitate the potential of renewables. However, observation shows that large amounts of VRE connected to the same area may cause interaction during or following a disturbance. Because renewable devices are based on power electronic interfaced technology, they can respond quickly due to the control system design of such devices. These fast responses can be translated in a way that aggravates disturbances. Thus far, reductions in SS that reduce the controllability of the power system have not been encountered in this case.

While there is limited practical experience and technical capability, the existing framework for managing the system strength of power systems is contributing to inefficient investment in SS services, rising cost of generator connections, and the increasing risks and costs of securing power system operation. Issues raised with the current arrangement include the requirement for AEMO to declare a system strength shortfall prior to TNSPs being required/able to take action. Some TNSPs have suggested that it is difficult for them to account for the occurrence of shortfalls in their own planning processes in a timely manner [26]. Thus, investment and economical scale is unforeseen due to the remediation costs of both connecting IBRs and TNSPs. Last but not the least, the obligations between TNSPs and AEMO are unclear under the 'do no harm' framework. In 2020, Transgrid proposed to abolish the 'do no harm' obligation and amend the minimum system strength requirements. This was intended to provide SS in the NEM in a more proactive manner, to maintain a secure power system, and to provide additional levels of system strength to streamline the connection of new non-synchronous generators. In order to establish confidence in RE investment, stakeholder engagement, transparency concerning grid constraints and processes undertaken by authorities, and most importantly, improvements to the existing framework should be highly considered by the AEMC and AEMO.

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 [27], 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

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. Table 4 lists outcomes for shortfall and potential inadequate areas of system strength and inertia for 2020 [26].

Having discussed constraints and key issues in reviewing literature in the previous section, this section overviews the transitional challenges from identifying and stating the current issues to locating possible solutions. There have been a wide range of technologies developed to address the SS shortfall, such as installation of synchronous condensers, transmission network equipment, emerging options on tuning of inverters, runback schemes, etc., and grid forming inverters are expected to be an area of strong technological innovation in the next several years as the industry adjusts to the new system strength. Different solutions and approaches are discussed in the following sections.

Table 4. Summary of system strength and inertia outcomes for 2020 in the NEM.

	Currently		**2025**	
	System Strength	**Inertia**	**System Strength**	**Inertia**
NSW			Potential for shortfalls at Newcastle and Sydney West	
QLD	Shortfall at Ross		Potential for shortfalls at Gin Gin	Potential for inertia shortfall
SA	Synchronous condensers project underway	Shortfall extended to June 2023		
TAS	Potential for shortfall at several nodes	Potential for inertia shortfall	Shortfall from May 2024	Shortfall from May 2024
VIC	Services in place at Red Cliffs until 2022			

6. Remediation Approaches and Challenges

The previous section presented the impact factors on the overall SS. The assessment of new generators is performed in order to determine whether there will be an adverse system strength impact. Generators may either propose a system strength remediation scheme (almost always cheaper), or NSP may propose system strength connection works at the expense of the generator to mitigate the SS issue.

Traditionally, asynchronous technology has been generally considered to have an adverse impact on system strength. While emerging technologies such as grid-forming inverters will likely have a positive contribution, network topology with aggregated IBRs and synchronous unit scarcity are other key influence factors to SS that need to be considered.

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 [28] 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.

Currently, AEMO has issued directions for synchronous generators to be online in order to meet minimum system strength requirements. Four Syn-Cons have been installed by ElectraNet in recent years to manage system strength.

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 [27] 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.

This approach was demonstrated in the recent resolution of the West Murray Zone and north Queensland IBR area. According to Irwin (2020), it is a major area of current interest within the field of "synthetic inertia" to provide constant voltage reference and stabilise generator performance. Ram (2020) explained the fundamental difference between synthetic inertia and rotational generation. Ram also highlighted the complexity of control logic and the potential problems and requirements for introducing new technology. Winodh mentioned that system stability study is carried out by analysing the characteristics of inverter impedance [21]. Much of the literature published to date has tended to focus on the improvement of control strategy or mechanisms such as grid forming/virtual inertia, which specify the power plant controller (PPC) and inverter setting in order to improve power plant performance. A recent case study [28] from Powerlink indicated that Syn-Con is not the only option for SS remediation, and IBRs are not always a concern for SS if they are well designed and tuned as IBR can improve SS.

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 [29,30], 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 and Other Approaches

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.

From a project development perspective, most designs in the early development phase target a higher matrix of internal rate of return (IRR), annual production, or net present value (NPV), while failing to give sufficient consideration to "grid connection capability". Difficulties arise when a project attempts to connect to a weak grid in order to commence its power system stability studies. As mentioned previously, the remediation scheme may be required, which can highly impact the project investment model. In practice, the journalist Maisch (2020) writing in PV-magazine reported that a 1GW solar project may have to be curtailed in QLD, and observed that more projects are suffering in the long run from the system strength issue, even in the commissioning or operation stage. These facts, however, set a clear signal to pioneering a whole-of-system approach and market perspective to collectively arrive at a technically and economically efficient solution which enhances VRE integration.

Taking cross-sectional studies and limitations into account, Table 5 summarizes the advantages and disadvantages for SS provision of different potential approaches. As most of the remediation schemes are deployed with unconservative expected cost estimates, aggregates of new technology are underexperienced in practical commissioning, and additional challenges may be faced from the perspective of both generators and system operators.

Table 5. Pros and Cons of Approaches to System Strength Provision.

Solution	Advantages	Disadvantages
Synchronous Condenser, contracting with existing generators	• System strength enhancement • Improved system stability • Increased line power transfer capability • Fault current contribution • Inertia provision	• Higher cost than SVC, • STATCOM and TCSC
IBG control enhancement, advancing technology, e.g., fine tuning, grid-forming	• Reduced system strength requirements • Less detrimental interactions between IBGs • Least cost	• Limited fault current contribution • Difficult to coordinate, vendors.
SVC, STATCOM	• Improved voltage stability. • Fault current contribution • Suppress inter-area oscillations	• No inertia
Synchronous Generator working in Syn-con mode, fast start SG to provide SS services	• System Strength Enhancement • Improved system stability • Increased line power transfer capability • Fault current contribution • Inertia provision	• Higher cost than synchronous condenser
Runback Schemes, Network augmentation infrastructure, upgrades, interconnector, configurations	• System Strength Enhancement • Improved system stability • Increased line power transfer capability • Configurations to reduce impedance • Reduce rating of proposed plant	• Higher cost • Environment impact • No inertia

6.6. Limitation and Further Consideration

The system strength shortfall not only affects new connections; it also affects existing networks and generators. Low system strength has emerged as an issue as the generation mix shifts from one dominated by synchronous generators to one with a growing proportion of asynchronous renewable generation. Low system strength issues can be expected to pose challenges in the NEM in the future.

Regarding the connection of new IBRs near existing inverter-based generation (IBG), practical experience indicates that this could degrade the performance of the existing IBG even though the total fault level including the new IBG would increase. While the fault current contribution from asynchronous generation would result in a higher three-phase fault level, this does not indicate that the SS has increased. Because the fault level is generally used as a simplified proxy for SS, it is essential to notice that AEMO calculates the minimum three-phase fault level at each fault level node contribution from SM only. In most situations, developer and manufacturer do not have access to the precious *SCR* label or SS at the point of connection (POC). Moreover, emerging advanced technologies such as grid forming and virtual synchronous technologies, provide both SS and fault current contribution. Such asynchronous generation should be included when determining the system strength requirements with their uptakes. SS is provided incidentally, and the provision of those services is closely linked to the timing of any closures and additional operators, which leads to uncertainty for market participants.

7. Conclusions

Australia has an enormous opportunity to become an energy transition leader and global test lab because of its status as a world leader in combatting transition barriers and issues of system strength and inertia scarcity. Industry authorities and researchers have been developing state of art reforms and solutions to tackle transitional challenges and pave the way for combating climate change. SS is an essential system service that is needed in order to support a secure, reliable and resilient power system. The provision of SS is becoming more crucial given the rapid connection of large numbers of new asynchronous generation in transitioning to a low-emissions future.

This paper has focused on analysing the current transitional barriers within the NEM, demonstrating the principles of system strength, and overviewing AEMO planning and regulatory reforms intended to clear path for the transformation, following with a discussion of various approach to addressing SS challenges. However, with most of the remediation schemes deployed at unconservative expected costs, new technology in the aggregates is not well-understood when it comes to experience with practical commissioning. Additional challenges remain from the perspective of both generators and system operators.

Finally, the limitations and recommendations presented here bridge the gap between market reforms and industry in order to confront and accommodate the constraints imposed by weakness in the grid, rebuild investor confidence, and unlock additional VRE opportunities.

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References

1. Blakers, A.; Lu, B.; Stocks, M. 100% renewable electricity in Australia. *IEEE J. Photovolt.* **2019**, *9*, 1828–1833. [CrossRef]
2. Smith, A. A Roadmap for Australia's Energy Transition. 2020. Available online: https://www.jonesday.com/en/insights/2020/08/a-roadmap-for-australias-energy-transition (accessed on 4 November 2020).
3. Gu, H.; Yan, R.; Saha, T. Review of system strength and inertia requirements for the national electricity market of Australia. *CSEE J. Power Energy Syst.* **2019**, *5*, 295–305. [CrossRef]
4. Finkel, A. *Implementing the Independent Review into the Future Security of the National Electricity Market (FINKEL REVIEW)*; AEMC: Sydney, Australia, 2018.
5. Australia Energy Market Operator. *Final 2020 Integrated System Plan (ISP)*; AEMO: Sydney, Australian, 2020; pp. 32–40.
6. 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).
7. 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).
8. 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. [CrossRef]
9. Peters, J.S. Control of Non-Synchronous Generating Plants to Improve Stability in Weak Grid Environments. Ph.D. Thesis, Monash University, Melbourne, Australia, 2018.
10. 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).

11. Maintaining Power System Security with High Penetrations of Wind and Solar Generation. 2020. Available online: https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/future-energy-systems/2019/aemo-ris-international-review-oct-19.pdf?la=en (accessed on 11 November 2020).
12. Krishayya, 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.
13. 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).
14. 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. [CrossRef]
15. Gavrilovic, A. AC/DC system strength as indicated by short circuit ratios. In *International Conference on AC and DC Power Transmission*; IET: London, UK, 1991; pp. 27–32.
16. Huang, L.; Xin, H.; Li, Z.; Ju, P.; Yuan, H.; Wang, G. Identification of Generalized Short-Circuit Ratio for On-Line Stability Monitoring of Wind Farms. *IEEE Trans. Power Syst.* **2020**, *35*, 3282–3285. [CrossRef]
17. Zhang, F.; Xin, H.; Wu, D.; Wang, Z.; Gan, D. Assessing Strength of Multi-Infeed LCC-HVDC Systems Using Generalized Short-Circuit Ratio. *IEEE Trans. Power Syst.* **2018**, *34*, 467–480. [CrossRef]
18. Yuan, H.; Xin, H.; Huang, L.; Wang, Z.; Wu, D. Stability Analysis and Enhancement of Type-4 Wind Turbines Connected to Very Weak Grids Under Severe Voltage Sags. *IEEE Trans. Energy Convers.* **2019**, *34*, 838–848. [CrossRef]
19. 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).
20. Australia Energy Market Operator. *Power System Requirement*; AEMO: Melbourne, Australia, 2020; p. 23.
21. AEMC. Managing Power System Fault Levels. 2017. Available online: https://www.aemc.gov.au/rule-changes/managing-power-system-fault-levels (accessed on 7 January 2021).
22. 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.
23. 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).
24. 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. [CrossRef]
25. 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 (accessed on 23 December 2021).
26. Australian Energy Market Commission. *Final Report-Investigation into System Strength Frameworks in the Nem*; AEMC: Sydney, Australia, 2020; pp. 23–35.
27. AEMO. (AEMC 2018) Operational Analysis and Engineering. In *System Strength Requirements Methodology*; AEMO: Melbourne, Australia, 2018; pp. 12–20.
28. GHD. Managing System Strength during the Transition to Renewables. 2020. Available online: https://arena.gov.au/assets/2020/05/managing-system-strength-during-the-transition-to-renewables.pdf (accessed on 9 January 2021).
29. Goyal, S. System Strength Challenges: An Overview of Energy Transition in Australia's National Electricity Market. In Proceedings of the 2021 IEEE 4th International Electrical and Energy Conference (CIEEC), Wuhan, China, 28−30 May 2021; pp. 1–6. [CrossRef]
30. Liu, Y.; Li, Y.; Gooi, H.B.; Jian, Y.; Xin, H.; Jiang, X.; Pan, J. ADMM Based Distributed Robust Energy Management of Multi-Microgrid System in the Real-Time Energy Market. *IEEE Trans. Sustain. Energy* **2017**, *10*, 396–406. [CrossRef]