System Strength

March 2020

System strength in the NEM explained

Important notice

PURPOSE

AEMO has prepared this document to provide general information about AEMO's interpretation of the application of the National Electricity Rules relating to system strength in the National Electricity Market, as at the date of publication.

DISCLAIMER

The interpretation of rules and assessments of system strength may change based on subsequent legal or technological developments, and the information in this document may not be current when you read it. This document does not constitute legal or business advice, and should not be relied on as a substitute for obtaining detailed advice about the National Electricity Law, National Electricity Rules or any other applicable laws, procedures or policies. Anyone considering the information in this publication for a specific purpose should obtain independent and specific advice from appropriate experts. AEMO has made every reasonable effort to ensure the quality of the information in this document but cannot guarantee its accuracy or completeness.

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VERSION CONTROL

Version	Release date	Changes
1.0	23/03/2020	Original document

Contents

1. Introduction

The Australian Energy Market Commission (AEMC) made a rule on managing power system fault levels in 2017[1] (Fault Level Rule), which created a new framework in the National Electricity Rules (NER) for the management of system strength. The Fault Level Rule responded to a need to facilitate the safe and secure operation of the National Electricity Market (NEM) power system with increasing levels of inverter-based resources (IBR)[2].

The Fault Level Rule sought to ensure that adequate sources of system strength would remain available (or be made available) to assist in the management of power system security and enable the secure operation of IBR. There are two parallel mechanisms in the NER to achieve this outcome: minimum three-phase fault levels to be maintained by transmission network service providers (TNSPs) for the power system to be in a secure operating state, and obligations on connection applicants (primarily Generators) to remediate adverse system strength impacts resulting from their connection (or alteration).

System strength is generally not well understood. This document seeks to address some common misunderstandings by presenting AEMO's views on:

- The meaning of system strength.
- The importance of system strength.
- Relationship between system strength and other power system stability phenomena.
- Assessing system strength.
- Impact on system strength from new connections, and the application of system strength remediation.
- System strength from a planning perspective.

2. Terminology

This section provides an explanation of the terms used in this paper to explain certain power system phenomena, and their relation to each other.

2.1 Fault current

The electrical current that flows during a fault (also referred to as the short circuit current) measured in Amps. Fault current is a location-specific parameter.

2.2 Fault level

This is a shorthand for the term 'three phase fault level' used in the NER. It is calculated at network nodes, called fault level nodes. Those located close to synchronous generating systems will be higher, whereas those that are remote from synchronous generating systems will be lower. This is generally measured in MVA. The three phase fault level (in MVA) is proportional to the fault current (in Amps) and the voltage (in Volts).

[1] National Electricity Amendment (Managing power system faults) Rule 2017 No.10. Available at: https://www.aemc.gov.au/sites/default/files/content/38cbd875-6295-4d8d-acd6-52d5adfc3041/System-Strength-Final-Rule-19-Sept-2017-VERSION-FOR-PUBLICATION.PDF.

[2] The term IBR is generally considered to cover wind and solar generation technologies, battery energy storage systems and direct current network links.

2.3 System Strength

System strength is not defined in the Fault Level Rule, however, in its Final Determination, the AEMC stated[3]:

> System strength is a characteristic of an electrical power system that relates to the size of the change in voltage following a fault or disturbance on the power system.

AEMO sees system strength as the ability of the power system to maintain and control the voltage waveform at any given location in the power system, both during steady state operation and following a disturbance. The system strength at a given location is proportional to the fault level at that location, inversely proportional to effective grid-following IBR penetration seen at that location (where close by grid-following IBR reduces system strength more so than electrically distant IBR). System strength is also a function of the severity of system events on the stability of IBR (for example, loss of a major transmission line connecting the aforementioned location to the broader power system, resulting in sudden changes in fault level and voltage angle at that location).

2.4 Short Circuit Ratio (SCR)

SCR is the synchronous three phase fault level (in MVA) divided by the rated output of an IBR generating system (in MW or MVA) measured at the generating system's connection point.

2.5 Synchronous machines

This is a shorthand referring to synchronous generating systems and synchronous condensers. Unlike most IBR, synchronous machines are electro-magnetically coupled to the power system. Synchronous machines are a source of system strength.

2.6 Inverter-based resources

Unlike synchronous machines, the current generation of grid-following IBR provide a significantly lower and different contribution towards fault level, which means that the lowest system strength on a power system is likely to be in a part where generation is dominated by IBR and electrically remote from synchronous machines.

2.7 Voltage waveform

Many variables are used to measure the outputs of a power system, but this paper concentrates on voltage. The NEM's power system operates at various alternating current (AC) voltage levels, and includes a dedicated DC interconnection between Victorian and Tasmania, as well as both AC and DC connections between Victoria and South Australia and NSW and Queensland. The transmission network used for the bulk transfer of power operates at higher voltages than the 'poles and wires' used for power distribution to most electricity consumers. When plotted on a two-dimensional graph, the AC voltage at any point on the power system can be represented as a sine waveform, as shown in Figure 1. The waves, in fact, are three dimensional, each one called a phase that flows at a 120° angle to each other. A power system fault could cause one or more of these perfect voltage waveforms to distort. Figure 2 depicts this for one phase, only.

[3] Page 3, AEMC 2017, Managing power system fault levels, Rule Determination, 19 September 2017, Sydney. Available at: https://www.aemc.gov.au/sites/default/files/content/4645acea-e66f-4b5b-94a1-1dd14e7f8a93/ERC0211-Final-determination.pdf.

Figure 1 Voltage waveform under normal operating conditions

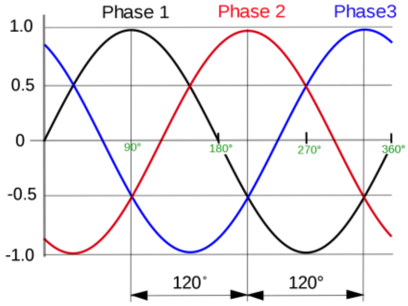
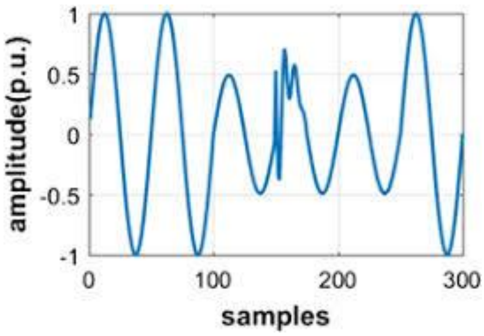


Figure 2 Voltage waveform depicting a disturbance



2.8 Relevance of system strength

System strength is one determinant of how well the power system can return to normal operation following a disturbance or fault, or to put it another way, how quickly the power system voltage waveform can be restored to the consistent sine wave seen in Figure 1. In practical terms, power systems with system strength can maintain more stable voltages following changes in power flows.

2.9 Relationship with inertia

The NER treat system strength and inertia differently, but it is not unusual to find that a fault level shortfall and inertia shortfall jointly arise, as both system strength and inertia are provided by synchronous machines. System strength contribution and inertia are design and operational characteristics of synchronous generation technology that are not easily replicated in IBR, as yet. They are provided by synchronous generation as a by-product of energy production, and by synchronous condensers.

As synchronous machines change operating patterns (for example, when they are displaced in the bid stack during high IBR output or when they retire) the power system loses both system strength and inertia. Local increases in the level of IBR can increase the need for system strength in that part of the power system since IBR currently require system strength to operate stably.[4]

System strength is expressed in the NER by reference to fault levels while inertia to rates of change in frequency (RoCoF). They are related because inertia is critical for the power system's resilience to changes in active power.

In spite of these similarities, their remediation is different. For example, if synchronous condensers are used to address a fault level shortfall, they will provide enough fault level, but will not address an inertia shortfall unless they are coupled with a rotating mass or flywheel.

3. The importance of system strength

3.1 Characteristics of low system strength

A power system with low system strength will exhibit one or more of the following:

- Wider area undamped voltage and power oscillations.
- Generator fault ride-through degradation.
- Mal-operation or failure of protection equipment to operate.

[4] For an alternative view, see the discussion of the relationship between system strength and inertia in National Grid, System Operability Framework 2014. Available at: https://www.nationalgrideso.com/document/63446/download.

- Prolonged voltage recovery after a disturbance.
- Larger voltage step changes after switching capacitor or reactor banks.
- Instability of generator / dynamic plant voltage control systems.
- Increased harmonic distortion (a by-product of low system strength and higher system impedances).
- Deeper voltage dips and higher over-voltages (e.g. transients).

3.2 The need for system strength

System strength is important for the maintainence of normal power system operation, for the power systems dynamic response during a disturbance, as well as for returning the power system to stable operating conditions. Adequate system strength is required to ensure:

- Stable operation of IBR.
- Ensure network voltage remains stable and stays within a standard range following:
  - Switching operations (capacitors, reactors and circuit).
  - Variations in load.
  - Disturbances on the network.
- Protection equipment to operate correctly during disturbances.
- Power quality is maintained.
- Support network voltage during faults and enable rapid recovery after fault clearance.
- Correct operation of generator control systems.
- Avoiding commutation failure of line commutated High Voltage Direct Current (HVDC) links.

3.3 Sources of system strength

Fault current levels are high in strongly interconnected (or meshed) transmission systems or in network areas with a material number of online synchronous machines. Synchronous machines have traditionally provided fault current in NEM transmission networks. In future, we expect to see more examples of inverter-based technology that doesn't reduce system strength, or even contributes towards system strength.

3.4 System strength and inverter-based resources

Modern wind and solar PV generation as well as battery energy storage systems connect to the grid using power electronics inverter-based technology and require adequate system strength for the inverters to work reliably.

The more remote the IBR is from synchronous machines and the higher the penetration of IBR, the more likely it is that voltage waveforms will be impacted by disturbances in the network as well as the IBR itself. This is because synchronous machines are electro-magnetically coupled to the power system's voltage waveform, whereas an inverter is decoupled from the grid by the inverter and, at present, inverters do not create a voltage waveform like a synchronous machine[5].

Complex interactions exist not only between an inverter and the grid, but also between connected inverters.

For grid following inverters to operate, inverters must follow the grid voltage waveform seen at their terminals and inject current at an angle that follows the measured voltage. In a process known as a phase-locked-loop,

[5] Some inverters have grid forming capability, where they can be placed in voltage source mode, but they have not yet been proven successful for normal operation when connected to the NEM.

the inverter creates a synchronous clock driven by the voltage phase angle it senses from the grid. Following the occurrence and cessation of a fault, the inverter must re-lock onto the grid quickly to ensure stable control. Under low system strength conditions, the phase angle change between the pre-fault condition to fault clearance will be larger than on stronger systems, making this much more difficult[6].

If the voltage phase angle detected by an inverter is inaccurate, the current is not injected correctly, and will impact the voltage waveform to which it is connected. This further impacts the voltage that the inverter sees at its terminals which, in turn, impacts the current it injects, and so the process repeats. These interactions can occur at low frequencies (below 50Hz) as well as high frequencies (above 50Hz). In an interconnected power system, these control interactions can have a cascading impact on the voltage waveform, and could result in widespread disruption if not corrected.

The larger the number and capacity of IBR connected in close proximity to each other, the greater the system strength the power system needs at that location to maintain stability because there is a higher potential to influence voltage. Hence, the ability of the network to resist the change in voltage needs to be greater. The North American Electric Reliability Council provides a good reference to the IBR requirements of system strength[7].

Many inverter manufacturers offer different strategies for weak and strong networks and also specify a minimum SCR for which their inverter's operation is able to operate in a stable manner. Where the SCR (calculated at the inverter terminals in this example) is above the manufacturer-specified minimum level, the operation of the inverter phase-lock-loop is more robust, which means that SCR-type measures can be used as a screening metric for likely inverter stability issues. Correct operation is still dependent on a range of other factors, however, including voltage angle changes and the stability of other IBR in the area.

Managing stability in low system strength conditions often requires a combination of minimum support from the network in conjunction with coordinated tuning of power electronic control systems of existing and new equipment.

4. Assessing system strength

4.1 Assessing system strength in a region

AEMO is responsible for setting and reviewing the minimum fault levels needed to maintain power system security across the NEM. This involves:

- Developing a methodology to determine fault level nodes in each transmission network in the NEM, and the required fault current level at those nodes to maintain the power system in a secure operating state. Together, these are the 'system strength requirements'. AEMO's initial System Strength Requirements Methodology[8] took effect on 1 July 2018. It is subject to review as part of the Integrated System Plan (ISP) process, formerly the National Transmission Network Development Plan (NTNDP).
- Determining the system strength requirements in accordance with the System Strength Requirements Methodology and identifying and declaring any current or emerging fault level shortfalls.

To assess the minimum fault level requirements in a region, AEMO's methodology considers the likely fault current contribution of synchronous machines and transmission lines in areas with different load, generation and network characteristics.

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[6] See North American Electric Reliability Corporation (NERC), Integrating Inverter-Based Resources into Low Short Circuit Strength Systems: Reliability Guideline, December 2017. Available at: https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Item_4a._Integrating%20_Inverter-Based_Resources_into_Low_Short_Circuit_Strength_Systems_-_2017-11-08-FINAL.pdf.

[7] Available at: https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf.

[8] Available at: https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-security-market-frameworks-review/2018/system_strength_requirements_methodology_published.pdf?la=en.

4.2 Assessing adverse system strength impact of proposed connections

AEMO's involvement in the framework for assessing the system strength impact of proposed connections and remediation measures includes:

- Developing an assessment methodology to be used by connecting network service providers (NSPs) when assessing the impact of a new or modified generation or market network service connection on system strength. This is set out in the System Strength Impact Assessment Guidelines[9].
- Providing, on request, power system models to connecting NSPs to carry out system strength impact assessments, consulting with them on these assessments, and advising them whether to approve proposed system strength remediation where there is an adverse system strength impact.

The methodology for assessing whether a proposed new or modified generation or market network service connection will have an adverse system strength impact has two stages:

1. Preliminary Assessment – this requires the calculation of the proposed connection's SCR to identify the likelihood of an adverse system strength impact, which triggers a full assessment.
2. Full Assessment – this is a more intensive study of the proposed connection using more sophisticated tools.

Details of the assessments, and the tools to be used by connecting NSPs, can be found in the System Strength Impact Assessment Guidelines.

4.3 Models used in assessments

As for any assessment of the power system or any of its components, it is important that AEMO has up-to-date, accurate and transparent PSS®E and PSCAD™/EMTDC™ models of plant as required by the Power System Model Guidelines[10]. If models become out of date, or prove to be inaccurate, AEMO may require owners of plant connected to the power system to provide up-to-date models and related information where they are required for the purpose of a system strength impact assessment.

5. System strength remediation

5.1 Responding to fault level shortfalls

Following the declaration of a fault level shortfall, TNSPs are required to provide system strength services to address the shortfall. These services may be procured by the TNSP from a third party, and made available to AEMO to be enabled as required.

The Energy Security Board is proposing changes to the NER to streamline several planning processes, including the ISP and the regulatory investment test for transmission (RIT-T). It is expected that these changes will permit proactive system strength remediation where appropriate[11].

[9] Available at: https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-security-market-frameworks-review/2018/system_strength_impact_assessment_guidelines_published.pdf?la=en&hash=771B8F6BC8B3D1787713C741F3A76F8B.

[10] Available at: https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-security-market-frameworks-review/2018/power_systems_model_guidelines_published.pdf?la=en&hash=A3DDF450DBEE1E7C1D7E2E379461538A.

[11] For further information, see: http://www.coagenergycouncil.gov.au/publications/consultation-draft-isp-rules.

5.2 Remediation in response to a proposed connection

Consistent with the 'do no harm' requirements introduced by the Fault Level Rule,[12] Generators and Market Network Service Providers must fund the remediation of any adverse system strength impact[13] resulting from a new[14] or modified connection for which they are responsible. This assessment is carried out during the connection process and must be finalised and documented in the resulting connection agreement.

There are two ways an adverse system strength can be remediated:

1. Generators and MNSPs may propose and fund a system strength remediation scheme.
2. The connecting NSP may carry out system strength connection works at the Generator or MNSP's expense.

Examples of both types are detailed in the System Strength Impact Assessment Guidelines.

A proposal to contract a third party (for example, the owner of a synchronous machine) to provide the necessary system strength remediation must not compromise the otherwise available fault levels considered in determining the relevant system strength requirements in the region. AEMO provides guidance on contracting options and their relative effectiveness in the System Strength Impact Assessment Guidelines[15]. Generators wishing to enter into a contract for the provision of system strength services should contact their local NSP and AEMO to ensure their proposed arrangement can be implemented operationally and is additive to the existing level of system strength.

6. Planning for system strength

Forecasting emerging system strength issues within a planning horizon of five years relies on good information about factors that are near impossible to predict reliably over an extended period. These factors include synchronous generating system withdrawals or changes in operating regimes, the location, size and capabilities of IBR, operational patterns of embedded generation, distributed energy resources, changes in networks and dispatch patterns.

System strength can change rapidly as network operations vary, and Generators react to economic and structural changes in, and affecting, the NEM. New technology generation can be proposed, built, and commissioned within 18 months, with immediate impacts on the dispatch patterns of synchronous generation, invalidating AEMO's longer-term forecasts. For these reasons AEMO reviews its assumptions annually and seeks to be proactive and innovative in its planning for system strength.

Considering these challenges, AEMO forecasts fault levels at the fault level nodes hourly using ISP market modelling scenario outcomes to assess the statistical likelihood of different fault levels under a variety of conditions and dispatch outcomes, including the impact of network augmentations and outage conditions.

[12] The expression 'do not harm' is used in the Determination, only. See section 5 of AEMC 2017, Managing power system fault levels, Rule Determination, 19 September 2017, Sydney.

[13] A term that is defined extensively in the System Strength Impact Assessment Guidelines.

[14] The liability resides in the connection applicant who ultimately becomes a Generator or MNSP.

[15] At the date of this document, a consultation to revise the System Strength Impact Assessment Guidelines is imminent. The update will include more information on contracting options than the current version.