Power system requirements

March 2018

Reference paper

Important notice

PURPOSE

AEMO has prepared this document to provide information about the technical and operational requirements of the power system.

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VERSION CONTROL

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Contents

Tables

Figures

1. Introduction

Modern **power systems** are giant, multi-faceted machines. To operate the complex ‘system of systems’ in Australia’s **National Electricity Market (NEM)**, AEMO oversees in aggregate millions of separate electricity **supply** and **demand** decisions in real time, all day, every day.

The NEM, like power systems worldwide, is being transformed from a system dominated by large thermal power stations, to a system including a multitude of power **generation** resources and technologies of various sizes[1]. At the same time, customers are engaging with their electricity supply in new ways.

The energy transformation involves a shift from:

- Homogenous to diverse supply resources.
- **Synchronous** to **non-synchronous** generation.
- A centralised to a decentralised system.
- Passive to active **consumers**.

All bolded terms are defined in the glossary at the end of this paper for easy reference.

Each of these trends has a common theme – each acts to increase the variability of the power system. AEMO’s challenge is to continually meet the needs of the power system, in the face of major structural changes and the resulting uncertainty across investment and operational timeframes.

While the power system is being transformed, the laws of physics that determine electrical flows do not change. To maintain a secure and reliable system, a range of interdependent technical and operational needs must be met at all times.

Physically, the NEM operates on one of the world’s longest interconnected power systems, stretching from Port Douglas in Queensland to Port Lincoln in South Australia and across the Bass Strait to Tasmania – a distance of around 5,000 kilometres. By international standards, the NEM is unusually long and sparse, which affects power system dynamics.

Interactions in any power system are highly complex and dynamic. Operating a power system involves a continuum of decisions. AEMO needs to know what is happening in real time, and anticipate what is likely to happen in the coming seconds, minutes, hours, days, weeks, years, even decades. This work culminates in the continuous matching of supply with demand and constant provision of essential **voltage** and **frequency** management services, ensuring sufficient reserves so the power system is robust enough to cope with unexpected events and stay within the power system operational design limits.

Unexpected events have the potential to compromise the operability of large parts of the power system, with potential consequences including cascading failures and widespread, prolonged supply disruption. No system can ever be made impervious to external events such as extreme weather. Defined system performance standards for security and reliability are critical to provide guidance on the acceptable trade-off between the costs of providing system security and reliability services and the potential impacts on consumers if these services are not provided.

This document aims to provide a foundational basis for understanding the technical and operational needs of the power system[2]. By providing clarity on the system’s fundamental needs, AEMO can help ensure market design and operating standards are supported by sound engineering, and thereby help provide for a smooth and focused energy transition which meets consumers’ needs for affordable and reliable **power**[3].

Chapter 2 describes operational prerequisites which give AEMO the levers we need to operate the system securely and reliably. Chapter 3 summarises the required technical attributes, and the essential services needed to maintain them. In Chapter 4, we have highlighted how a range of technologies and solutions could contribute to the system’s technical and operational needs being met.

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[1] A short overview of the changes underway in the power system is in AEMO’s Future Power System Security video at https://www.youtube.com/watch?v=Ffi_TWasa9A.

[2] For a basic introduction on how a power system operates, and some technologies operating now in the NEM, see AEMO’s EnergyLive website at http://energylive.aemo.com.au/Energy-Explained.

[3] AEMO notes that the theories and practices associated with power system operation are undergoing continuous review and development by power system operators internationally. AEMO will continue to work with stakeholders to convey the most up-to-date information.

2. Operability

To achieve a secure and reliable power system, capable of supplying consumers with the electricity they demand with a very high degree of confidence, AEMO and network service providers (NSPs) must have access to a number of critical operational levers to manage the power system within its technical limits. 'Operational pre-requisites' are summarised in Table 1 and discussed in the remainder of this chapter.

Table 1 Operational pre-requisites for the power system

Attribute	Description
Dispatchability of the power system	Ability to manage dispatch and configure power system services to maintain system security and reliability. "Dispatch" refers to the process whereby AEMO issues instructions to generators (and certain loads) to operate at a certain output.
Predictability of the power system	Ability to: • Measure or derive accurate data on energy demand, power system flows, and generation output across numerous time frames (real time, hours/days/weeks/years ahead) as key inputs into planning and operational decision-making. • Forecast upcoming power system conditions and have confidence in how the system will perform.

Using these operational levers, AEMO keeps the power system in balance using **security-constrained economic dispatch**.

Security-constrained economic dispatch

Every five minutes, AEMO dispatches the market to meet demand and **ancillary services** using the 'least-cost' combination of generation (or **demand response**) available. To do this, AEMO's dispatch computer calculates an optimal solution to a security-constrained dispatch problem, which contains a large number of variables, parameters, limits, and constraints, including:

- Forecast demand – AEMO's estimate of the aggregate electricity to be consumed by all customers in each NEM region during the next 5-minute period.
- Forecast output from wind and solar generators, non-scheduled generation (generation that does not participate in the market), and **distributed energy resources** (DER, such as rooftop PV).
- The prices and quantities contained in the bids and offers submitted by generators and loads that participate in the market.
- Network flows – constraining generation where required to keep power flows within the technical limits of available network infrastructure (further details are in Section 3.1).
- Frequency – maintaining frequency in the NEM close to 50 hertz (Hz) (further details are in Section 3.2).
- Voltage – co-ordinating the voltage profile across the main **transmission grid** using resources from generators and network assets to maintain voltages within technical limits (further details are in Section 3.3).
- Equipment limits – ensuring equipment remains within its technical limits.

The optimal solution will be to dispatch the 'least-cost' combination of generation (and dispatchable load) to meet demand and ancillary services, based on bids and offers, while remaining within the security and reliability parameters.

2.1 Dispatchability

The balancing process hinges on the **dispatchability** of the overall portfolio of available energy resources and key characteristics of each technology.

The concept of the dispatchability of an energy resource can be considered as the extent to which its output can be relied on to 'follow a target'.

To ensure a resilient power system, however, operators need a deeper understanding of the characteristics of the portfolio, both in investment and operational timeframes. As well as understanding whether energy assets can adhere to a dispatch target, AEMO also needs to understand how controllable the assets it has at its disposal are, how much they can be relied upon, and how flexible they are. These dimensions of dispatchability are introduced below.

2.1.1 Controllability

The controllability of a resource relates to the resource's ability to reach a set point (output target) requested by an AEMO dispatch process, whether that be zero megawatts, the maximum available capacity of the unit, or something in between.

It can also apply to demand response and batteries, for instance, an industrial load that can be turned down or up to meet system requirements, or aggregated household resources such as pool pumps, refrigerators, and air conditioners. At a minimum, this capability might be limited to the ability to switch off if required to manage security or reliability.

Examples of fully controllable resources include thermal generators like coal or gas power stations that have control systems that interface directly with AEMO's dispatch systems.

Full control is not always practical or possible, and some assets, like wind farms, may be visible to AEMO's systems but not fully controlled by them. For example, wind farms tend to produce at their full output given the wind resources available, which means that unless already capped at below their full potential output, they can only be dispatched down.

Other assets, like behind-the-meter rooftop solar PV, are presently not centrally controllable at all. Instead, rooftop PV simply feeds any surplus energy into the grid, irrespective of the needs of the power system at the time.

2.1.2 Firmness

System operators need to have some level of confidence that resources are available. The firmness of a resource relates to the resource's ability to confirm its energy availability.

For example, how long can the source provide a requested amount of energy once dispatched, and how far in advance can the energy be guaranteed by the source? This could be a probabilistic quantification for wind and solar. Firmness also relates to whether a resource is dependable or prone to technical failures.

Knowing how firm the portfolio of resources is allows the operator to efficiently and effectively orchestrate the balance of supply and demand in real time and to identify the need for new investment in the future.

This level of confidence also provides a benchmark for system operators to calculate efficient levels of reserve capacity, that is, the additional headroom needed to protect the system from unexpected **contingency** events.

2.1.3 Flexibility

The ability to respond rapidly to changes in the supply-demand position (such as changes in variable renewable energy generation output, generation failures, and variations in demand) is another critical dimension of dispatchability.

The flexibility of a resource is the extent to which its output can be adjusted or committed in or out of service. This includes:

- The speed of response to start up and shut down.
- The rate of ramping.
- Whether it can operate in the full range of capability, or has restrictions (such as a minimum generation requirement, or a limitation on the amount of bulk energy that can be produced).

Flexible energy resources include demand response. This can be in the in the form of controllable and uncontrollable loads, varying electricity usage in response to market signals, both behind-the-meter resources and large industrial facilities directly connected to the transmission network, such as aluminium smelters.

Flexibility is relevant over a range of timeframes. In the short term (as close as five minutes) flexibility is required to manage variations in demand or the sudden drop-off of generation, such as a sudden reduction in wind or utility-scale PV resource output. A more gradual ramping period (2-3 hours) may be required as the contribution of rooftop PV reduces and consumer demand increases.

While a power system has a strong supply of generally homogenous and conventional generation technologies, this may sufficiently capture a system operator's needs.

However, like the NEM, power systems around the world are entering a transitional period where both the generation and demand side are far more diverse and variable.

In this context, system operators require a far more detailed understanding of what the portfolio is capable of at any given time.

2.2 Predictability

To be able to keep the power system continuously in balance, AEMO must be able to anticipate supply and demand, to have the right mix of resources available.

AEMO continuously determines and revises the limitations on the system, taking into account the prevailing power system and plant conditions, and predicting the impacts of reasonably foreseeable events.

This requires access to sufficient information and data about the power system and its components to effectively model how the power system might respond to system conditions and events. The information needs to be both comprehensive and made available in a timeframe that allows for an optimised response.

This includes real-time information regarding electrical demand, the output level of generating systems, availability of demand response, system voltages, system frequency, and the status (on/off) and power flows on major network elements.

Historically, demand followed a predictable pattern, and supply was dispatched to meet demand. This is no longer the case, because both supply and demand are affected by a more diverse range of factors.

Increasingly, electricity supply and demand are influenced by factors such as wind speed and cloud cover[4]. As variable renewable energy becomes more prevalent, the power system needs to be able to manage the unpredictability associated with the weather.

Consumers are more actively managing their energy supply and consumption, including by installing rooftop PV. Even though, individually, each PV system is small, there are over 1.5 million households with rooftop PV installed across the NEM. In aggregate, that is over 5.5 gigawatts (GW) of PV capacity – substantially more than the single largest power station in the NEM (Eraring in New South Wales, which has approximately 2.9 GW of capacity).

To be able to anticipate supply and demand, system operators require visibility[5] of system conditions and how they may change. However, unlike other generation sources (such as large-scale wind or solar, GPG, hydro, or coal), the million-plus households generating rooftop PV in the NEM power system are not required to register with AEMO.

With increasing levels of localised, individual generation coming into the power system, the continued safe, secure, and reliable supply of electricity to consumers becomes more dependent on visibility of these components to AEMO. More details about the need for visibility of the power system, and the techniques AEMO currently uses to operate and control the power system, can be found in AEMO's *Visibility of the Power System* factsheet[6] and *Visibility of Distributed Energy Resources* report[7].

Power system operators require adequate models and tools to effectively forecast upcoming system conditions and simulate likely system performance under future conditions, to have confidence in how the system will perform.

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[4] Rooftop PV manifests within the power system as negative demand because it is located behind the customer's meter.

[5] Visibility is sometimes referred to as observability.

[6] AEMO's fact sheet on *Visibility of the Power System* is available at http://aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/-/media/0DE87F5ADD5D42F7B225D7D0799568A8.ashx.

[7] AEMO. *Visibility of Distributed Energy Resources*, January 2017, available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/FPSSP-Reports-and-Analysis.

AEMO requires information about new and emerging plant characteristics, to be used as critical inputs into new plant models and modelling tools.
Even changes in how appliances such as refrigerators and air-conditioners are connected to the network can, in aggregate, affect characteristics of the power system.

Recent system **disturbances** in the NEM have highlighted the dynamic characteristics of DER and loads. In particular, there have been multiple instances where deep voltage dips have resulted in hundreds of megawatts of nearby loads being removed from the power system for several minutes, before slowly returning in the following dispatch periods[8].

Immediate focus is therefore required on better understanding the response of load to system disturbances, in particular large-disturbance events, but also on everyday voltage management, such that constraints and operating philosophies are optimised and system security is maintained.

The performance standards for smaller-scale distribution-connected generation are not aligned with those of transmission-connected generation. Minimum connection standards are required to ensure that distribution-connected generation capability, including disturbance ride-through ability, aligns with power system needs. This capability will become critical for system security as distribution-connected generation systems begin to dominate certain operational periods.

Improved accuracy and confidence in AEMO's simulation models allows the system to be run in a less conservative manner (for example, holding less energy or frequency control reserves), leading to more efficient outcomes for consumers. Without knowledge of how DER and loads respond to faults, constraints and **interconnector** transfer limits may be too conservative (underutilising network capacity), or too optimistic (risking system security).

The effective, efficient planning and operation of the NEM relies on the ability of AEMO and NSPs to:

- Measure power system security and **stability** in real time.
- Accurately forecast demand and variable generation.
- Model economically efficient solutions to power system congestion.
- Quantify the behaviour of the power system when it is subjected to disturbances, and therefore the level of system services required to keep the system secure and reliable to defined system performance standards and place limitations on network transfer capability.
- Determine suitable performance standards for generation and loads intending to connect to the network, defining how generation must perform under different system conditions.
- Ensure the necessary power system services are provided in real time.

The modelling AEMO conducts also provides the market with information and ranges from real-time analysis to longer-term horizons (10-20 years).

Increasing penetrations of variable renewable generation sources, and a rapid increase in DER installed behind the meter and demand response, mean AEMO must include uncertainty as a key element in forecasting methodologies so it can be managed in a least-cost way.

AEMO and other market participants, in particular wind and solar generators, are continually developing their operational forecasting capabilities.

AEMO is working with market participants to pursue new and innovative approaches to forecasting demand and supply and system service levels.

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[8] Examples include incidents on the South Australian transmission network on 3 March 2017 and in the Victorian transmission system on 19 January 2018. AEMO will be estimating the response of DER to disturbances through a program of work involving extensive bench testing of common domestic inverters, and with monitoring of DER responses in-situ with high speed disturbance recorders installed at locations in the distribution network.

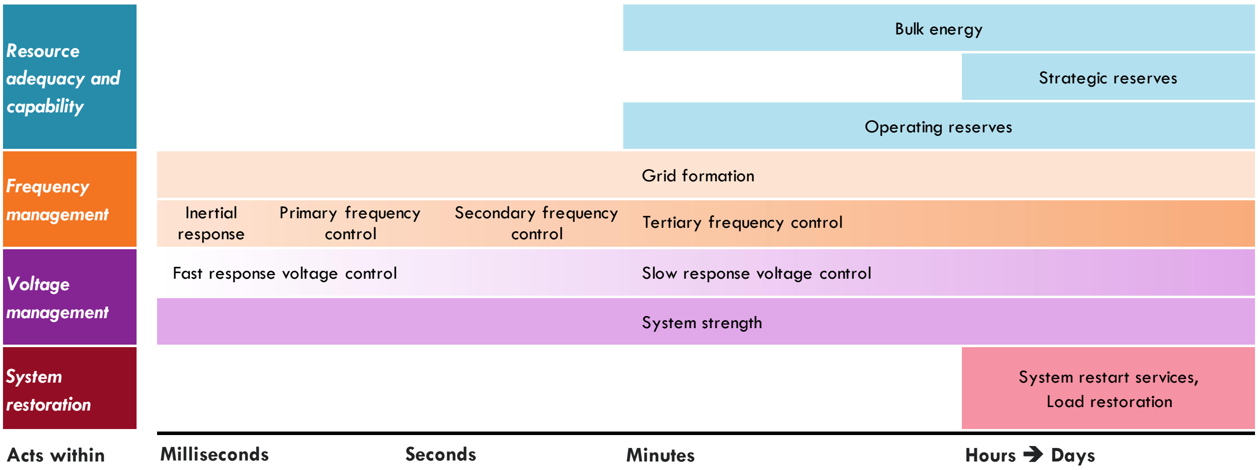
3. Technical attributes

A resilient power system can withstand unexpected disturbances, including generator failures and high impact, low probability events such as interconnector failures. Table 2 summarises the fundamental 'technical attributes' of the power system and the essential services needed to maintain them. Figure 1 shows the timescale in which each service responds.

Table 2 Technical attributes, and services required to deliver them

System attribute and section of report where addressed	Requirement	Service(s) needed to meet requirement
Resource adequacy and capability • **There is a sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of supply and demand. (See Section 3.1)**	Provision of sufficient supply to match demand from consumers	Bulk energy
		Strategic reserves
	Capability to respond to large continuing changes in energy requirements	Operating reserves
	Network transport capability	Transmission and distribution services
Frequency management • **Ability to set and maintain system frequency within acceptable limits. (See Section 3.2)**	Ability to set frequency	Grid formation
	Frequency within limits	Inertial response Primary frequency control Secondary frequency control Tertiary frequency control
Voltage management • **Ability to maintain voltages on the network within acceptable limits. (See Section 3.3)**	Voltage within limits	Slow response voltage control Fast response voltage control
		System strength
System restoration • **Ability to restart and restore the system in the unlikely event of a major supply disruption. (See Section 3.4)**	Ability to restore the system	System restart services

Figure 1 Operation timescales for services needed



While the services are detailed separately, it is important to note that there are many interrelationships between these services, and a deficiency in one service can lead to issues in several system attributes. This chapter provides an overview of each service and how it is currently sourced in the NEM. In some cases, there is no current framework for procuring the relevant service, as historically these services have been provided as a by-product of sufficient size of in-service synchronous generators.

3.1 Resource adequacy and capability

Resource adequacy and capability relates to having a sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of supply and demand. Achieving this balance is an intricate optimisation, operationally in real time and over longer-term planning timescales, of available energy resources – a diverse mix of centralised generation and DER, demand response, and network capacity. It is the capability of the overall, aggregated portfolio of available energy resources which is important in the real-time balancing of supply and demand.

To manage uncertainty, it is necessary to have enough spare capacity to manage the full range of reasonably foreseeable outcomes, in both investment timeframes and operational timeframes. Energy reserves refers to generating capacity (or demand response) that can be used when required, but is not actively engaged in supplying bulk energy. There are a range of different types of reserves, depending on the timeframe in which they are to be able to be called into use. At a high level, these can be classified as either strategic reserves or operating reserves[9]. Reserves may take a variety of forms, such as "headroom" in market participants' portfolios or an explicit service procured by the system operator.

The key components of resource adequacy and capability are summarised in Table 3.

Table 3 Overview of resource adequacy and capability requirements and services

Requirement	Description	Service and section of report where addressed
Provision of sufficient supply to match demand from consumers	• Capacity adequacy – ability of the energy resource mix to achieve balance at a single point in time. The most onerous requirements are typically: – **Maximum demand** conditions – highest plausible system demand, even if it occurs infrequently[10]. – Rare dispatch conditions – outside the norm for the given time of year and time of day. Examples include: periods of low variable renewable generation during a particularly warm or cold night, when demand is high; and periods when a key energy resource is unavailable or has reduced capability, such as the extended outage of an interconnection to a neighbouring region, or gas supply disruptions. • Energy adequacy – ability of the energy resource mix to achieve balance over a period of time. This includes fuel source adequacy (having enough capacity to meet energy balancing needs over the longer term, typically over a season or year).	Bulk energy (3.1.1) Strategic reserves (3.1.2)
Capability to respond to large continuing changes in energy requirements	The overall generation supply mix must have sufficient flexibility to ensure the power system can respond to significant changes in energy requirements over a wide range of time periods. Sufficient flexible capability is necessary to continue to balance supply and demand over these periods.	Operating reserves) (3.1.3)
Network transport capability	The ability to deliver sufficient power to consumers when and where it is required. This includes provision of sufficient network services. Well-planned transmission networks[11] contribute to resource adequacy by enabling the dispatch of a geographically diverse range of energy sources, allowing: • Access to the best quality fuel resources and economic dispatch of low-cost resources, which can be constrained by network congestion. • Guarding against disruptions that might impact the price or availability of any one resource, especially critical during long-term, unplanned outages of large generation units. • Firming of the overall, aggregated output of disperse variable resources, reducing dependence on potentially more expensive generators with firm and flexible capabilities. Power transfer across the network must be within the secure **technical envelope** of the system. Flows can be constrained to maintain power system security. Provision of security services can, therefore, improve network transport capability.	Transmission and distribution services (3.1.4)

Under current NEM frameworks, the reliability standard is the primary criterion used to evaluate whether the power system has sufficient supply resources to meet future consumer demand.

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[9] In very short timeframes – sub 5-minute to milliseconds – reserves take the form of frequency control services, which are discussed in Section 3.2.

[10] In our long-term, 20-year demand forecasts, AEMO forecasts the maximum demand which could be expected at any one time each year, for:

- A summer of average weather – based on weather patterns likely to occur one in every two years, these are called 50% probability of exceedance (POE) forecasts.
- A summer of extreme weather – based on weather patterns that have a one in 10 year chance of occurring, these are called 10% POE forecasts.

The actual maximum demand can be highly variable from year to year.

[11] Modernisation of distribution networks can also help with resource adequacy by allowing demand response and DER to more dynamically contribute to achieving supply-demand balance in a more coordinated fashion. This would result in greatly enhanced controllability of decentralised resources located behind the meter (on consumers' premises), allowing AEMO and network operators to better mobilise this capacity and co-optimise with secure system operation.

AEMO uses the reliability standard to assess and report on whether there is sufficient generation capacity to meet forecast demand. As a driver of investment decisions, it is relevant in investment timeframes. At present, the NEM framework does not indicate how the reliability standard should apply in operating timeframes.

The key reliability metric is the maximum expected unserved energy (USE), or the amount of demand which the power system is forecast to be unable to meet. The reliability standard accepts that up to 0.002% of demand might not be met in a region each financial year due to insufficient energy resources. In addition, not all instances of energy shortfalls are counted when applying the standard.

Since the reliability standard intends that at least 99.998% of all demand is met and not all energy shortfalls are counted, it accepts some energy shortfalls. This approach is based on a probabilistic analysis, and was developed when there was significantly less variability in supply and demand than there is today. The changing demand profiles experienced today would suggest there is merit in discussing whether this mechanism remains sufficient for the future.

AEMO continually assesses supply adequacy and the status of available energy reserves. The Projected Assessment of System Adequacy (PASA) and other processes identify low or lack of reserve (LOR) conditions for each NEM region based on specific threshold triggers. LOR conditions indicate the system may not have enough spare energy if something major and unexpected happened, like the loss of a generator or interconnector. The lowest notice, LOR1, tells the market more reserves are needed to cover a major contingency – the highest, LOR3, indicates the balance of supply and demand is so tight that load shedding is imminent or has begun. LOR conditions are created by variations in both supply and demand.

3.1.1 Bulk energy

Bulk energy is the core product supplied by the power system. The NEM's performance in meeting the reliability standard is measured in terms of whether there is a shortfall in the supply of bulk energy.

This service represents the provision of electricity from generators to match demand from consumers, at least cost. It relates to the overall energy adequacy of the aggregated portfolio of available energy resources. Traditionally, bulk energy has been provided from large **synchronous generators**, procured through the wholesale spot market.

Longer-term contracts between generators and retailers reduce risks associated with spot market volatility and often underpin investment in generation that ultimately provides the bulk energy.

Recent years have seen increasing contributions of energy from wind and solar farms. This has been accompanied by a reduction in overall energy required to be dispatched, due to rooftop PV generation offsetting demand.

Operationally, AEMO's pre-dispatch process assesses if adequate supply resources are available to meet demand forecasts and real-time requirements. It estimates 5-minute targets from one hour prior to dispatch, and 30-minute targets up to 40 hours prior. The centrally-coordinated dispatch process is then conducted every five minutes according to current bids, offers, rebids, and any network constraints.

3.1.2 Strategic reserves

Strategic reserves refers to reserve capacity that sits outside the market to insure against unexpected demand growth and/or reductions in supply. At present, the NEM does not include a strategic reserve mechanism for generation. Instead, market participants may make a commercial decision to maintain reserves within their portfolios to ensure they can meet their contractual obligations.

Capacity investment decisions determine the mix of resources which may be available to provide bulk energy or energy reserve services in the future. This relates to both the building of new capacity infrastructure and decisions to retire or temporarily 'mothball' capacity. Historically, there have been lead times of several years for new generation investment[12]. Strategic reserves sit outside of the market and are required to maintain reliability given the difficulties of precisely forecasting future demand and supply or when the markets doesn't respond to investment signals.

If in place, strategic reserves could be called on in the event of an anticipated supply shortfall, providing insurance against supply interruptions as a result of generator closures or unavailability due to plant failures or fuel shortages, or unexpectedly high demand. To the extent that the costs to customers associated with involuntary load shedding exceed the value of the market price cap, strategic reserves are able to reduce the overall costs to the community associated with a market shortfall by introducing an intermediate step before involuntary load shedding is invoked.

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[12] New technologies, especially PV and batteries, are able to come online much more quickly.

Where required to meet the reliability standard, AEMO may elect to contract for reserves through the Reliability and Emergency Reserve Trader (RERT) provisions in the National Electricity Rules (NER). This occurs during periods where risks of supply disruptions have been indicated. Under the RERT, AEMO can maintain a panel of providers which can provide short notice (between three hours and seven days) and medium notice (between seven days and ten weeks) reserve if required. If the market is unsuccessful in alleviating an LOR condition, AEMO will intervene by exercising the RERT mechanism where available or issuing a direction.

In light of increasing uncertainty and reduced powers of AEMO to source strategic reserves, a new strategic reserve mechanism is required[13].

3.1.3 Operating reserves

Generators can require many hours' notice before they can start generating; similarly, demand response may require numerous hours' notice. To ensure the system operates in real time with high technical integrity, it is necessary to have operating reserves available, but unutilised, to ensure the system is able to cope with unexpected variations in supply and demand.

The NEM currently has no specific mechanism apart from system operator intervention to ensure that operating reserves are available, although alternative approaches are being considered.

Traditionally, operating reserves have taken the form of the unused capacity of synchronous generators which are generating below the full capacity they have made available to the market. In contrast, since their fuel source is free, wind and solar generators are generally dispatched to their full potential output given the prevailing wind/sun conditions. With fewer synchronous generators in the supply mix, operating reserve margins are declining.

At the same time, variability is increasing, and hence the amount of headroom required to prudently manage the power system is increasing.

If slower response generators are unable to come online quickly enough to meet a need for increased generation, and wind and solar plant are already fully dispatched, it becomes increasingly necessary to rely on more expensive fast start generation such as open cycle gas turbines.

A key characteristic to be considered when assessing the power systems' need for operating reserves is flexibility (see Section 2.1.3).

Most electricity markets around the world mobilise operating reserves in a range of different timeframes, to ensure the most efficient combination of resources is able to be dispatched when needed. For instance, operating reserves could be triggered on a day ahead, hour ahead, or 15 minutes ahead basis.

The NEM relies on spot market prices (which can rise as high as the Market Price Cap, presently set at $14,200 a megawatt hour (MWh)) to provide an incentive for market participants to ensure their generating capacity is available when needed, even though they are only paid if they are actually dispatched.

As variability increases, this mechanism is proving insufficient and requires AEMO to intervene into the market with increasing frequency. This matter will be discussed further in AEMO's submission to the Australian Energy Market Commission (AEMC) Reliability Frameworks Review Interim Report[14].

3.1.4 Transmission and distribution services

To ensure a reliable power supply to end use customers, network infrastructure capable of transporting the electricity from generation to load must be in place. Transmission and distribution infrastructure requirements are driven by the need to meet demand during peak periods for each part of the network.

Investment in network capacity within or between regions can facilitate the entry of new generation, allow additional generation to be dispatched, or allow the transfer of energy between regions (which is becoming increasingly important due to variability in supply).

Any expansion in network capacity can also help to deliver energy reserves and flexibility.

In the absence of sufficient transmission capacity to transport electricity, generators are unable to get their products to market.

The NEM is an unusually long, sparse power system. Broadly, it is a grouping of several historically self-sufficient power systems via relatively low capacity interconnectors. Power transfers across these interconnectors are subject to constraints of various kinds.

As synchronous generation is displaced by variable renewable generation, transmission capacity has an important role in promoting diversity, so power can be transferred, for example, from a region where the wind is blowing to a region where it is not blowing.

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[13] AEMO, *Advice to Commonwealth Government on Dispatchable Capability*, September 2017, available at https://www.aemo.com.au/-/media/Files/Media_Centre/2017/Advice-To-Commonwealth-Government-On-Dispatchable-Capability.PDF.

[14] For information and documents related to this review, see http://www.aemc.gov.au/Markets-Reviews-Advice/Reliability-Frameworks-Review.

The changing generation mix also has consequences for AEMO's ability to ensure that all parts of the power system are able to access critical services such as frequency control. There may be benefits for the broader resilience of the power system in having frequency control services broadly dispersed throughout the power system.

As a result, the NEM is moving away from a situation where regions of the NEM were mostly self-sufficient, towards a situation where interconnectors have an increasing role in providing reliability and security services.

Network infrastructure investments typically have high upfront costs, long lead times, and very long asset lives (around 50 years). Network investments are currently coordinated by the regulated networks, with input from AEMO under its National Planning function. Network services providers in the NEM are required to invest at levels that enable them to meet service performance obligations and reliability standards (set by state and territory agencies).

Currently, almost 25,000 MW of transmission- and sub-transmission-connected generating systems are proposed across the NEM, with the large majority of these being variable renewable generation projects.

These renewable energy sources are proposed in predominantly remote and weak[15] locations without adequate transmission capacity. Generators located in congested parts of the network may be partially or fully constrained off.

These trends entail significant changes for power system flows and transmission infrastructure needs. In this period of change and uncertainty, a strategic, NEM-wide plan for infrastructure development which can be implemented effectively is critical.

AEMO's *Integrated System Plan* (ISP), to be published mid-2018, will evaluate and assess the most efficient combination of network and generation assets[16]. The ISP will consider transformations at both end of the energy supply chain (large-scale generation and distributed level).

3.2 Frequency management

To operate, the system must have the ability to set and maintain frequency[17].

Power system frequency is controlled by the constant balancing of electricity supply and demand. If electricity supply exceeds demand at an instant in time, power system frequency will increase. If electricity demand exceeds supply at an instant in time, power system frequency will decrease.

To maintain this balance, AEMO relies on frequency control services, which are mostly designed to inject or remove power from the grid to restore the balance of supply and demand.

In addition to a number of services which help to maintain frequency, a grid formation service is also required to set frequency for the system. The services which maintain frequency must collectively provide a continuous response to arrest any deviation in frequency, and then return it to desired levels.

Historically, these services have typically been defined as a series of cascading services with different active operation times and functions.

Table 4 provides an overview of the services currently used to set and maintain frequency.

Figure 2 shows how frequency control services contribute to restoring power system frequency after a disruption.

In future, the definition of frequency control services may be defined in a different way, including potentially as an overall continuum of frequency response rather than discrete service categories. This question is being considered as part of the AEMC's Frequency Control Frameworks Review[18].

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[15] Parts of the system lacking system strength (see Section 3.3.3).

[16] More information about the *Integrated System Plan* is available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Integrated-System-Plan.

[17] Further background information about frequency control can be found in AEMO's *Frequency Control* factsheet, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/AEMO-Fact-Sheet_Frequency-Control---Final.pdf.

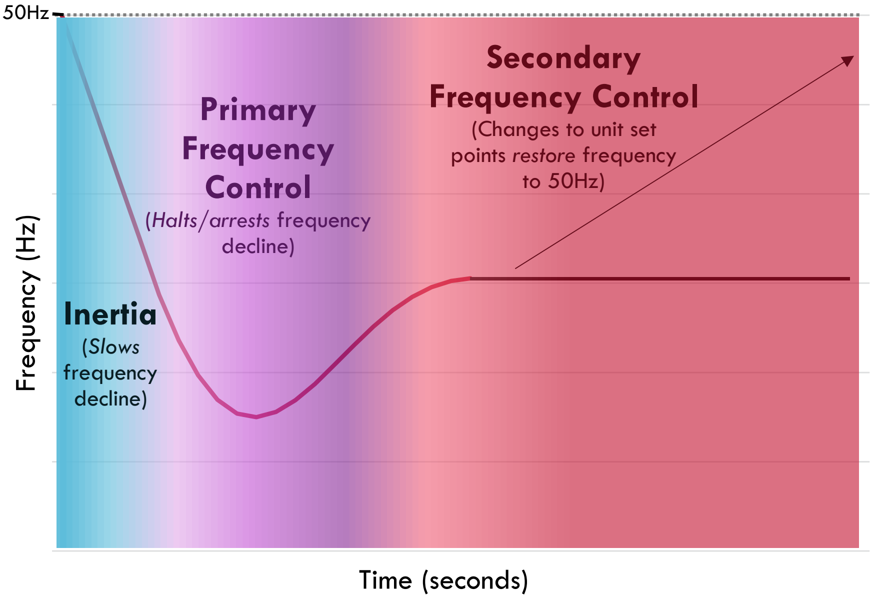
[18] For information and documents related to this review, see http://www.aemc.gov.au/Markets-Reviews-Advice/Frequency-control-frameworks-review.

Table 4 **Overview of frequency management services**

Service	Description
Grid formation	Ability to set the frequency to which the rest of the system is able to be synchronised.
Inertial response	A rapid and automatic injection of energy to suppress rapid frequency deviations, slowing the rate of change of frequency.
Primary frequency control	**Active power**[A] controls act in a proportional manner to respond quickly to measured changes in local frequency and arrest deviations.
Secondary frequency control	Automatic generation controls and manual dispatch commands act to restore frequency to 50 Hz and relieve providers of primary frequency control.
Tertiary frequency control	Active power controls, such as the start-up of new units or set point changes on already operating units, act to replace depleted secondary frequency control resources to ensure the system continues to remain within its normal operating band.

A. Instantaneous rate at which electrical energy is consumed, generated, or transmitted.

Figure 2 **Frequency control services acting to restore power system frequency after a disturbance**



From Table 4, grid formation services are not shown in Figure 2, because they are required continuously. Similarly, tertiary frequency control services are not shown, because they are used once frequency has been stabilised back to 50 Hz.

There is also an emerging opportunity for resources with **fast frequency response (FFR)**[19] capabilities to provide frequency control services. AEMO has published a paper[20] which seeks to provide a common language for discussion across industry on FFR and provide early guidance on the suite of FFR services which may be valuable in future to assist in the efficient management of power system frequency.

It is important to note that FFR is not necessarily a separate service, but rather an alternative way of providing one or more of the services described above.

In the event of a large disturbance causing an extreme frequency change which is beyond the capability of frequency control services, emergency frequency control schemes are used as a last resort to try and arrest the frequency disturbance. Emergency frequency control schemes involve the automatic disconnection of generation or load in an attempt to rapidly rebalance the system.

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[19] A very rapid response to re-balance megawatts on the power system. May be automatic in response to frequency, or a centrally controlled response (that is, a control scheme to shed load).

[20] AEMO. *Fast Frequency Response in the NEM – Working Paper*, August 2017, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/FFR-Working-Paper---Final.pdf.

3.2.1 Grid formation

Grid formation refers to the ability of the power system to set and maintain frequency. It has only recently begun to receive attention as an essential technical need in its own right, since grid formation occurs as a matter of course when synchronous generation is online. If frequency can be thought of as the heartbeat of the power system, grid formation is like its pacemaker.

In large, synchronous power systems like the NEM, frequency has historically been set by synchronous generating units as a by-product of their normal operation. At this time, grid formation is an emerging need rather than a defined service. There is currently no formal framework to incentivise investment in grid formation services in the NEM.

AEMO's current understanding is that synchronous generators are the only proven technology that can provide grid forming services in large power systems. **Synchronous condensers** are unable to set frequency. **Non-synchronous generators** with grid forming capabilities are available and have been proven on small power systems, however there are not yet any international examples of larger power systems operating solely with grid-forming non-synchronous generators.

In the absence of synchronous generation, multiple devices would be required to set a stable system-wide frequency, and all non-synchronous devices would need to be synchronised to the same frequency. This would require robust communication and control linkages between large numbers of distributed devices to maintain system security.

Development of grid forming power electronic converters for large power systems is an emerging area of international research.

3.2.2 Inertial response

Inertial responses provide a rapid and automatic injection of energy to suppress rapid frequency deviations, slowing the rate of change of frequency. This response has predominantly been provided in the NEM by the inherent electromechanical inertial response of large synchronous generators, as a by-product of energy production. It arises because the rotating parts of synchronous generating units (such as the turbine and rotor) connected to an AC power system spin in lock step with the system frequency.

This inertial response was historically abundant in many parts of the network. This is, however, no longer the case in certain parts of the network that have high levels of non-synchronous generation. A lack of inertial response can present risks to system security in the event that these regions become separated from the rest of the NEM.

A recent Rule change by the AEMC on *Managing the rate of change of power system frequency* places obligations on Transmission Network Service Providers (TNSPs) to procure minimum levels of inertia[21], which will likely be delivered by contracting with existing synchronous generators or by constructing synchronous condensers.

The Rule also places obligations on AEMO to ensure minimum levels of inertia are online to maintain the power system in a secure operating state.

Additional Rules may be required to support procurement of additional inertia above these minimum levels where there would be a market benefit in doing so.

Some non-synchronous technologies can provide a very fast frequency response which may be equivalent to an 'emulated' synchronous inertial response. To AEMO's knowledge, such alternatives have not yet been proven as a complete replacement for synchronous inertia, although some manufacturers refer to development work in this area[22].

As discussed in AEMO's working paper[23], the FFR capabilities of non-synchronous technologies have the potential to be more valuable to the power system than as just a substitute for synchronous inertia. Rather than simply slowing the rate of change of frequency following a disturbance, FFR can help to return the power system to the correct frequency.

3.2.3 Primary frequency control

Primary frequency control is designed to act within several seconds (and generally up to approximately 60 seconds where secondary frequency control acts) to provide a proportional response to measured changes in local frequency and arrest deviations.

To provide primary frequency control, generator settings are configured to respond in a certain way when locally measured frequency exceeds specified thresholds. When frequency falls, the generator controls automatically increase the electrical power.

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[21] For information and documents related to this review, see http://www.aemc.gov.au/Rule-Changes/Managing-the-rate-of-change-of-power-system-freque.

[22] AEMO. *Fast Frequency Response in the NEM – Working Paper*, Section 4.5, available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2017/FFR-Working-Paper---Final.pdf.

[23] Ibid. Section 3.3.

Primary frequency control has predominantly been sourced from synchronous generators with governor control systems sensitive to frequency change.

Recent technology trials have demonstrated that non-synchronous generators and battery storage systems are also able to provide equivalent primary frequency control.

Fast switched loads, such as distributed and large industrial loads, are also able to provide primary frequency response (to raise frequency only) when combined with frequency responsive relays.

The current NEM design only requires a primary frequency response when the system frequency leaves the normal operating frequency band[24], rather than acting to stop the frequency leaving the normal operating frequency band in the first place.

Fast and slow contingency frequency control ancillary services (FCAS) are forms of primary frequency control in the current NEM design.

Contingency events, such as the sudden failure and disconnection of a generator or load, can cause a sudden imbalance in supply and demand, leading to a rapid frequency change which can shift frequency outside its normal operating band.

Contingency FCAS acts to contain these significant deviations and co-operate with regulation FCAS to restore the frequency back to normal levels. In the NEM, these raise or lower services are currently specified such that they must act within:

- 6 seconds (fast), to arrest deviations in frequency.
- 60 seconds (slow), to stabilise frequency within the contingency band.

3.2.4 Secondary frequency control

Following initial stabilisation of frequency by primary frequency control services, secondary frequency control services provide an injection or removal of power from the grid, in response to a remote signal, to bring the system frequency back to 50 Hz. Secondary frequency control is currently managed in the NEM through the use of regulation and delayed contingency FCAS services.

During normal system operation, regulation frequency control services respond to an external signal from AEMO which fine-tunes their dispatch targets to correct deviations in frequency within the normal operating band of 49.85 Hz to 50.15 Hz.

Regulation FCAS bids and offers are co-optimised with energy as part of security constrained economic dispatch.

In the NEM, regulation FCAS is delivered by generators controlled by AEMO's automatic generation control system (AGC).

The AGC calculates how much additional generation is required, or how much generation needs to be reduced, to correct deviations in frequency. The AGC will then change the electricity production target for the generators enabled for regulation FCAS to correct the frequency deviation.

The 5-minute (delayed) contingency FCAS service is used to restore frequency to the normal operating band. It is used where a frequency deviation event has occurred that has taken frequency outside the normal operating band for some time.

- Delayed contingency FCAS is typically pre-configured by AEMO but triggered in response to locally sensed frequency.
- Delayed FCAS is typically delivered by generating units with control systems that increase or decrease the electricity production target in relation to sustained changes in frequency. Once the frequency has recovered into the normal operating frequency band, or 10 minutes has passed, the delayed service is withdrawn.
- Switched loads, both distributed and large industrial loads, are also able to provide primary frequency response (raise service only) when combined with frequency responsive relays.

3.2.5 Tertiary frequency control

Because the NEM has a relatively short dispatch interval of five minutes, tertiary frequency control, which acts to relieve sources of primary and secondary frequency control, is effectively achieved through the central dispatch process which re-balances the system every five minutes.

In other power systems around the globe, especially where much longer dispatch intervals exist, a tertiary frequency control product may be a separately procured service used to manage imbalance between dispatch cycles.

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[24] The normal operating frequency band is defined in the Frequency Operating Standard (FOS), which specifies the frequency levels required to meet power system security standards. The FOS set in accordance with the principles of clause 4.2.6 of the NER and is available at http://www.aemc.gov.au/getattachment/c2716a96-e099-441d-9e46-8ac05d36f5a7/Frequency-operating-standard.aspx.

3.3 Voltage management

Voltage control in the power system acts to maintain voltages at different points in the network within acceptable ranges during normal operation, and to enable recovery to acceptable levels following a disturbance. Acceptable voltage ranges are defined in the NER[25].

Voltage control is managed through balancing the production or absorption of **reactive power**[26]. Reactive power does not 'travel' far, meaning it is generally more effective to address reactive power imbalances locally, close to where it is required. Adequate reactive power reserves are maintained to ensure the security of the transmission system in the event of a credible contingency.

AEMO operates the power system to maintain voltage levels across **connection points** in the transmission network within limits set by NSPs and to a target voltage range. This involves the coordination of available reactive power resources in the network and from generators.

If voltages still remain outside their technical limits, other tools available to system operators include:

- Network reconfiguration – operational switching of transmission elements in and out of service to redirect network flows.
- Contracts with TNSPs and generators – agreements for specific reactive support under specific circumstances.
- Load shedding – automatic or manual load shedding as an emergency last resort.

NSPs are responsible for planning, designing, and operating their networks so that voltages at connection points are within technical limits. Reactive power support and other associated costs are recovered through the network regulation process. Generators' responsibility for providing voltage support at their connection points is determined as part of the generation connection application process and set out in the generator performance standards. AEMO undertakes a further annual review to identify any potential gaps in voltage management from a system-wide perspective as part of the Network Support and Control Ancillary Services (NSCAS) process.

3.3.1 Fast response voltage control

Fast-response voltage control provides large, rapid adjustments in reactive power to maintain stability in the event of system disturbances.

Adequate reactive reserves need to be maintained to ensure the security of the transmission system. Equipment that provides fast dynamic reactive reserves includes:

- Automatic voltage regulation from synchronous generators acting to maintain planned voltage levels.
- Active compensation – fast acting equipment[27] using power electronics to control power flow and compensate reactive power as needed in the system. These include **static VAR compensators (SVCs)**, synchronous condensers, and **static synchronous compensators (STATCOMS)**.
- Non-synchronous generating units, such as wind turbines and solar inverters.

Fast response voltage control is related to voltage stability and hence system strength.

3.3.2 Slow response voltage control

Slow response voltage control relates to managing small adjustments to reactive power during normal operation as demand and generation varies, in timescales within seconds or minutes.

Slow response voltage control is primarily provided locally by:

- Voltage regulators – control voltages farther from the substation and installed at substations and along **distribution system** feeders.
- Transformer[28] load tap changes – to increase and decrease voltages as needed.
- Passive reactive power compensation from capacitors and **reactors** within substations, providing base level voltage and reactive support.

3.3.3 System strength

"System strength"[29] is an umbrella term for a suite of interrelated factors that together contribute to power system stability. Power system stability is the ability of the power system to return to stable operating conditions following a physical disturbance.

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[25] AEMC. Schedule 5.1a of the NER, available at http://www.aemc.gov.au/Energy-Rules/National-electricity-rules/Current-Rules.

[26] The rate at which reactive energy is transferred. Reactive power, which is different to active power, is a necessary component of alternating current (AC) electricity. Management of reactive power is necessary to ensure network voltage levels remains within required limits, which is in turn essential for maintaining power system security and reliability.

[27] Collectively known as flexible AC transmission systems (FACTS) devices.

[28] A transformer is a device that reduces or increases the voltage of alternating current. Where a tap changer is fitted to a transformer, each tap position represents a change in voltage ratio of the transformer which can be manually or automatically adjusted to change the transformer output voltage. The tap position is used as a reference for the output voltage of the transformer. This process is known as "transformer tap changing".

[29] AEMO's factsheet on *System Strength* is available at https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/AEMO-Fact-Sheet-System-Strength-Final-20.pdf.

System strength in the NEM has predominantly been provided as a by-product when energy is produced by large synchronous generators, and was historically abundant in many parts of the network.

System strength reflects the sensitivity of power system variables to disturbances. It indicates inherent local system robustness, with respect to properties other than inertia. As a service, system strength services represent a complex interaction of electrical and mechanical elements which support system stability, including, but not limited to, fault levels and synchronising torque.

Fault levels relate to the size of the disturbance that can impact the system when a fault occurs. A key metric for measuring fault levels is short circuit ratio. Synchronising torque is a form of electrical torque produced by synchronous generators when they rotate to generate electrical power[30]. It helps to keeps the generator in synchronism with the system and has an important role in determining synchronous generator behaviour immediately after a disturbance[31].

System strength affects the stability and dynamics of generating systems' control systems, and the ability of the power system to both remain stable under normal conditions, and to return to steady-state conditions following a disturbance, as set out in Table 5.

Table 5 Summary of main issues associated with low system strength

Issue	Description
Non-synchronous plant stability	Non-synchronous generation that is connected to the network using power electronic converters (PECs) requires a minimum system strength 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 AC system, this can lead to: • Disconnections of plant following credible faults, in particular in remote parts of the network. • Adverse interactions with other non-synchronous plant (instabilities/oscillations have been observed in practice in the NEM). • Failure to provide sufficient active and reactive power support following fault clearance.
Synchronous plant stability	Low system strength can affect the ability of generators to operate correctly, resulting in disconnections of synchronous machines during credible contingencies.
Operation of protection equipment	Protection equipment within power systems work to clear faults on only the effected equipment, prevent damage to network assets and mitigate risk to public safety. In weak systems: • Protection mechanisms have a higher likelihood of maloperation. • Protection mechanisms may fail to operate, resulting in uncleared faults and/or cascaded tripping of transmission elements due to eventual clearance of the fault by an 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.

Left unmanaged, these issues could result in additional generation tripping during power system disturbances, loss of load due to maloperation of network equipment, and public safety risks if faults are not being cleared.

Operationally, AEMO currently ensures sufficient system strength by ensuring a minimum number of synchronous machines remain online at all times[32]. This is because large synchronous machines (hydro, gas, coal generators, and synchronous condensers[33]) inherently contribute to system strength, whereas non-synchronous generators (batteries, wind, solar) do not. Recent Rule changes by the AEMC on *Managing power system fault levels* and *Managing rates of change of power system frequency* place obligations on TNSPs to procure minimum levels of fault current and inertia[34], which will likely be delivered by contracting with existing synchronous generators or by constructing synchronous condensers. New Rules may be required to support procurement of additional fault current or inertia above these minimum levels where there would be a market benefit in doing so.

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[30] A description of synchronising torque is provided in AEMO's *South Australia System Strength Assessment*, September 2017, available at https://www.aemo.com.au/-/media/Files/Media_Centre/2017/South_Australia_System_Strength_Assessment.pdf.

[31] Synchronising torque differs from inertial response in that it is an electrical characteristic, where inertia is a mechanical characteristic.

[32] More details on AEMO's current operational requirements for system strength can be found in AEMO's *South Australia System Strength Assessment*.

[33] Synchronous condensers are a type of network element that contribute to system strength (providing fault current and synchronising torque), synchronous inertia, and dynamic voltage control. Synchronous condensers do not contribute active power, and therefore do not displace non-synchronous generation when they operate.

[34] For information and documents related to these reviews, see http://www.aemc.gov.au/Rule-Changes/Managing-power-system-fault-levels and http://www.aemc.gov.au/Rule-Changes/Managing-the-rate-of-change-of-power-system-freque.

3.4 System restoration

While AEMO endeavours to manage the system in a secure and reliable state, major disturbances (such as sudden equipment failure, multiple equipment failures in close succession, or extreme weather events) can sometimes lead to cascading failures across the system, resulting in the complete loss of supply to a large portion of the network, even a region. This is called a “black system” event.

Black system events occur rarely in the NEM (South Australia in 2016, northern Queensland in 2009, and New South Wales in 1964). While these events are rare, system operators must have resources available to restart and restore the system to a secure and reliable operating state as safely and quickly as possible in the event of a major supply disruption.

Generators typically need an electrical supply to start up. Normally, this supply would come from the transmission or distribution system.

During a black system event, it is necessary for at least one generator to start itself up and carry out initial energisation of a section of power system, to support sufficient demand to create and control a stable ‘power island’[35]. This would include re-establishing the grid frequency (see Section 3.2.1).

The energised part of the power system is then used to start up additional generators and restore power to more load so that power is gradually restored[36]. Eventually, the islanded part of the network is able to synchronise with the rest of the power system.

3.4.1 System restart services

AEMO procures system restart ancillary services (SRAS)[37] in each region according to the AEMC Reliability Panel’s system restart standard (SRS)[38], through a competitive tender process.

This process is designed to procure SRAS at the least-cost combination of submissions, and considers a number of parameters, specifically aggregate reliability, which includes individual (generation system restart equipment) reliability, transmission reliability, strategic location, geographic location, and fuel diversity of SRAS, as well as principles AEMO needs to consider when developing boundaries of sub-networks[39].

SRAS can currently only be provided by synchronous generators[40].

AEMO has recently updated the SRAS guidelines, and is undertaking a new tender process to procure SRAS services from 1 July 2018[41].

3.4.2 Load restoration services

Following initial system restart, the energised part of the power system is then used to start up additional generators and restore power to more load so that power is gradually restored.

Many services are required to support load restoration, however adequate voltage support is the most critical.

Voltage control services are required to prevent the power system becoming insecure and preventing damage to equipment. These services are located at specific locations in the network, and can help to control voltage levels within design and operational limits while load restoration is undertaken.

Load restoration services are not currently sourced through any formal tender process. Instead, AEMO and relevant TNSPs work collaboratively during any system restoration process to make use of known voltage support devices to ensure a secure and satisfactory power system is maintained at all times.

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[35] Some synchronous generation technologies have the capability to start their main generating units using small auxiliary generating plant located on-site, without reliance on external electricity supplies. Some generating systems can continue running in isolation from the rest of network in the event of a major supply disruption, remaining available to support system restoration when requested.

[36] Restoration of load must be done in a controlled manner following a major supply disruption to ensure the system remains balanced at all times. This involves a staggered process of bringing on equivalent blocks of additional generation and load.

[37] AEMO. *System Restart Ancillary Service Guidelines*, September 2014, available at https://www.aemo.com.au/-/media/Files/PDF/SRAS-Guidelines.pdf.

[38] For information and documents related to this AEMC review, see http://www.aemc.gov.au/Markets-Reviews-Advice/System-Restart-Standard.

[39] DGA Consulting. *Independent Review of System Restart Ancillary Services Process Improvement*, June 2015, available at https://www.aemo.com.au/-/media/Files/PDF/Independent-Review-of-System-Restart-Ancillary-Services-Process-Improvem.pdf.

[40] At its current state of development, non-synchronous generation technology is unable to provide system restart capability. This primarily stems from the need for a minimum system strength or fault level to commence stable operation, which is not available during black system conditions. Further, variable renewable energy generators cannot guarantee they will be able to provide sufficient constant energy to restart the system, and batteries would need to permanently reserve a level of charge to guarantee their ability to support system restart (foregoing other revenue opportunities for that battery capacity).

[41] See http://www.aemo.com.au/Stakeholder-Consultation/Consultations/SRAS-Guidelines-2017.

4. Meeting the technical and operational needs of the power system

4.1 Ability of different technologies to provide services

The services described in Chapters 2-3 can be provided by a variety of existing technologies.

Figure 3 maps these services against the required power system technical attributes from Chapter 3 and provides a comparison of the known and emerging ability of different technologies to provide these services.

Technologies are grouped under the broad sub-categories of supply side, network, and demand side.

Figure 3 also includes:

- The "spatial level of need" – differentiating between local service requirements (which must be sourced from within a region) and global services requirements (which can be sourced from anywhere in the NEM and transported via an interconnector).

  The extent to which each technology is capable of providing the service, based on demonstrated capability in Australia or equivalent large power systems internationally, or by the results of large-scale technology trials. This level of demonstrated capability is represented by the filled, half-filled, and empty circles. The extent to which a network element can enable the delivery of the service from a different location in the power system (rather than a service necessarily having to be sourced locally), is represented by the filled and hollow arrows.
- Clarifying comments regarding specific technology capabilities, particularly where there are emerging capabilities.

AEMO expects the summary in Figure 3 to evolve over time, as technology providers continue to broaden the range of services their equipment provides.

Where opportunities exist to provide a service from a new technology, AEMO would like to work with project proponents via our Innovation Office to ensure new technologies have been subject to a rigorous innovation funnel and incorporated into NEM systems. This should ideally occur in a timeframe which permits the new technology to support any emerging shortfalls in the service.

To lodge an inquiry or make contact with the Innovation Office, please send correspondence to innovation@aemo.com.au.

4.2 The need for a portfolio of technical solutions

Efficient policy frameworks will take a portfolio approach to sourcing system services, making optimal use of the capabilities of all assets in the power system, which, when used in combination, should be capable of providing the same or better system performance than in the past.

The matrix in Figure 3 allows consideration of the many linkages and patterns between the different services, and between the various technologies that can provide these services. Some of these linkages and patterns include:

- Where there are current and emerging opportunities to provide services from more than one technology (such as for energy reserves and flexibility services) – indicating the potential value in enabling a portfolio of service providers.
- Where multiple services can be provided by common groups of technologies (such as bulk energy, primary frequency control, and secondary frequency control) – indicating opportunities for co-optimising services.
- Where there are limited technologies capable of providing a service (such as for inertial response and system strength) – indicating that there may be economic efficiencies in decoupling the services from the provision of energy.

Figure 3 Summary of required system services, and capability of technologies to provide them

Service description				Supply side		Network						Demand side		
				Centralised generation		Transfer between regions		Transfer within regions	Stabilising devices			Load	Decentralised resources	
System Attribute	Requirement	Service	Spatial level of need	Synchronous generator	Non-synchronous generator	DC interconnection	AC interconnection	Transmission and distribution networks	Grid reactor, grid capacitor, static VAR compensator	Static synchronous compensator	Synchronous condenser[1]	Large industrial, residential, commercial	Solar PV	Battery storage
Resource adequacy	*Provision of sufficient supply to match demand from customers*	**Bulk energy**	System wide	●	●	➔	➔	➔	○	○	○	●	●	●
		Strategic reserves	System wide	● [2a]	◐ [3a]	➔	➔	➔	○	○	○	●	◐ [3b]	◐ [3b]
	Capability to respond to large continuing changes in energy requirements	**Operating reserves**	System wide	● [2b]	◐ [3a]	➔	➔	➔	○	○	○	●	◐ [3b]	◐ [3b]
	Services to transport energy generated to customers	**Transmission & distribution services**	Local	● [4]	● [4]	●	●	●	●	●	●	● [4]	◐	◐
Frequency management	*Ability to set frequency*	**Grid formation**	Regional	●	◐ [5]	⇨ [5]	●	●	○	○	○	○	○	◐ [5]
	Maintain frequency within limits	**Inertial response**	Regional	●	◐ [6]	◐ [6]	➔	➔	○	◐ [7]	●	○ [8]	○	◐ [6]
		Primary frequency control	Regional	●	● [9]	➔	➔	➔	○	○	○	●	●	● [9]
		Secondary frequency control	Regional	●	● [9]	➔	➔	➔	○	○	○	●	●	● [9]
		Tertiary frequency control	Regional	●	● [9]	➔	➔	➔	○	○	○	●	●	● [9]
Voltage management	*Maintain voltages within limits*	**Fast response voltage control**	Local	●	●	●	○	○	●	●	●	●	◐	●
		Slow response voltage control	Local	●	●	●	○	○	●	●	●	●	◐	●
		System strength	Local	●	○	○	⇨	➔	○	○	●	○	○	○
System restoration	*Ability to restore the system*	**System restart services**	Local	●	◐ [10]	◐ [10]	●	➔	○	○	○	○	○	◐ [10]
		Load restoration	Local	●	●	●	●	⇨	●	●	●	●	◐	◐

1 This includes generators with ability to operate in synchronous condenser mode.
2a While many synchronous generators can provide energy reserves, some less firm technologies (solar thermal or pumped hydro storage) will be limited by the amount of energy storage they include.
2b While many synchronous generators can provide flexibility services, coal generators are limited in their ability to provide such services.
3a Limited by duration for which service can be delivered.
3b Limited by duration for which service can be delivered; existing controllability is limited.
4 The provision of local voltage support from generators and loads can improve the network transport capability near their respective connection points.
5 Grid forming power electronic converters are available and have been proven on small power systems. Development of grid forming converters for large power systems is an emerging area of international research.
6 Some fast frequency response capabilities can provide emulated inertia response, but are not yet proven as a total replacement for synchronous inertia.
7 Static synchronous compensators with energy storage devices are being trialled as an emerging provider of inertial response.
8 Except for load relief.
9 Includes fast frequency response capabilities.
10 System restoration services from variable non-synchronous generators is an emerging area of international research. If they are grid scale, batteries are likely to provide some system restoration support.

Ability to provide service		
●	◐	○
Fully capable	Partial or emerging	Unable
➔	⇨	
Enables delivery	Partial or limited delivery	

Note: Classifications are indicative of the general ability of each technology type. The extent to which technologies can provide each service must be assessed on the specifics of each individual system.

By considering these linkages, policy-makers can develop efficient policy frameworks that ensure availability of these services, drawing on complementary technologies whose collective capabilities can meet the needs of the power system.

Future AEMO publications will explore these linkages in more detail.

4.3 Future work to understand and address system needs

Building on previous work[42], AEMO is exploring how the requirements for meeting the needs of the power system may change over time, including identifying potential alternative means of sourcing these services.

As noted earlier, this document provides a foundational resource for policy-makers and stakeholders, establishing a common language for the technical and operational requirements of the power system.

Priority areas for future AEMO strategic projects and policy proposals will build on this paper to explore:

- Whether the current operating standards, particularly those impacting frequency, voltage, and operating reliability, are fit for purpose today and into the future.
- The capabilities of existing and new technologies to deliver essential services, and the emergence of new business models.
- Opportunities to improve the way these services are sourced in the NEM, drawing from international trends and practices.
- Emerging opportunities and risks that need to be managed to ensure consumer expectations for electricity supply are met.

As the energy transformation progresses, the theories and practices associated with power system operation are undergoing continuous review and development by power system operators internationally.

AEMO will continue to work with stakeholders to convey the most up-to-date information. As part of this, we will explore the opportunities and risks of how technical services may need to change over time. This will include consideration of the various system services essential for system security and reliability, the appropriate mechanisms to secure these services cost-effectively and efficiently, and the rules and standards which are appropriate for the transforming system.

We will also continue to enhance our ability to comprehensively model the power system and understand its technical limits, given changing operational dynamics and emerging technologies.

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[42] AEMO's reports and analysis since 2013, related to future power system security, are available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Security-and-reliability/FPSSP-Reports-and-Analysis.

Measures, abbreviations, and glossary

Units of measure

Abbreviation	Unit of measure
GW	Gigawatt (equivalent to 1,000,000,000 Watts, or 1,000 MW)
kW	Kilowatt (equivalent to 1,000 watts)
MW	Megawatt (equivalent to 1,000,000 Watts, or 1,000 kilowatts)
W	Watt – a standard unit of power. 1 watt = 1 joule per second, and can be used to quantify the rate of energy transfer.

Abbreviations

Abbreviation	Expanded name
AC	Alternating current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
DC	Direct current
FCAS	Frequency control ancillary services
NEM	National Electricity Market
NER	National Electricity Rules
NSP	Network service provider
PV	Photovoltaic
TNSP	Transmission network service provider

Glossary

This document uses many terms that have meanings defined in the National Electricity Rules (NER). The NER meanings are adopted unless otherwise specified.

Term	Meaning
Active power	Instantaneous rate at which electrical energy is consumed, generated or transmitted (see also 'Power').
Central dispatch process	This process maintains energy balance in the system through the centrally-coordinated matching of supply and demand, with the aim to maximise efficiency by optimising the contribution of available resources while maintaining system security. AEMO conducts this process in accordance with clause 3.8 of the National Electricity Rules (NER).
Connection point	The agreed point of electrical connection established between network service provider(s) and a generator or consumer.
Constraint	A physical system limitation or requirement that must be considered by the central dispatch algorithm when determining the optimum economic dispatch outcome.

Term	Meaning
Consumer	A person or organisation who engages in the activity of purchasing electricity supplied through a transmission or distribution system to a connection point.
Contingency	An event affecting the power system which is likely to involve an electricity generating unit's or transmission element's failure or removal from service.
Demand	The total amount of electricity consumed at any given time. Demand sub-definitions are used for technical purposes and are outlined in Appendix A of AEMO's *Forecasting Methodology Information Paper*, available at https://www.aemo.com.au/media/Files/Electricity/NEM/Planning_and_Forecasting/NEFR/2016/Forecasting-Methodology-Information-Paper---2016-NEFR---Final.pdf.
Demand response	The ability of consumers to vary electricity consumption in response to a change in market conditions, such as a change in the spot price.
Dispatch	The act of initiating or enabling all or part of an offer by a scheduled generating unit, semi-scheduled generating unit, scheduled load, scheduled network service, or ancillary service provider. AEMO conducts dispatch in accordance with NER clause 3.8.
Dispatch schedule	Dispatch instructions AEMO issues to generators (in the central dispatch process) at 5-minute intervals throughout each day, based on offers submitted in the bidding process.
Dispatchability	Extent to which the output of an energy resource or portfolio of resources can be relied on to 'follow a target' and adhere to a dispatch schedule at some time in the future.
Distributed energy resources (DER)	Resources embedded within the distribution network and behind the meter which can be used individually or in aggregate to help balance supply and demand or provide system services. Examples include residential or commercial installations of solar PV, wind turbines, energy storage, demand management systems, electric vehicles (EVs), combustion generators, variable speed motor drives, and cogeneration units. The capabilities of DER depend on the specific technology. AEMO currently has limited visibility of DER.
Distribution system	Poles and wires, and other equipment transporting power from the transmission network to end users.
Disturbance	Unexpected events affecting power system operation. Large disturbances include loss of a major transmission line or a large generator or load. Small disturbances arise due to switching on or off small loads, tripping of less significant lines and small generators.
Fast Frequency Response (FFR)	A very rapid response to re-balance megawatts on the power system. May be automatic in response to frequency, or a centrally controlled response (that is, a control scheme to shed load).
Frequency	For alternating current (AC) electricity, the number of cycles occurring in each second, measured in Hertz (Hz).
Generation	The production of electrical power by converting another form of energy in a generating unit.
Generation capacity	The amount (in megawatts) of electricity that a generating unit can produce under nominated conditions. The capacity of a generating unit may vary due to a range of factors (for example, the capacity of many thermal generating units is higher in winter than in summer).
Interconnector	A transmission line or group of transmission lines that connects transmission networks in adjacent regions. Can facilitate AC or DC power flow.
Load	A connection point or defined set of connection points at which electrical power is delivered to a person or to another network or the amount of electrical power delivered at a defined instant at a connection point, or aggregated over a defined set of connection points. The term also refers to devices at the end user's location drawing electrical energy from the network and converting it to some other useful form.
Maximum demand	The highest amount of electrical power delivered, or forecast to be delivered, over a defined period (day, week, month, season, or year), either at a connection point or simultaneously at a defined set of connection points.
National Electricity Market (NEM)	The wholesale exchange of electricity operated by AEMO under the NER. NEM regions are New South Wales, Queensland, South Australia, Tasmania, and Victoria.
Non-synchronous generator	Non-synchronous generators (also referred to as asynchronous generators) include wind farms, solar PV generators, and batteries that export power to the grid. They do not have moving parts rotating in synchronism with the grid frequency, but instead are interfaced to the power system via power electronic converters which electronically replicate grid frequency.
Power	Rate at which energy is transferred through an electrical system. Power is comprised of two components: active power and reactive power. Discussions on energy balance (the balance of supply and demand) are related to active power, while reactive power affects voltages in the system (see also 'Active power' and 'Reactive power').

Term	Meaning
Power system	The NEM's entire electricity infrastructure (including associated generation, transmission, and distribution networks) for the supply of electricity, operated as an integrated arrangement.
Power system reliability	The ability of the power system to supply adequate power to satisfy consumer demand, allowing for credible generation and transmission network contingencies.
Power system security	Power system security arises when the power system is operating within defined technical limits, and is likely to return within those technical limits after a disruptive event occurs, such as the disconnection of a major power system element (such as a power station or major powerline).
Power system stability	Ability of the power system to return to stable operating conditions following a physical disturbance.
Reactive power	Reactive power, which is different to active power, is a necessary component of alternating current electricity (see also 'Power'). Management of reactive power is necessary to ensure network voltage levels remains within required limits, which is in turn essential for maintaining power system security and reliability.
Reactor	A device specifically arranged to be connected into the transmission system during periods of low load demand or low reactive power demand to counteract the natural capacitive effects of long transmission lines in generating excess reactive power and so correct any transmission voltage effects during these periods.
Reliability (of supply)	See 'Power system reliability'.
Reliability standard	The power system reliability benchmark set by the NER. The reliability standard for generation and inter-regional transmission elements in the NEM is a maximum expected unserved energy (USE) in a region of 0.002% of the total energy demanded in that region for a given financial year.
Rooftop photovoltaic (PV)	Includes both residential and commercial solar panel installations, typically located on consumers' rooftops.
Security	See 'Power system Security'.
Static synchronous compensator (STATCOM)	Regulating device based on a power electronics voltage-source converter that can act as either a source or sink of reactive power to an AC network.
Static VAR compensator (SVC)	A device specifically provided on a network to provide the ability to generate and absorb reactive power and to respond automatically and rapidly to voltage fluctuations or voltage instability arising from a disturbance or disruption on the network.
Supply	The total amount of electricity generated at any given time.
Synchronous condenser	Synchronous condensers are synchronous machines, specially built to supply only reactive power. The rotating mass of a synchronous condenser will contribute to the total inertia of the network from its stored kinetic energy.
Synchronous generator	Generator which is directly connected to the power system and rotates in synchronism with grid frequency. Thermal (coal, gas) and hydro (water) driven power turbines are synchronous generators
System strength	System strength is an umbrella term that refers to a suite of interrelated factors which together contribute to power system stability. It reflects the sensitivity of power system variables to disturbance, and indicates inherent local system robustness, with respect to properties other than inertia. System strength affects the stability and dynamics of generating systems' control systems, and the ability of the power system to both remain stable under normal conditions and return to steady-state conditions following a disturbance.
Technical envelope	Technical boundary limits of the power system for achieving and maintaining the secure operating state of the power system for a given demand and power system scenario. Also called "secure technical envelope".
Transmission grid (Transmission network/system)	Towers, large poles, and wires and other equipment transporting power from generators to large energy users and distribution connection points for routing to downstream consumers.
Voltage	The electrical force or electric potential between two points that gives rise to the flow of electricity.