THE UNIVERSITY *of* ADELAIDE

SUB CRUCE LUMEN

Course:

ELEC ENG 3110 Electric Power Systems
ELEC ENG 7074 Power Systems PG

(Semester 2, 2021)

Overview of Electric Power Systems

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Mission of a Power System

The following is meant to be a "plain English" interpretation of the *National Electricity Objective* (NEO) under the *National Electricity Law* (NEL).

In accordance with an encompassing legal and regulatory framework perform the following key functions. Safely and stably generate and deliver electrical power to consumers, on their demand, at prescribed levels of reliability and security whilst ensuring the system frequency and voltage levels are maintained nearly constant at 50 Hz and 1 per-unit respectively. These functions are to be performed at the least cost consistent with the encompassing framework and the long-term economic sustainability of the system.

Not stated but implied:

The operation of the power system *will at all times* satisfy the *universal laws of nature*.

- *Humanity can decide how to best work with nature but she makes the rules ... not legislators, economists or engineers.*

BIG questions: Does the basic mission statement need to change?

- Recognize **environmental sustainability** of the power system?
- Recognize that **consumers** will become **active market participants**?

The Legal Framework of the South and East Australian Power System

The National Electricity Law (NEL) is established by an Act of the South Australian Parliament: The National Electricity (South Australia) Act 1996[1].

The National Electricity Rules (NER) govern the operation of the National Electricity Market (NEM). The NER have the force of law, and are made under the NEL. They are amended by the Australian Energy Market Commission (AEMC) or, in special and limited circumstances, by the South Australian Minister for Mineral Resources & Energy who is the Minister responsible for the AEMC to the Council of Australian Governments (COAG).

The NER apply in the NEM, which comprises New South Wales, the Australian Capital Territory, Queensland, South Australia, Victoria and Tasmania.

The current version (107) of the rules (as at 24/5/18) is dated 10 April 2018 and comprises 1575 pages[2].

1. URL: https://www.legislation.sa.gov.au/LZ/C/A/NATIONAL%20ELECTRICITY%20(SOUTH%20AUSTRALIA)%20ACT%201996/CURRENT/1996.44.UN.PDF
(Viewed 23/7/17)
2. URL: https://www.aemc.gov.au/sites/default/files/2018-04/National%20Electricity%20Rules%20version%20107.pdf
(Viewed 24/5/18)

Human Achievement Embodied in Power Systems

Power Systems are very large, complex and highly non-linear **dynamic** machines.

Reasonably argue most complex and yet reliable systems built by humanity.

Operate on time-frames from decades to light-speed.

Power systems at the heart of our civilization:

- drawn on – and continue to draw on – the diverse talents, skills and dedication of countless people from a vast array of disciplines to collaboratively invent, plan, build and operate them for the benefit of society as a whole.

In another **transitional phase** in the development of power systems.

- Since the beginning power systems have been subject to continuous improvement and modernization.
- Power systems engineers always near the cutting edge of technological development.
- The modernization process, now, as always, involves the reliable and secure application of modern technologies to the production, delivery and utilization of electrical energy.

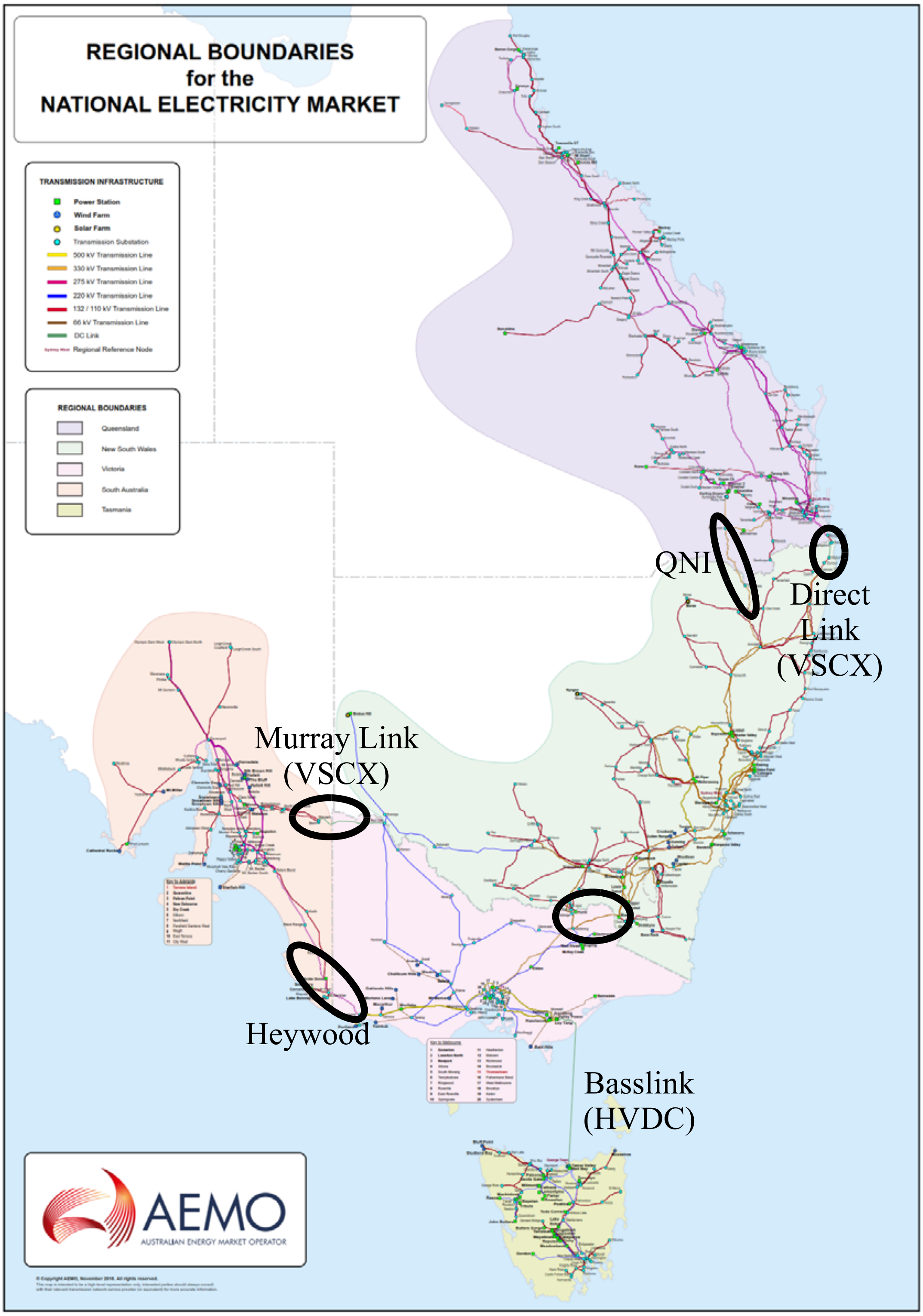
Brief History of Australian Power System[1]

1878/83	First light, Sydney GPO / Adelaide train Station.
1899	Young, NSW – First 3 phase power.
1906	36 MW capacity nationally – light, power and traction **(the first micro grids)**.
1916	First energy source remote from load. 6.8 MW Waddamana hydro power station in Tasmania. 100 km, 88 kV 3-phase line to Hobart.
1924	First La Trobe Valley (Vic.) power station; brown coal deposits. Yallourn PS 50 MW; 160 km, 132 kV line to Melbourne. Start of 70+ year development of Victorian power generation.
	Vic. and Tas. first to establish central power authorities: focussed economic development.
	Other states leave electricity supply to local government. Stunted economic development.
1946	Post WWII. ETSA established (Tom Playford). Compulsory acquisition of private Supply Co. Aim to establish basic infrastructure for industrial development. Leigh Creek coal fields developed for power generation at Pt. Augusta.
	Post WWII construction boom to satisfy pent up demand – major electrification drive.
1948	Start major drive into electro-metallurgical industries – aluminium, copper, zinc, etc.
	Accelerated development of remote fuel sources and the associated transmission networks.
1949	Start building Snowy Mountains hydro-electric scheme. Eventually completed in 1972.

1. Frank Brady (Ed.), "A Dictionary of Electricity: Contribution on AUSTRALIA", A joint project of CIGRE and AHEF.

1950's	NSW begins mapping and exploiting black coal deposits for electricity generation. Basis for subsequent 50+ years of power generation.
1959	330 kV interconnection between NSW and Vic. The resulting system is 1,400 km long. Automation of economic dispatch. Other mutually beneficial interconnection opportunities exploited
1963	Point Henry Aluminium Smelter (Geelong, Vic.)
1969	ETSA stimulates Moomba gas development.
1970–1986	Large aluminium smelters constructed in Vic., NSW, Qld. Triggered significant development in electricity production and transmission.
1987	First Aust. commercial wind farm near Esperance
1990	Portland Smelter near SA border. Opportunity to construct Heywood SA-Vic. interconnection.
1993	Commenced work to corporatize / privatize the electricity industry. Commenced in Vic. in 1995.
1996	Establishment of the National Electricity Market and the market operator (NEMMCO).
1998	The NEM commenced operation.
1999	ETSA privatized 53 years after its creation.
2000	Qld. – NSW interconnection: Grid 5000 km long.
2003	Starfish Hill windfarm (Cape Jarvis) commenced the rapid development of wind power in SA.
2005	Basslink HVDC Vic.–Tas. interconnection
2007	Commence decade+ energy policy paralysis
2009	AEMO replaces NEMMCO and assumes responsibility for the gas market in addition to electricity.
2017	100 MW / 129 MWh battery adjacent Hornsdale windfarm, SA.

South and East Australian Power System



AEMO, URL: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Maps/2016-NEM-Regional-Boundaries-Map-WEB.pdf
Accessed: 21 July 2017.

SE Australian Power System – Networks

Mainland 3-phase a.c. **transmission system:** Pt. Lincoln (SA) ~5000 km around coast to Pt. Douglas in far North Queensland.

- Very long and sparse network
- Relatively weak regional interconnections
- Challenging to maintain power system stability
- Tas.-Vic. 290 km submarine HVDC link, 500 MW (cont. rating); line-commutated converters at Loy Yang (500 kV) and George Town (220 kV).

Transmission system ~**40,000 km** of HV transmission lines & cables[1].

- SA transmission system (ElectraNet) approx. 5,600 km of transmission lines at voltages of 275, 132 and 66 kV.

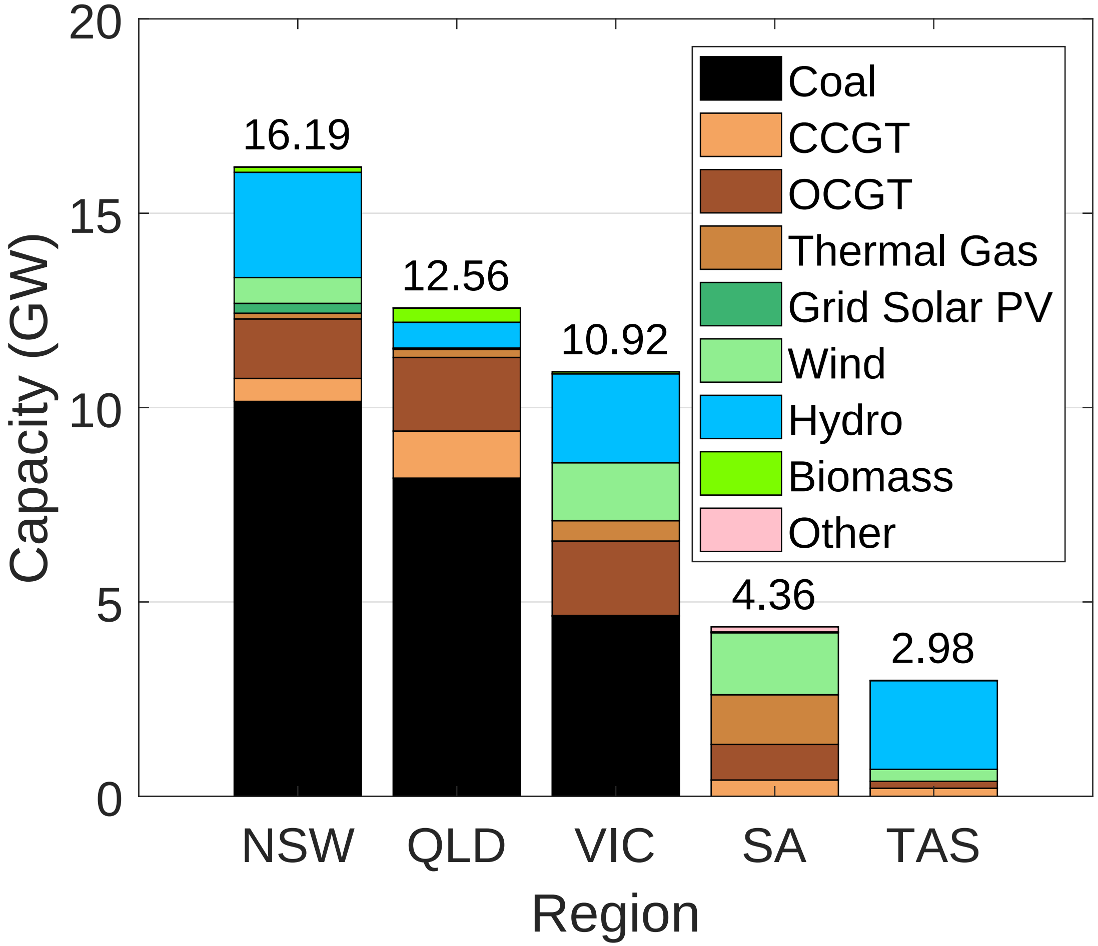
Distribution systems: ~**746,000 km** of lines and cables (i.e. notionally 66 kV and lower)[2]

- SA distribution system (SAPN), comprises a network route length of ~ 88,000 km, 400 zone substations, > 73,000 transformers and 720,000 Stobie poles[3].

1. AEMO: URL: https://www.aemo.com.au/media/Files/Other/corporate/AEMO16839_FactSheet_NationalElectricityMarket_D6.pdf.pdf (Viewed 23/7/17).
2. Bureau of Infrastructure, Transport and Regional Economics, Australian Infrastructure Statistics, 2016, URL: https://bitre.gov.au/publications/2016/files/BITRE_yearbook_2016_statistics_full_report.pdf (Viewed 23/7/17).
3. URL: http://www.sapowernetworks.com.au/centric/industry/our_network.jsp

South and East Australian Power System

- Total NEM installed generating capacity 47 GW (June 2017)[1].
- NEM max. demand 32.9 GW (summer), 32.0 GW (Winter)
- Total NEM energy consumption 196.5 TWh[2] (2016/17 FY).
  - 25 kWh / person / day (equivalent to about 10 times the average Australian adult's daily food energy intake of 8,700 kJ)
  - Average generated power: $196.5 \times 10^3 / (365 \times 24) = 22.4$ GW
  - Capacity Factor = 22.4/47 = 0.48
- NEM Regional Generation Mix and Capacity (5 June 2017)[3]



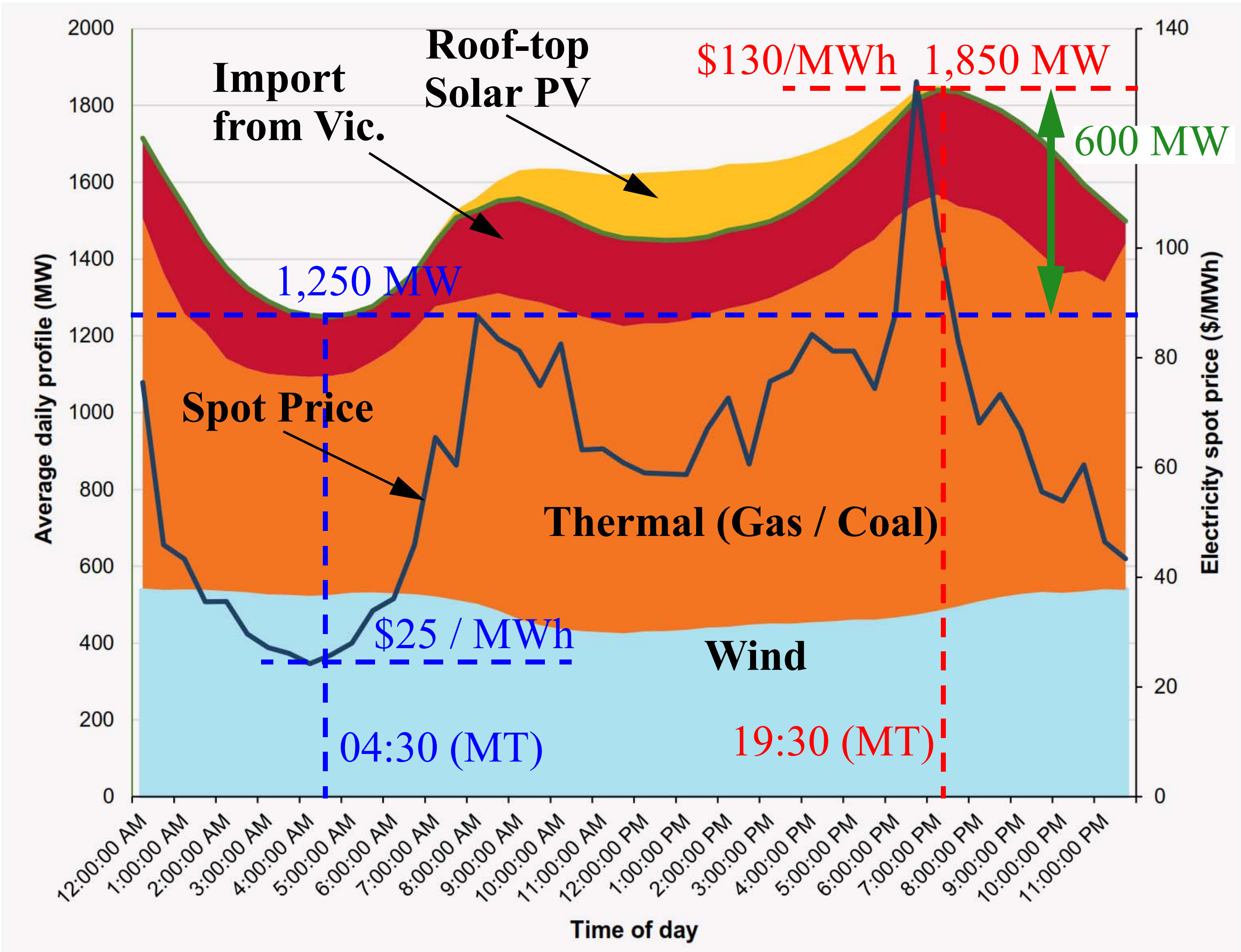
1. AEMO: URL: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information (Viewed 23/7/17).
2. AER: URL: https://www.aer.gov.au/wholesale-markets/wholesale-statistics/national-electricity-market-electricity-consumption (Viewed 23/7/17).
3. Data Source: AEMO – URL: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Generation-information

Key Characteristics of Main Generation Sources

Type of Generation	Generation Method	Important characteristics for grid operation.
Coal Thermal Gas	Fuel (coal, natural gas) combusted to heat water in a boiler to produce high pressure steam. Working fluid fed a steam turbine (ST) that produces rotary mechanical energy which is converted to electrical energy by a synchronous generator.	Dispatchable base load synchronous generation. Have high minimum output levels. Relatively slow ramp rates. Long startup times (several hours to 1-2 days). Polluting.
OCGT	An Open Cycle (OC) Gas Turbine (GT) compresses air drawn from the atmosphere to a high pressure. The air is then heated to a high temperature by passing it through a combustion chamber into which a fuel (e.g. natural gas) is injected and ignited. The high-pressure, high-temperature stream is then expanded through a turbine where it produces rotary mechanical power that is converted to electrical energy by a synchronous generator.	Dispatchable intermediate / peak load synchronous generation. Fast start (10’s of minutes). Can operate at relatively low output. Higher ramp rates than for ST. Polluting.
CCGT	The Combine Cycle Gas Turbine comprises both gas- and steam-turbines. The exhaust heat from the gas-turbines is used to produce steam for the steam turbine(s).	Dispatchable base/intermediate/peak load synchronous generation. GTs can be started quickly (as for OCGT) but ST takes longer. More efficient than OCGT.

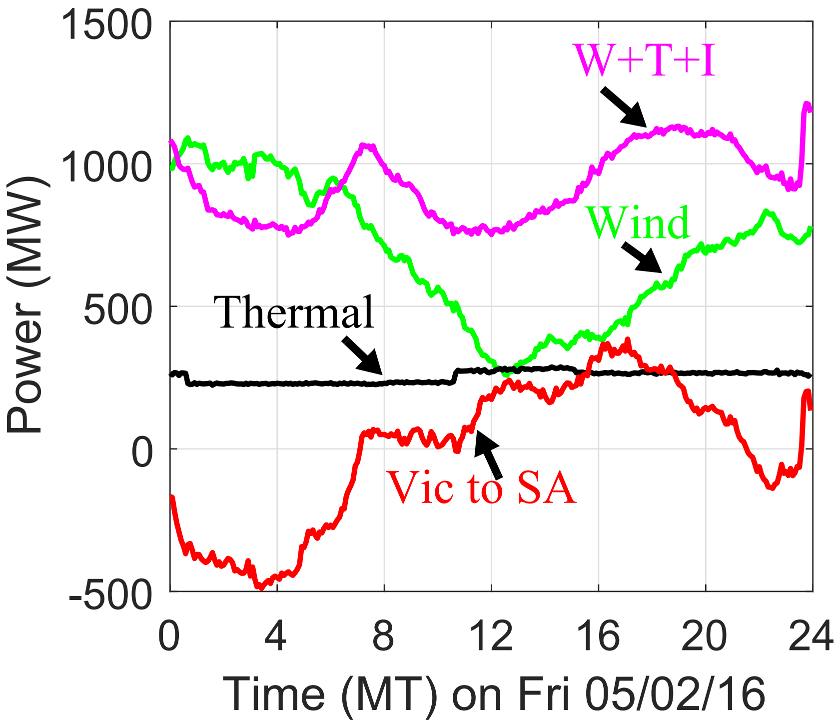
Type of Generation	Generation Method	Important characteristics for grid operation.
Hydro	The potential energy of water in an upper reservoir is converted to kinetic energy by flowing downhill through pipes and tunnels. The kinetic energy in the flowing water is converted to rotary mechanical energy by a hydraulic turbine whence it is converted to electrical energy by a synchronous gen.	Dispatchable base/intermediate/peak load synchronous generation. Can be started and stopped very quickly. Relatively fast ramp rates.
Wind	Wind energy is converted to rotary mechanical energy by propeller whence it is converted to electrical energy by a generator. Due to the requirement for variable speed operation the electrical energy is supplied to the power system through a power-electronic converter. Many wind-turbines rated at 2-9 MW interconnected to form wind farms (larger rated turbines (5-9 MW) used in offshore farms)	Intermittent but predictable source. Zero fuel cost. Must operate together with dispatchable energy sources (including storage) to ensure demand-supply balance. Geographical diversity of wind / solar PV farm locations in a large grid helps to smooth variation in power production from intermittent sources. Potential for power-electronic controls to be added to assist with system frequency control.
Grid Solar PV	Direct conversion of sunlight to d.c. electrical energy by semiconductors using the photoelectric effect. Solar photovoltaic (PV) modules interconnected and their d.c. energy is converted to a.c. by power-electronic inverters before being connected to step-up transformers for connection to the grid.	

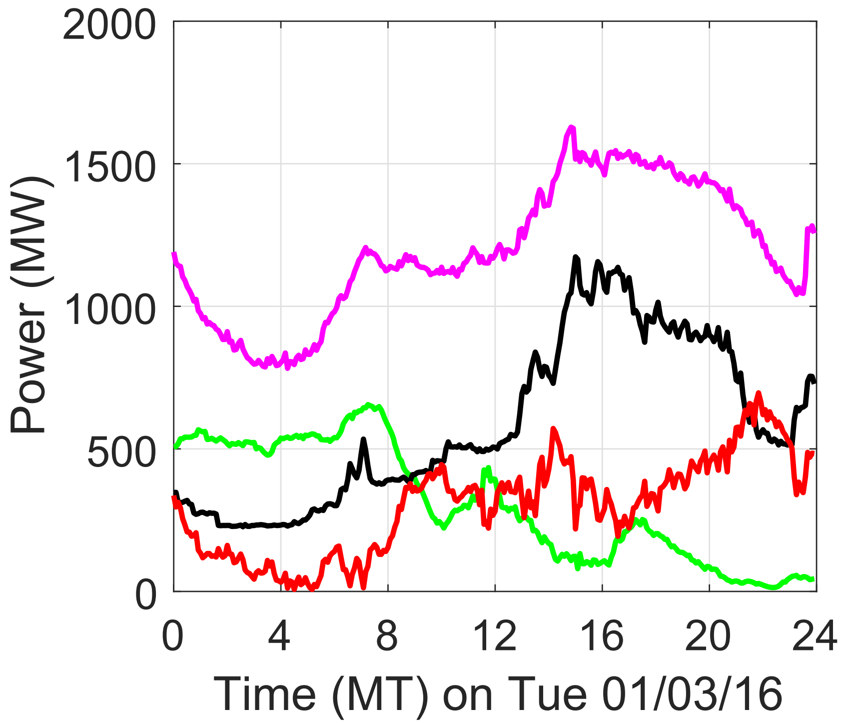
Average SA Daily Load and Generation Profile (2015/16)



AEMO, “South Australian Electricity Report: South Australian Advisory Function”, August 2016

Illustration of Intermittency and Variability of SA Wind Generation

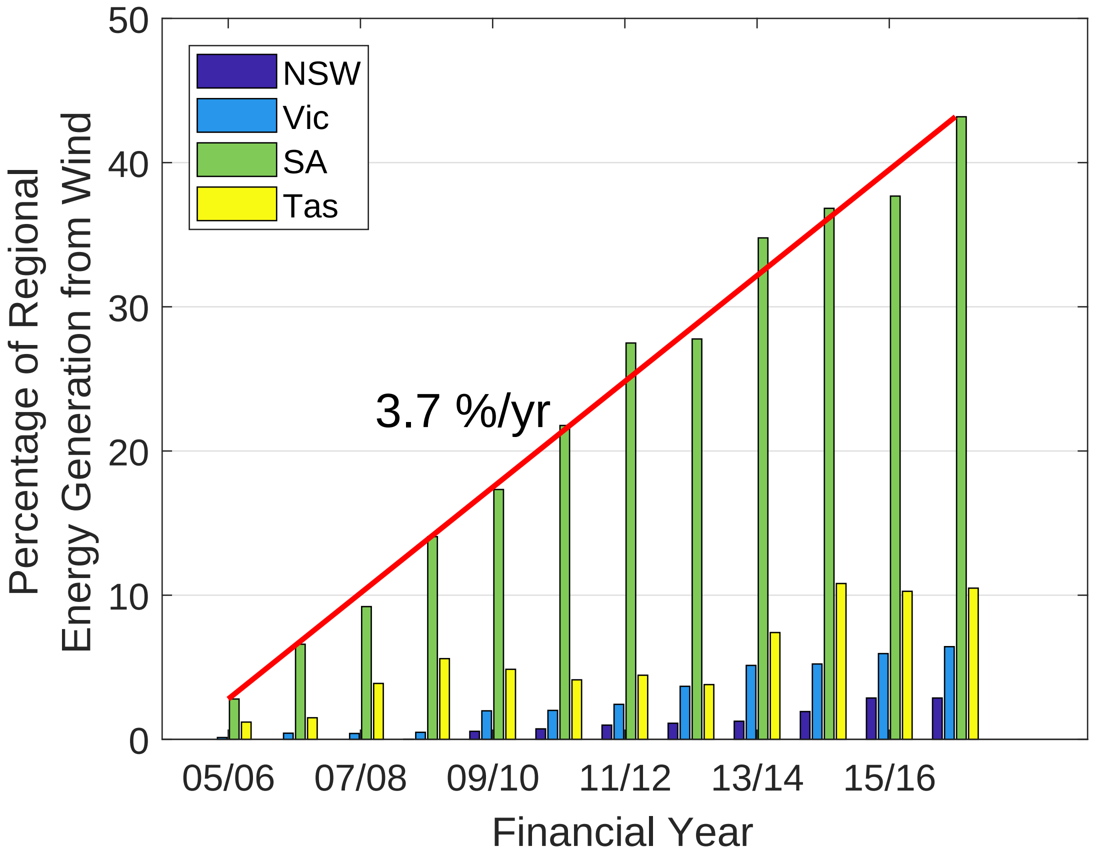




- Light load, SA thermal generation minimum
- High wind (1000 MW) overnight, SA exports excess wind to Vic.
- Wind falls by 750 MW to 250 MW by midday and then increases again. Slack taken up by interconnectors.

- Light-medium load, moderate wind (500 MW) overnight, falls to very low level later in the day.
- SA thermal generation and interconnectors responsive to variation in load and wind generation.

Contribution of Wind Energy to Regional Electrical Energy Production



- The contribution of SA wind energy to the state's total electrical energy production has grown at about 3.7% on average for the last eleven years.
- In the 2016/17 financial year which followed the closure of the Northern Power Station the contribution of wind to SA's total electrical energy production is now 43%.

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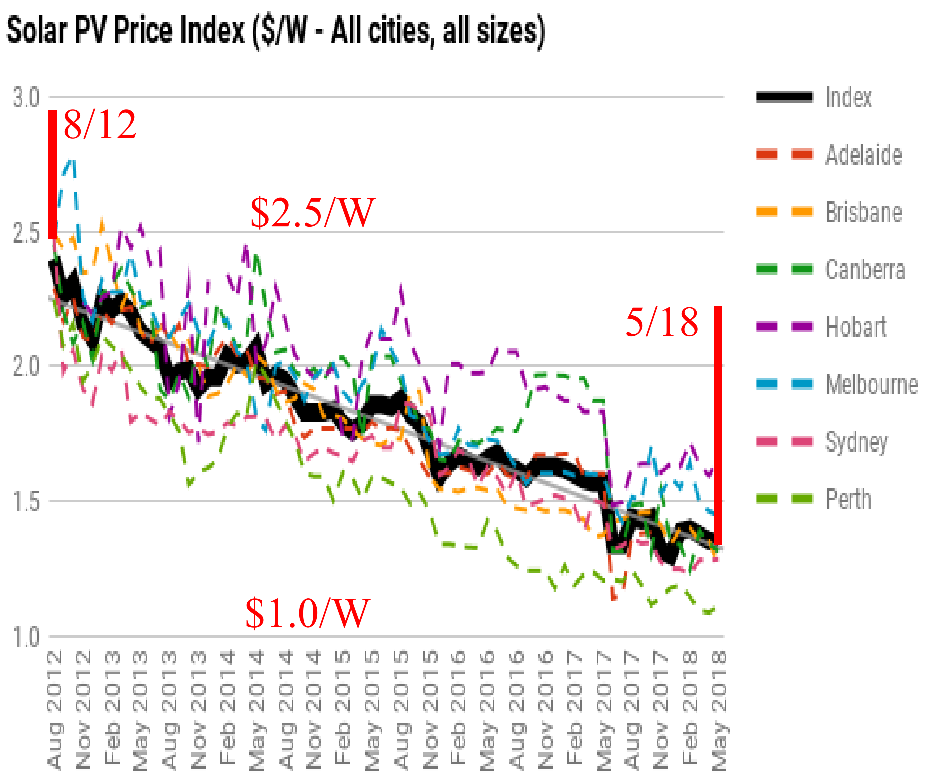
Distributed Energy Resources – Rooftop Solar PV

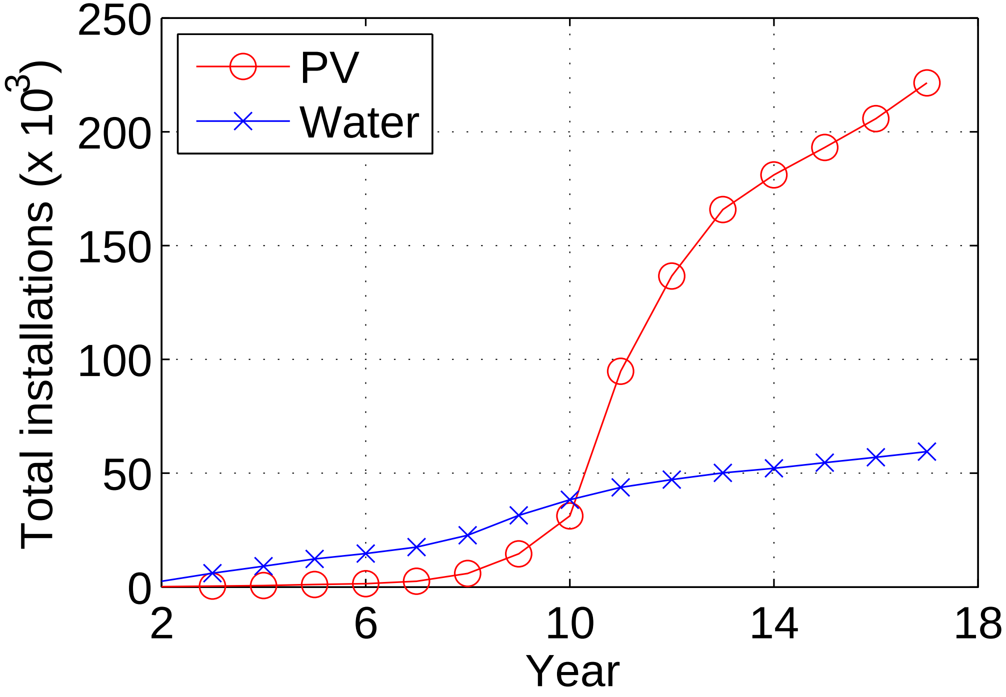


- 5 kW PV system in Adelaide ~ $5,270 (installed, cost to owner)
- For single phase system:
  max. inverter capacity 10 kW, max. export 5 kW
- For three-phase system:
  max. inverter capacity / max. export 30 kW
- Feed-in tariff for new installations ~ 11 – 18 c/kWh
- Average SA retail tariff ~ 38 c/kWh (2016/ 17 est.)[2]

- Price falling at ~$200.00 / kW / year from 2012-2018[1]

1. https://www.solarchoice.net.au/blog/solar-power-system-prices
2. https://www.solarquotes.com.au/systems/feed-in-tariffs/sa/?gclid=CjwKCAjwx-ZnYBRAVEiwANMTRX68ntLXw58502oHYIl85Awr-bVNa11-GJ3ioBlS2-jVSVq7Y3AQHJehoC2eoQAvD_BwE (Viewed 24/5/18)

Distributed Energy Resources – Rooftop Solar PV / Solar Hot water



- High penetration => large decrease in afternoon grid demand[1].
  - ~30% SA households have rooftop solar PV
  - In 2015/16 SA rooftop solar PV
    - capacity (679 MW) about 11% of SA total; and
    - energy production (938 GWh) about 6.5% of SA total

1. AEMO: "South Australian Renewable Energy Report", SA Advisory Functions, Dec. 2016.

Distributed Energy Sources

Domestic Scale Batteries

- Low penetration at this stage
  - ~792 (0.12%) solar/battery installations in SA
  - Increase penetration if:
    - battery trials are successful;
    - retail electricity prices continue to increase;
    - battery prices continue to fall (~20% per doubling of production).
- Initial use of embedded batteries likely to be used for energy arbitrage (storing energy produced during the day for use at night and the following morning).
- AEMO project 6.6 GWh battery energy storage capacity nationally by 2036[1].

1. http://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/-/media/080A47DA86C04BE0AF93812A548F722E.ashx (Viewed 24/5/18)

Demand Side Response

- Potential for medium- to small-prosumers to contribute to maintaining demand-supply balance by controlling their load &/or generation. (Framework exists for large consumers to contribute)
  - Battery storage &/or electric vehicles will increase potential
  - Significant differential between retail and wholesale prices provide significant potential value for consumers?
  - Opportunities for “aggregation” businesses to develop.
  - Are further NER changes needed to facilitate DSR?

Serving the Demand

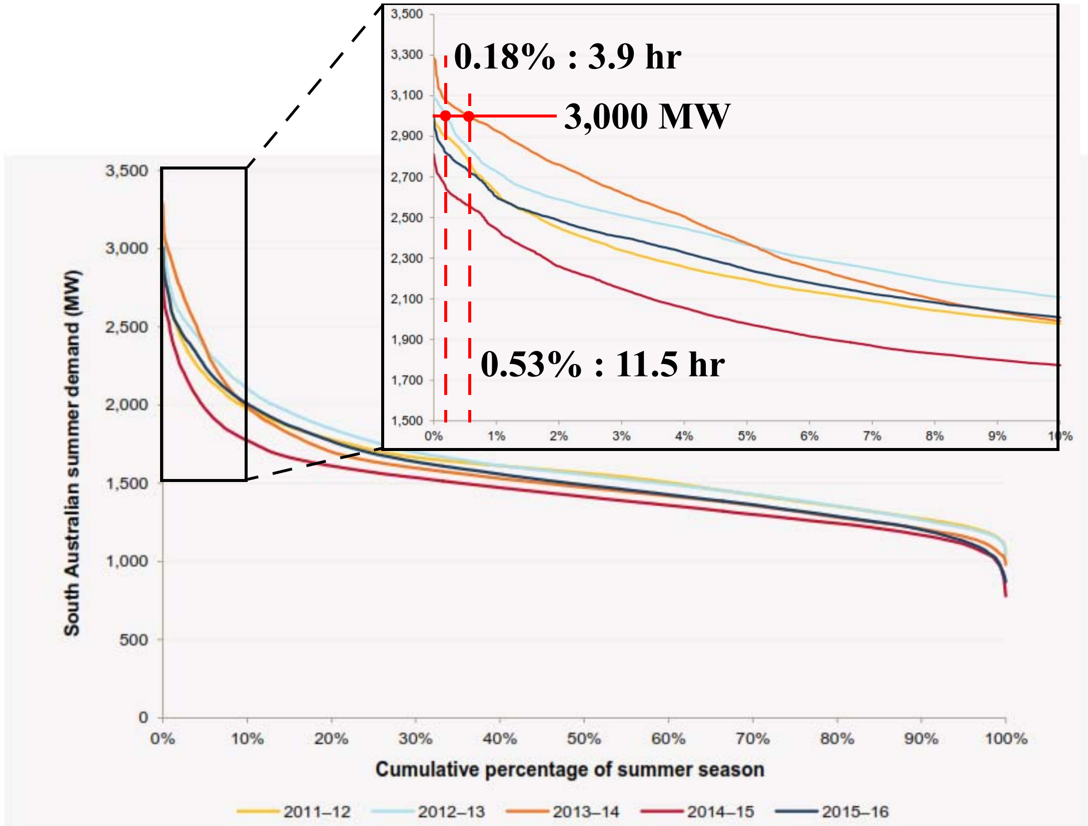
- Demand varies during the day, week, seasonally.
- Demand highly weather dependent on the weather with peak demand on very hot days in SA.
- Accurate maximum demand forecasting for system and network elements (e.g. transformers, lines, etc.) is essential.
  - Complex task and increasingly involves probabilistic analysis. Demand duration curves provide useful insight into the proportion of time during a period (e.g. a year or season) for which the demand will exceed (or be less than) a specified amount.
- Minimum demand on the system is also a critical factor for a number of reasons, a few of which are listed.
- Voltage control
  - Low demand means lower transmission line flows and significantly less reactive power losses in line and cables than when demand is higher.
  - Elevated voltages can thus occur under light load conditions due to line charging effects.
  - A means of absorbing excessive reactive power must be provided, if necessary, to maintain voltages within limits under light load conditions.
- Rotor-angle stability and frequency control
  - Synchronous generators are more likely to be absorbing reactive power which tends to reduce system damping.
  - Fewer machines are available to respond to significant mismatches between supply and demand.

Serving the Demand

Demand duration curves provide useful insight into the proportion of time during a period (e.g. a year or season) for which the demand will exceed (or be less than) a specified amount.

From the demand duration curves of the SA summer season for 2011/12 to 2015/16 it is observed that maximum demand exceeds 3000 MW in two years only (2012/13 – 3,100 MW and 2013/14 – 3,300 MW).

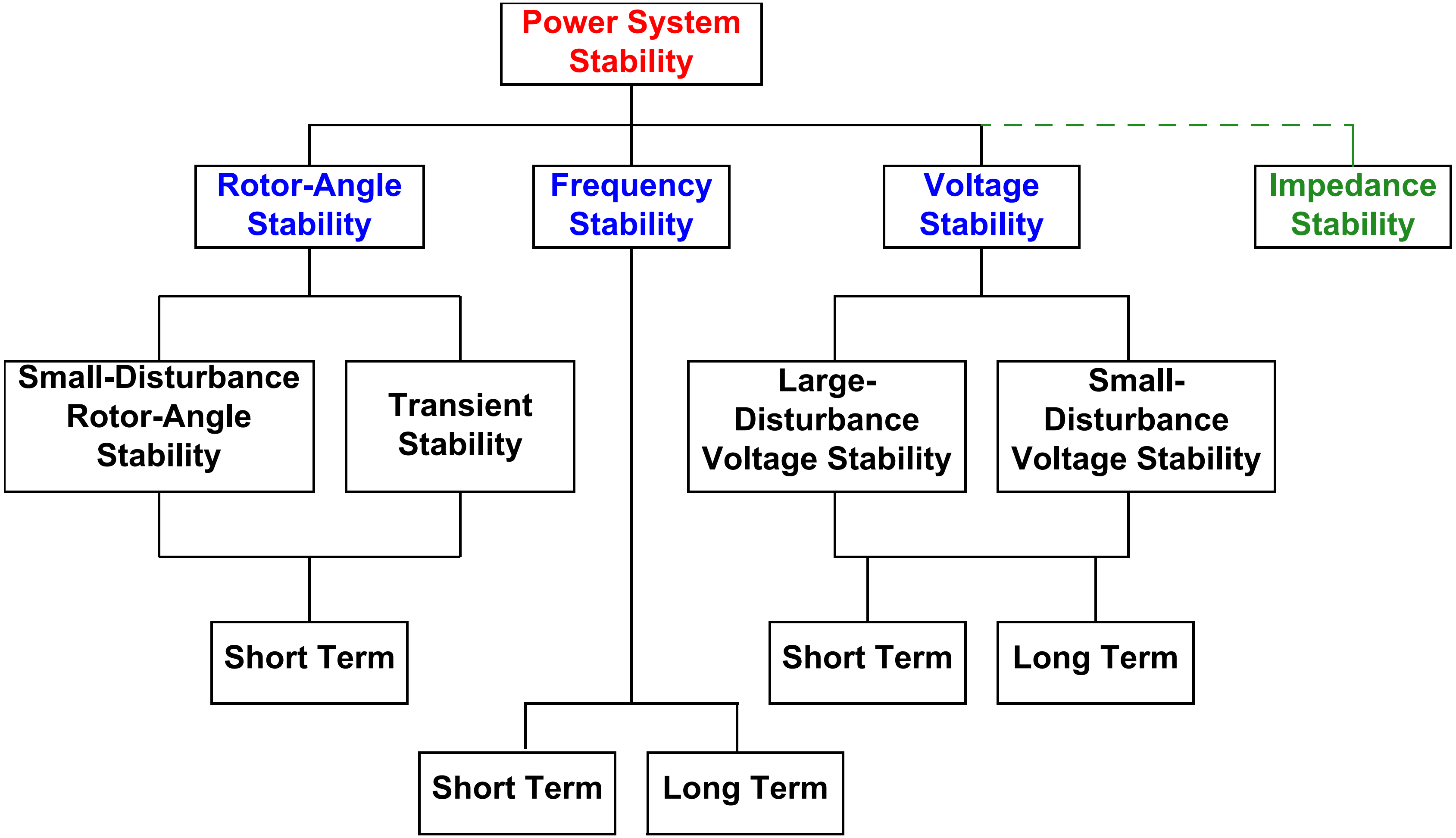
- In 2012/13 summer, demand exceeded 3000 MW for 0.18% of the time, i.e. 0.18/100 x (3 / 12) x 365 x 24 = 3.9 hr.
- Thus, the generation required to serve the load from 3,000 to 3,100 MW in that year was only required for 3.9 hr.
- Very high demand for few hours / year – *<u>can the peak be shaved?</u>*
- <u>Demand Response</u>



Source: AEMO: "South Australian Historical Information Report", South Australian Advisory Functions, August 2016.

Power System Stability

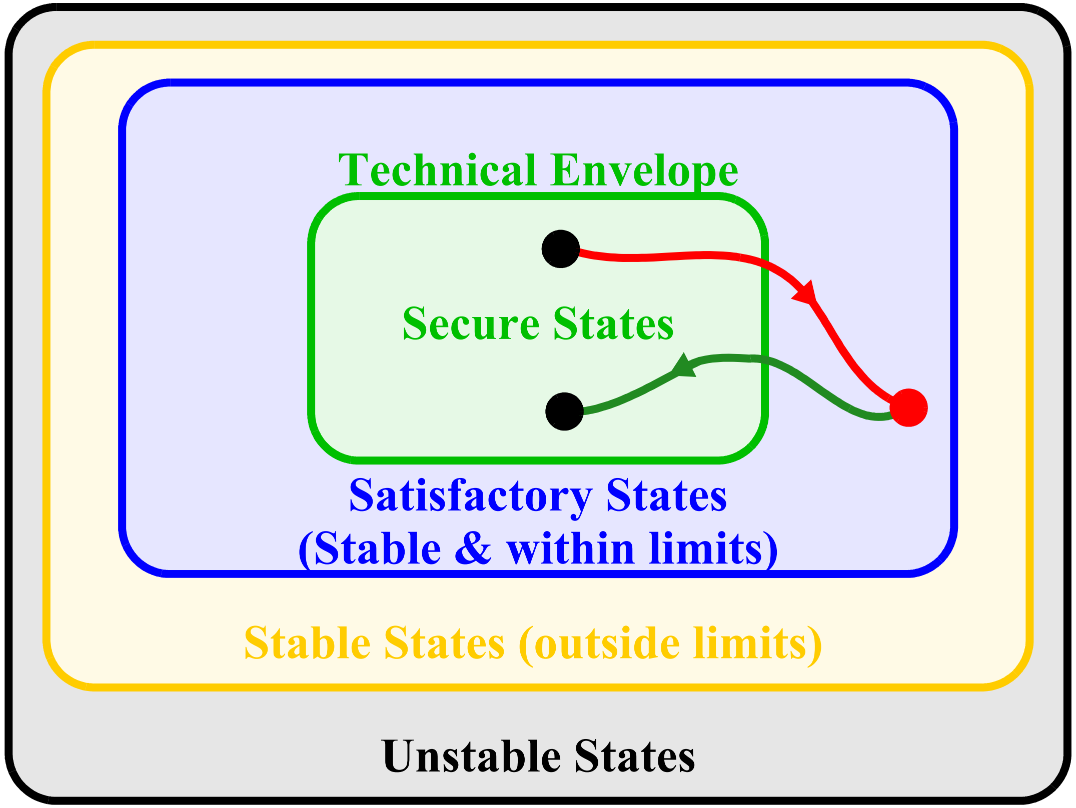
Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.



Power System Stability (cont)

Maintaining stability of a dynamic system generally involves the ability to maintain balance between opposing 'forces'.

- Rotor-angle stability requires that there are sufficient synchronizing torques between the rotors of synchronous machines to maintain synchronism (i.e. transient stability) and that there are sufficient damping-torques to damp oscillations of the rotors of synchronous machines.
  - Synchronizing torque is a component of torque that opposes changes in the rotor-angle of a synchronous machine.
  - Damping torque is a component of torque that opposes changes in the rotor-speed of a synchronous machine.
  - Rotor-angle dynamics occur in a time frame of between about 20 and 30 s on a large power system.
- Frequency stability concerns the ability of the system to maintain balance between the demand (or load) and supply. When demand exceeds supply the system frequency falls below the nominal synchronous frequency of the system (i.e. 50 Hz in Australia); and vice-versa when supply exceeds demand. Unless balance is restored system frequency will change to such an extent that synchronism will be lost.
- Voltage stability concerns the ability of the system to maintain balance between the supply and consumption of reactive power at all system nodes in order to maintain node voltages within prescribed limits. If the reactive power demanded by a load exceeds the supply then voltage at the node will fall. Unless balance is restored voltage collapse will occur.



Power System Security

- **Secure State** – In Satisfactory State & if subject to *credible contingency* will remain in a satisfactory state.
- **Technical Envelope** – TE encompasses set of Secure States.
- **Satisfactory State** – Stable, voltages and frequency within normal limits, equipment operating within ratings.
- **Stable State** – System is stable but some variables may be outside acceptable limits.
- **Unstable State** – System (or parts of it) prone to collapse.

- *System designed and operated to be secure, without loss of load, for credible contingencies and, in the event of multiple contingencies, to continue operation, possibly with (significant) load loss.*
- TE changes continuously depending on the current operating state.

- TE determined from simulation studies:
  - Offline: State-dependent limit-equations
  - Online: Dynamic security assessment (DSA)
- System observation: SCADA, PMUs, State-estimation, online damping-estimation.
- System dispatch is subject to security constraints.

Power System Security[1]

A power system is in a ***satisfactory operating state*** if the frequency and voltages at energized busbars are within prescribed limits, all transmission lines and other system devices are operating within their ratings and the system is stable.

A power system is in a ***secure operating state*** if (i) it is in a satisfactory operating state; and (ii) if, when subject to a credible contingency event, the system will return to a satisfactory operating state. (A contingency is a disturbance that will cause the disconnection of a network element; a credible contingency is a contingency that the system operator believes to be reasonably possible).

The (infinite) set of secure operating states are bounded by an envelope called the ***technical envelope***. The technical envelope changes depending on such things as the system load, transmission line power flows, the outages of network elements and generators, etc.

1. Refer to the NER.

Following a contingency event the system may not be in a secure operating state. In that case it is necessary for the system operator to safely, and with prudent speed, manoeuvre the system into a new secure operating state in readiness for the next contingency.

Determining the technical envelope of the power system requires complex and detailed modelling and analysis of critical contingencies which encompass a comprehensive set of critical operating conditions. For example, loadflow analysis, transient stability analysis, small-signal stability analysis, etc.

Supervisory control and data acquisition (SCADA) systems and, increasingly, phasor measurement units (PMUs) provide measurements of the current state of the system which are then processed to determine if the system is operating within the technical envelope. This situational awareness provides the basis for security constrained economic dispatch of generation (and load) within the NEM.

The [Generation Capacity] Reliability Standard

The AEMC Reliability Panel regularly reviews and updates the NEM Reliability Standard[1]. An abridged version of the current standard follows.

AEMC Reliability Standard

- Concerned with ensuring that adequate generation capacity is available to meet demand. (Includes demand side management)
- The reliability standard is a *probabilistic planning requirement* which is expressed in terms of the maximum amount of electrical energy *expected to be at risk* of *not being supplied* to consumers within a region (or regions) during a financial year.
- Accounts for credible contingencies only (e.g. loss of a generator, single line).

1. AEMC Reliability Panel 2014, “Reliability Standard and Reliability Settings Review 2014”, Final Report, 16 July 2014, Sydney

- The amount of this *expected* UnServed Energy (USE) is expressed as a percentage of the total energy supplied to the region(s) during the year.
- Currently the requirement is for a **USE < 0.002%** for each region
    - For SA in 2015-16 actual consumption was ~13,000 GWh[2]. Compliance with the reliability standard required that no more than 260 MWh of load could be unserved *due to supply inadequacy*.
    - For a flat load-profile this would amount to total loss of load for at most 10.5 minutes in a year.

2. AEMO, “South Australian Electricity Report”, August 2016

Reliability Standard – AEMC Settings

To achieve the reliability standard within an energy-only market whilst mitigating the risks of very high energy costs specify following price controls.

Market Price Cap (MPC) – Maximum allowable limit for the energy spot price, per MWh.

- **Designed** to provide **adequate incentive to prosumers** to build **additional capacity** that may be needed to satisfy the reliability standard, without requiring last resort intervention by the operator.
- Thus the MPC is a short-term **capacity** (i.e. power) **price signal** that is built into the cost structure of an energy only market.
- Current **MPC = $14,200 / MWh**[1] (> 100 times average spot price)

1. "AEMC publishes the Schedule of Reliability Settings for 2017-2018", URL: http://www.aemc.gov.au/News-Center/What-s-New/Announcements/AEMC-publishes-the-Schedule-of-Reliability-Set-(5).

Cumulative Price Threshold (CPT) – Risk mitigation to avoid excessive periods of extreme prices.

- If rolling sum of half-hourly regional spot prices over 7 consecutive days exceeds the CPT then the APC will be applied in the region. (Equates to average spot price of $660 / MWh).
- Current **CPT = $212,800** (15 times the MPC)

Administrative Price Cap (APC) – Risk mitigating spot price.

- Energy price cap that is applied in periods when CPT exceeded
- Current **APC = $300 / MWh**

Other settings and measures

- Market Price Floor (MPF) and Administrative Price Floor (APF)
- Operator has last resort powers of direction to avoid load shedding to ensure reliability in the short term.

Network Reliability.

Transmission and distribution system elements (e.g. power lines, cables, transformers, circuit breakers, switches, primary measurement sensors, etc.) are subject to faults (e.g. lightening strikes, internal faults) and may need to be removed from service for maintenance.

Such events cause network elements to be removed from service by:

- operation of protection to open circuit breakers / fuses to clear a fault (unplanned outage); or
- operator switching operations to remove and make safe one or more network elements for maintenance (planned outage).

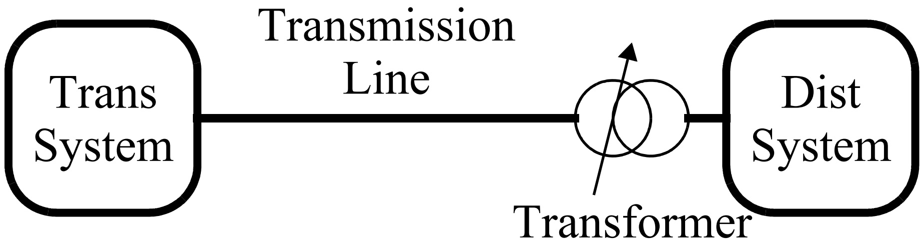
To preserve power supply to customers during a planned or unplanned outage a certain level of network redundancy is necessary.

Network reliability expressed using ‘N’ terminology:

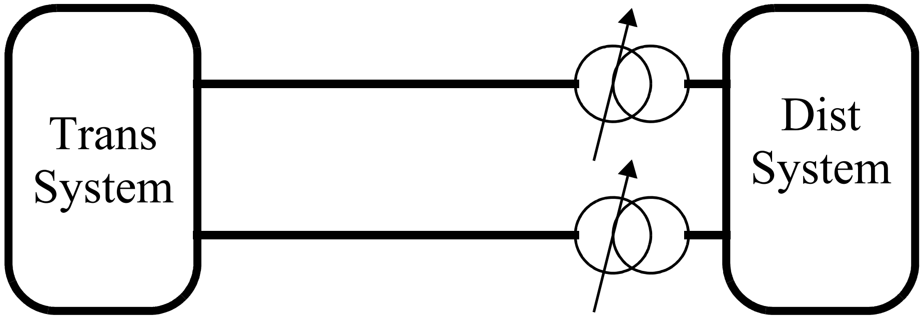
- N – supply max. demand only if all network elements intact.
- N-1 – supply max. demand if one network element o.o.s.
- N-2 – supply max. demand if two network elements o.o.s. etc.

Higher reliability is achieved with a substantial increase in cost.

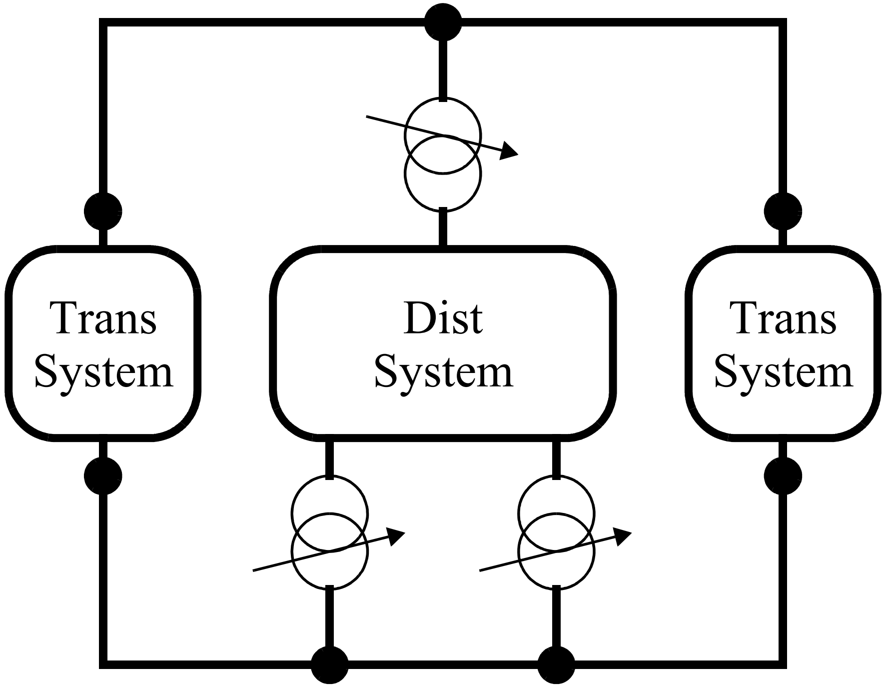
Network Reliability – Level of Redundancy



N reliability: Unable to disconnect any line or transformer without loss of supply to the distribution system.



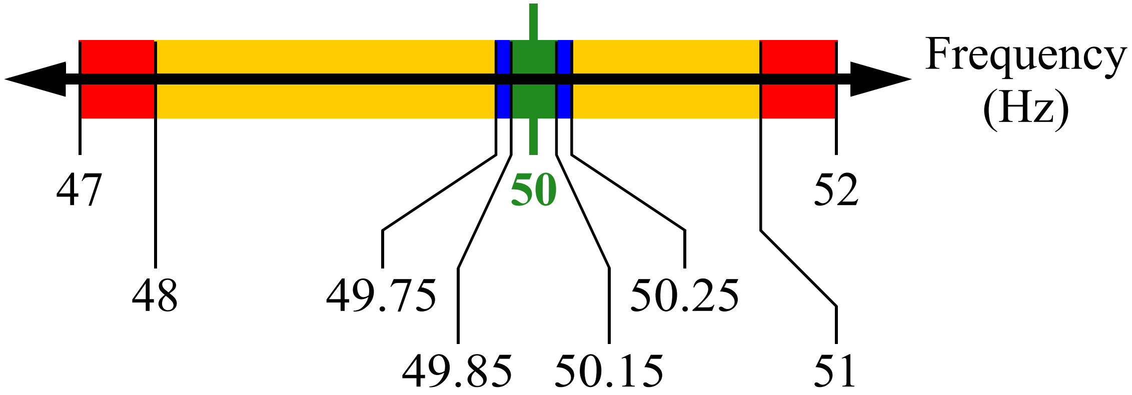
N-1 reliability: May disconnect **any one** line or transformer without loss of supply to the distribution system.



N-2 reliability: May disconnect **any two** lines or transformers without loss of supply to the distribution system.

Frequency Control Requirements

The *Reliability Panel* within the AEMC has set the following Frequency Operating Standard (FOS)[1]. Following is an abridged version of the mainland FOS. The current FOS are under review by the AEMC Reliability Panel.



- Normal operating frequency band (No contingency, 99% of time in any 30 day period)
- Temporary excursion from normal operating frequency band (No contingency, return to normal band within 5 min)
- Operational frequency band after credible contingency (Graded stabilization and recovery times depending on the type of contingency. Stabilization to 49.5 to 50.5 Hz band in up to 2 min; Recovery to within normal band in up to 10 min.)
- Extreme frequency band following multiple contingencies. (Under-frequency load-shedding, protection operation; Stabilization within 2 min., recovery within 10 min.)

1. Reliability Panel, AEMC, “Application of Frequency Operating Standards during periods of supply scarcity”, Final Report, 15 April 2009.

Frequency Control Requirements (cont)

Operation within the above very tight tolerances is required to ensure satisfactory operation of the power system.

Near constant system frequency is necessary to maintain near constant speed of induction machines which are the workhorse in industry, commerce and domestically.

Adequate performance of induction motors driving pumps, fans and compressors in industry generally and power stations in particular requires close control of system frequency.

Significant reduction in frequency can result in excessive magnetizing currents in induction machines and transformers and may result in the operation of V/Hz limiters on synchronous machines.

Overview of Frequency and Power Control

- In a synchronous-system frequency is very closely related to the balance between power supply and demand.
- Except in the transient period following a significant disturbance, the frequency of voltages is the same throughout the system. Furthermore, the (electrical) speed of synchronous machine rotors are very closely related to the frequency of the generated voltage.
- The deviation of frequency, Δf, from the nominal synchronous value (i.e. 50 Hz in Australia) is given by the following equation.

$$\frac{d\Delta f}{dt} = \frac{f_0}{2H_s}(P_S - P_D) = 25\frac{\Delta P}{H_s} \text{ where} \tag{1}$$

H_s <u>*total inertia*</u> of all <u>***online synchronous generators***</u> (MW.s);

P_S total generation from all sources (MW);

P_D total load (including losses) on the system (MW); and

$\Delta P = P_S - P_D$ amount supply exceeds demand (MW).

- If $\Delta P < 0$ (i.e. demand exceeds supply) then the system frequency will fall below synchronous frequency and vice-versa.

Overview of Frequency and Power Control (Cont)

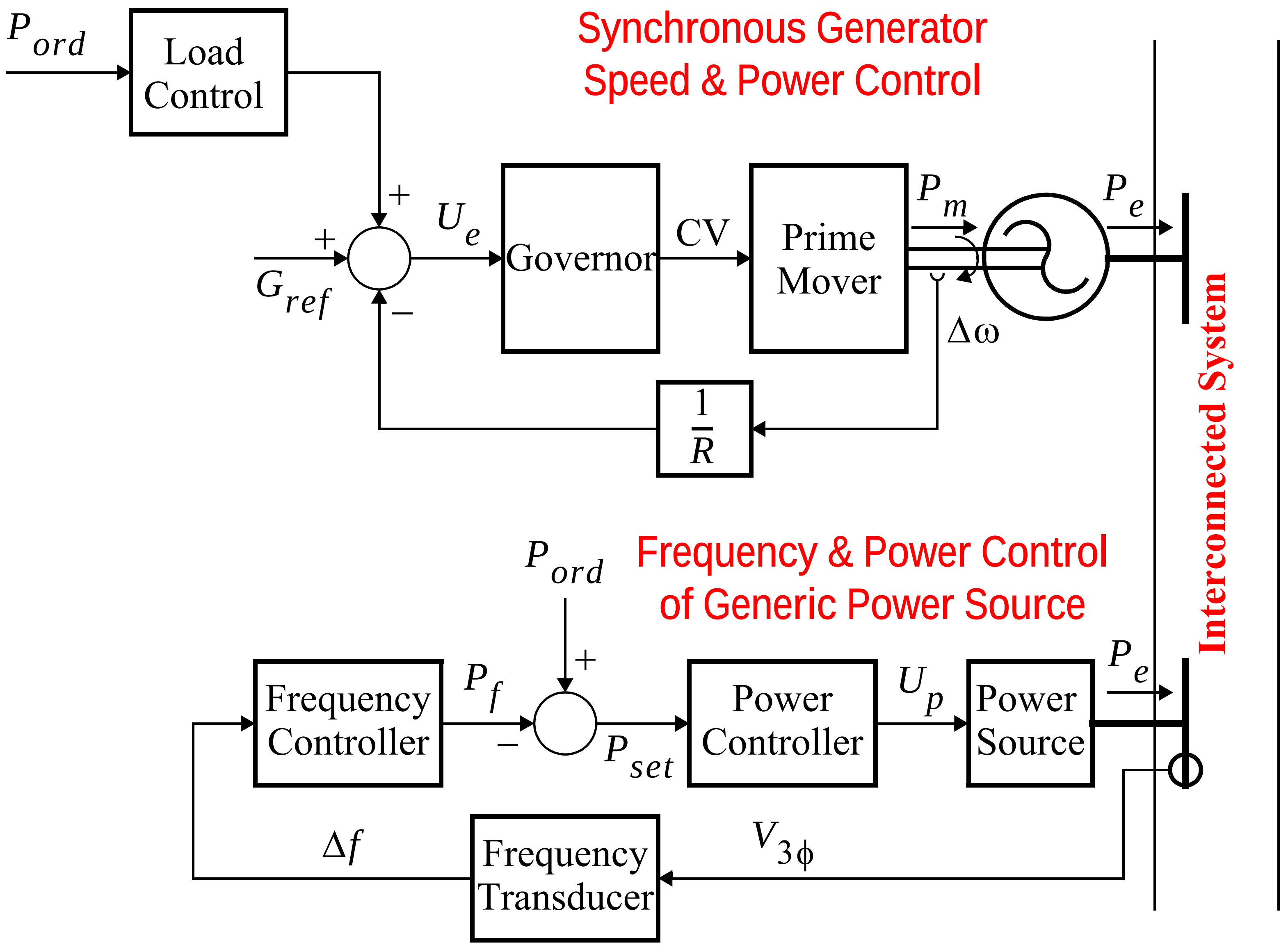
The above equation shows if we can modulate either or both the supply and demand in response to the deviation of frequency from its setpoint (i.e. 50 Hz) then we have a means of controlling the frequency.

The following figure shows two such control schemes for just two of the many power sources connected to a large modern power system:

- The speed and power control system of a synchronous generator.
- The frequency and power control system for any type of power source. It could be a wind farm, battery storage farm, an aggregation of many domestic scale loads that together form a 'virtual power plant'.

In the short-term operational time frame power and frequency ***control*** is divided into the four time separated tiers listed below from slowest to fastest.

- Centralized security constrained market dispatch
- Centralized Automatic Generation Control (AGC) system
- Local synchronous generator speed-governing controls and local frequency control systems fitted to asynchronously connected generators or loads (including asynchronous storage).
- The inherent and ***uncontrolled inertial response*** of synchronous machines to an imbalance between supply and demand occurs first.


Synchronous Generator
Speed & Power Control
P ord
Load Control
+
U e
G ref
+
−
Governor
CV
Prime Mover
P m
P e
Δω
1/R
Interconnected System
Frequency & Power Control
of Generic Power Source
P ord
+
P f
−
P set
Frequency Controller
Power Controller
U p
Power Source
P e
Δf
Frequency Transducer
V 3ϕ

Overview of Power and Frequency Control (Cont)

Referring again to the power and frequency control system structure observe that the power output (or consumption) is adjusted in a direction that opposes the measured change in frequency (or rotor speed in the case of the synchronous generator governor).

In addition to the local frequency (or speed) control function an external power order, *Pord*, is provided. This signal is sent from a central control system managed by the system operator. It is representative of both:

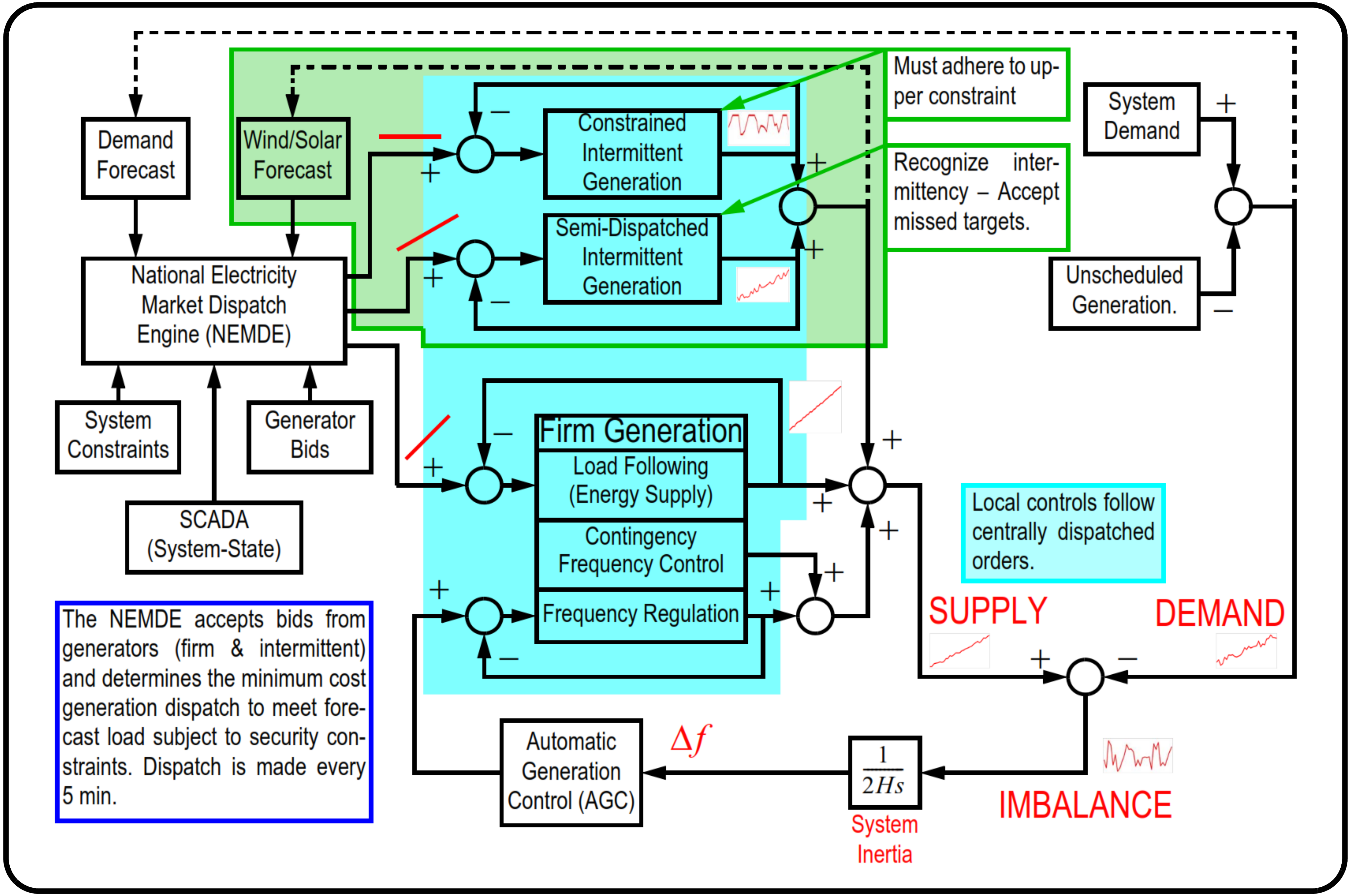
- the power order for the present dispatch interval; and
- the power order from the Automatic Generation Control system (AGC)

Such control devices thus maintain the demand-supply balance by maintaining the frequency within prescribed limits.

It is important to recognise that frequency control devices require a power source with adequate reserves to be effective. Otherwise, they will (collectively) have insufficient capacity to balance supply and demand and therefore frequency will not be controllable and instability may result.

It is also essential that frequency control devices be well co-ordinated. This task is made easier by the fact that frequency is a global signal.

The following figure provides a conceptual overview of the system power and frequency control system.


Demand Forecast
Wind/Solar Forecast
National Electricity Market Dispatch Engine (NEMDE)
System Constraints
Generator Bids
SCADA (System-State)
Constrained Intermittent Generation
Semi-Dispatched Intermittent Generation
Must adhere to upper constraint
Recognize intermittency – Accept missed targets.
System Demand
Unscheduled Generation.
Firm Generation
Load Following (Energy Supply)
Contingency Frequency Control
Frequency Regulation
Local controls follow centrally dispatched orders.
SUPPLY
DEMAND
IMBALANCE
Automatic Generation Control (AGC)
Δf
1/2Hs
System Inertia
The NEMDE accepts bids from generators (firm & intermittent) and determines the minimum cost generation dispatch to meet forecast load subject to security constraints. Dispatch is made every 5 min.

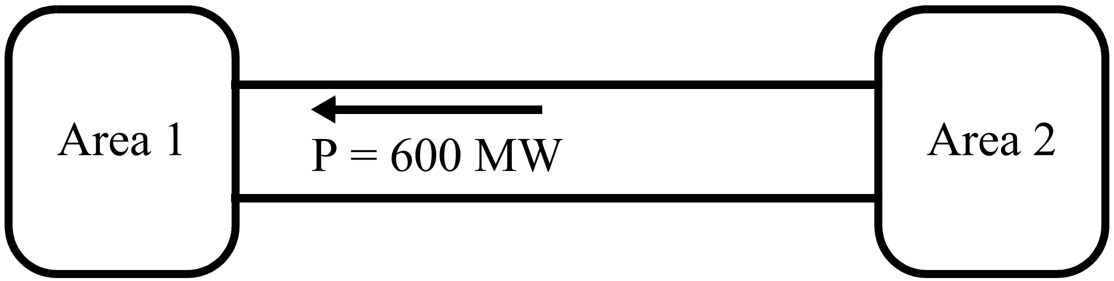
Emergency Frequency Control – Under-Frequency Load-Shedding

In the event of a non-credible contingency large frequency deviations may occur which are beyond the capacity of the normal frequency control system. In such circumstances emergency control measures are required to restore the demand-supply balance.

Consider an example in which Area 1 has a load of 1,600 MW and a reserve generating capacity of 100 MW.

Area 1 is importing 600 MW from Area 2 as shown below. This reserve capacity is considered by the system operator to be adequate for any credible contingency. Area 2 is some 20 times larger than Area 1. A non-credible contingency occurs in which BOTH transmission lines between the two areas are disconnected.

There is an immediate supply deficit of 600 MW and at most only 100 MW can be made up from the reserve capacity in Area 1. To avoid frequency instability and consequential blackout in Area 1 it is necessary to automatically detect the rapid decrease in frequency and, in response, disconnect at least 500 MW of load in Area 1. Under-Frequency Load-Shedding (UFLS) schemes are designed to perform such emergency backup control to 'save' the system in the event of such large and non-credible contingencies.



Example: Effect of Displacement of Synchronous Generation on Frequency Stability – Conceptual Analysis

An increasing concern is the *reduction in synchronous inertia in SA* due to the displacement of synchronous generators in favour of asynchronously connected renewable sources.

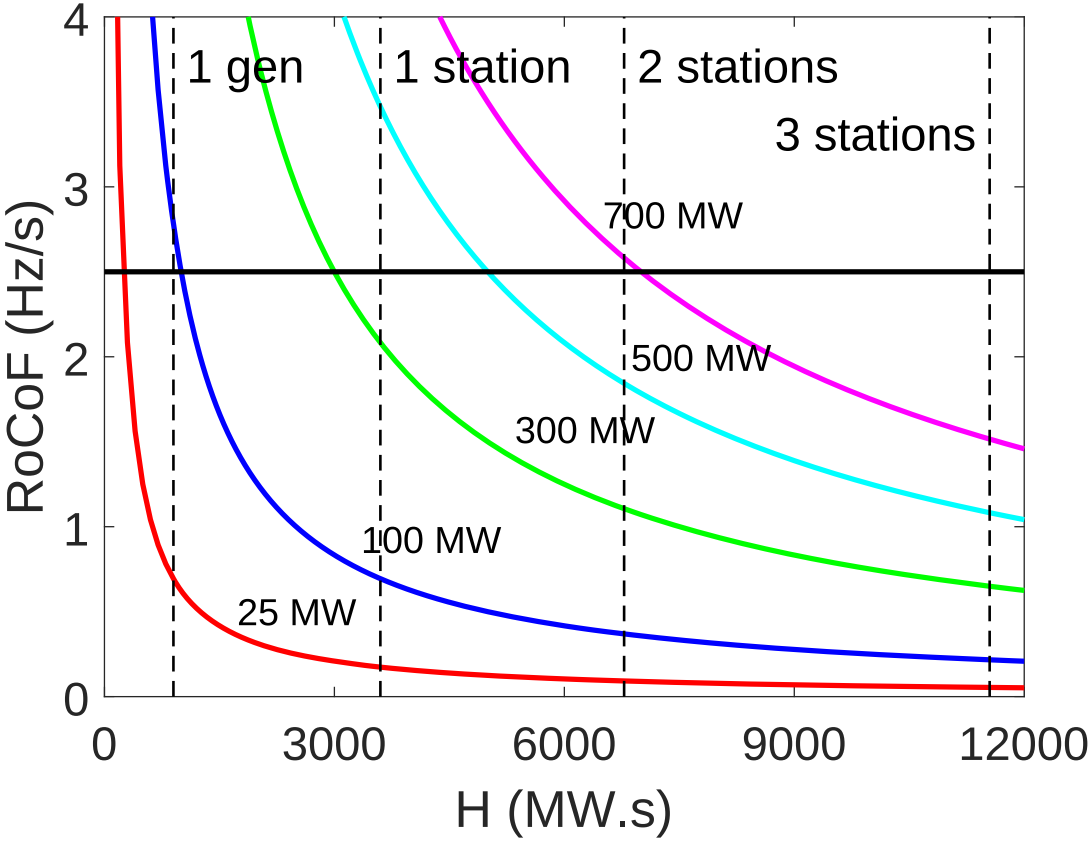
One manifestation of this concern is that the rate-of-change-of-frequency (RoCoF) – $\frac{d\Delta f}{dt}$ (Hz/s) – immediately following the disconnection of a large load or generator increases as the synchronous inertia decreases.

The power-balance equation (1) is used to plot below the RoCoF as a function of synchronous inertia with the power change as a parameter. This plot is indicative of the RoCoF that could occur in the event that the Heywood interconnector between SA and Vic. is disconnected.

In such a contingency, primary frequency control will not be able to maintain frequency stability unless the interconnector flow is very low. Marked on the plot is a RoCoF threshold of 2.5 Hz/s. For higher values of RoCoF there is substantial risk that the protection of some generating plants may operate and that (for under-frequency events) UFLS controls may not have time to operate to disconnect sufficient load before the system frequency collapses and a blackout occurs.

The plot shows that with only one synchronous machine online (which would not be acceptable in practice) interconnector power transfer would need to be less than 100 MW to limit RoCoF to less than 2.5 Hz/s.

Inertial Response (cont)



If the Heywood interconnector is transferring 300 MW then the online synchronous inertia must be at least 3000 MW.s to limit the RoCoF to 2.5 Hz/s. This result is readily deduced from (1) as follows:

$$H_s = \frac{25\Delta P}{\left(\frac{d\Delta f}{dt}\right)} = \frac{25 \times 300}{2.5} = 3000 \text{ MW.s}$$

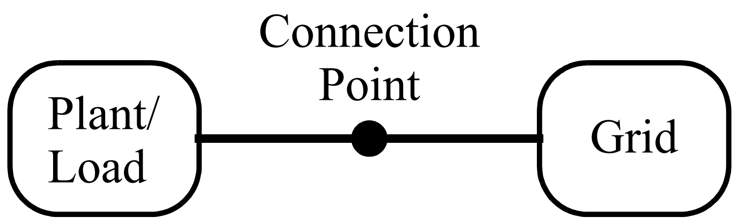
A RoCoF of 2.5 Hz/s means that frequency will change by 2 Hz in 0.8 s. It is unlikely that governors will respond to any significant degree in this time to arrest the change in frequency.

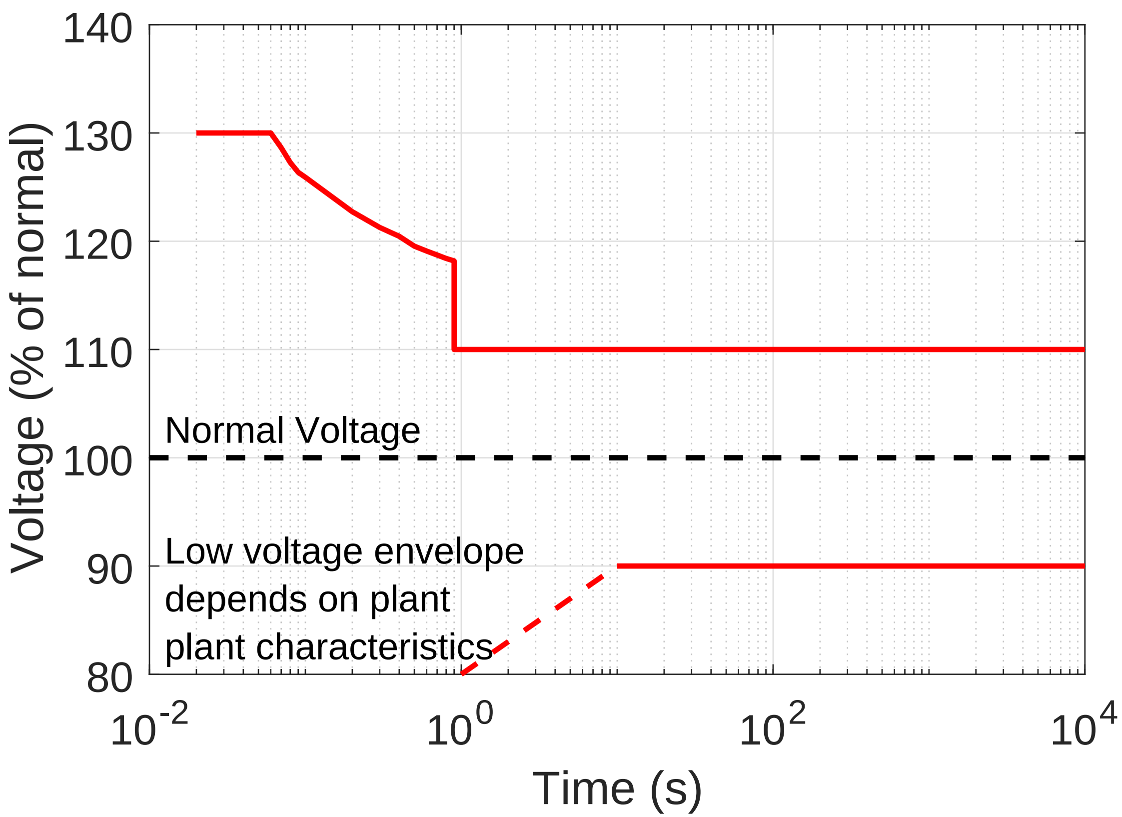
- UFLS may operate to restore frequency

Voltage Control Requirements

The NER sets the following requirements for fundamental frequency voltage:

- Except due to a contingency, the connection point voltage should not vary by more than 10% above or below its normal voltage.
- Due to a credible contingency the connection point voltage should not exceed the time/over-voltage envelope below.
- Due to a credible contingency the connection point voltage may fall to and remain zero.
- If, however, the plant remains connected to the grid following a contingency then the time/low-voltage envelope is subject to agreement.





Overview of Voltage Control

Power systems must control voltage and reactive power to:

- maintain voltages within prescribed limits;
- enhance system stability; and
- minimize real, I^2R, and reactive, I^2X losses.

Equipment connected to the power system is designed to operate continuously with voltages within the envelope defined under the NER. Sustained operation beyond these limits may damage connected equipment.

Voltage control is complex because of:

- the vast number of loads and generators connected to the grid;
- the significant variation in both real and reactive power consumption of loads during the daily, weekly, seasonal, etc. load cycles;
- the associated wide variation in the reactive power consumed or produced by transmission lines and transformers due the variation in real and reactive losses that occur during transmission; and
- the fact that reactive power can not be transmitted over long distances.

Therefore, it is necessary to disperse voltage control devices throughout the system.

- Continuously acting voltage controls:
  - Synchronous generators
  - Static VAR compensators
  - Increasingly renewable energy plants
- Discontinuous voltage controls
  - Switched shunt capacitors and reactors
  - Transformer tap-changing

Overview of Voltage Control (Cont)

Continuously acting voltage controls are of particular importance in controlling system voltages and the allocation of reactive power resources.

The primary means of voltage control are the *Automatic Voltage Regulators (AVRs) fitted to synchronous generators*.

- The AVRs control the generator excitation so as to generate or absorb reactive power to regulate the generator terminal voltages to the specified voltage set-point.

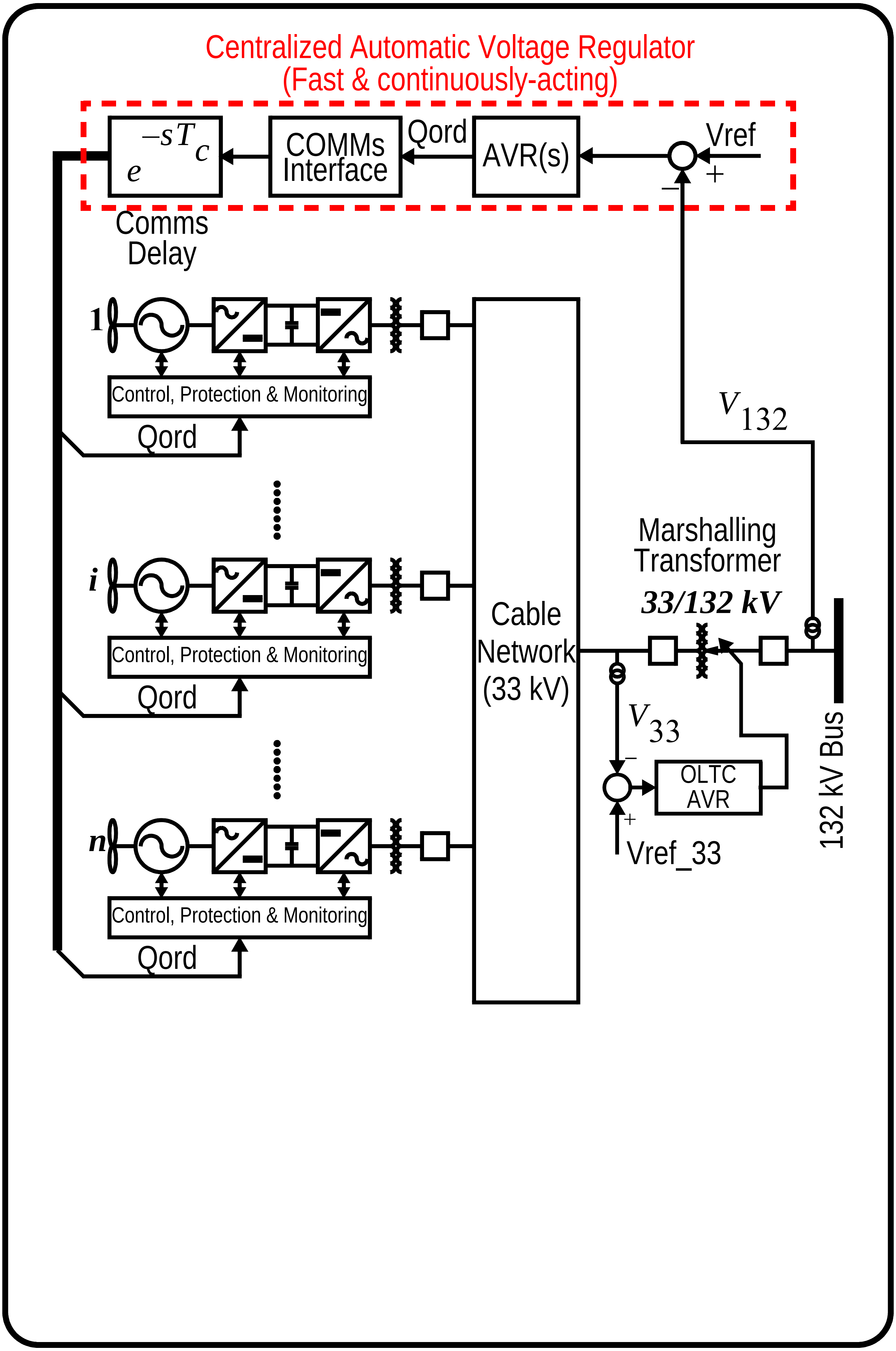
Static Var Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) incorporate AVRs that regulate voltage continuously within the limits of their reactive power capability.

Increasingly, asynchronously connected renewable power plants (e.g. wind and solar PV farms) are equipped with plant level voltage and reactive-power controls to regulate the voltage of a point at or near the connection point of the plant. One such scheme is shown in the following figure.

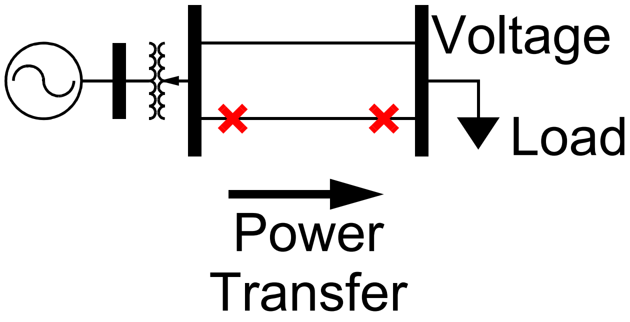
Discontinuous control devices include:

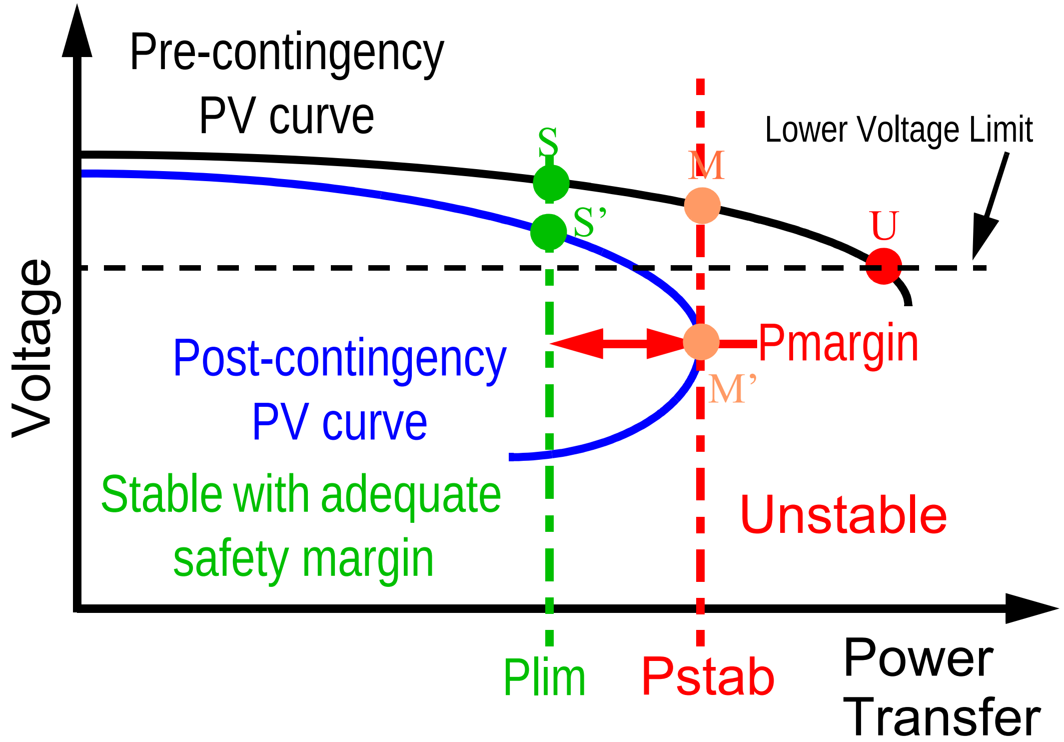
- Regulating transformers within the distribution and transmission system.
- Fixed and discretely switched shunt capacitors and shunt reactors.

Loadflow analysis is a powerful tool for managing system voltages and planning the allocation and procurement of reactive power resources required to ensure system voltages are manageable as the system evolves.


Centralized Automatic Voltage Regulator
(Fast & continuously-acting)
e^{-sT_c}
COMMs Interface
Qord
AVR(s)
Vref
+
–
Comms Delay
1
Control, Protection & Monitoring
Qord
i
Control, Protection & Monitoring
Qord
n
Control, Protection & Monitoring
Qord
Cable Network (33 kV)
V_{132}
Marshalling Transformer
33/132 kV
V_{33}
–
+
OLTC AVR
Vref_33
132 kV Bus

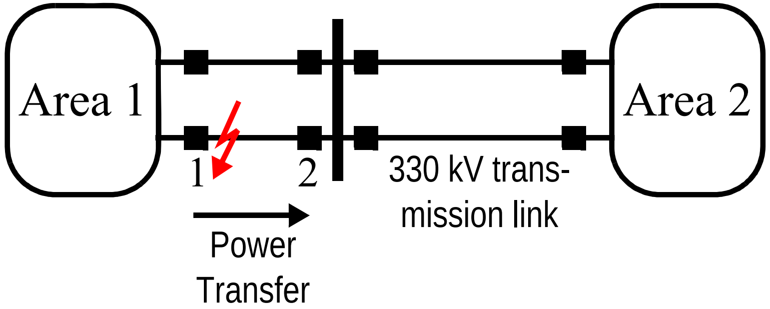
Example: Steady-State Voltage Stability

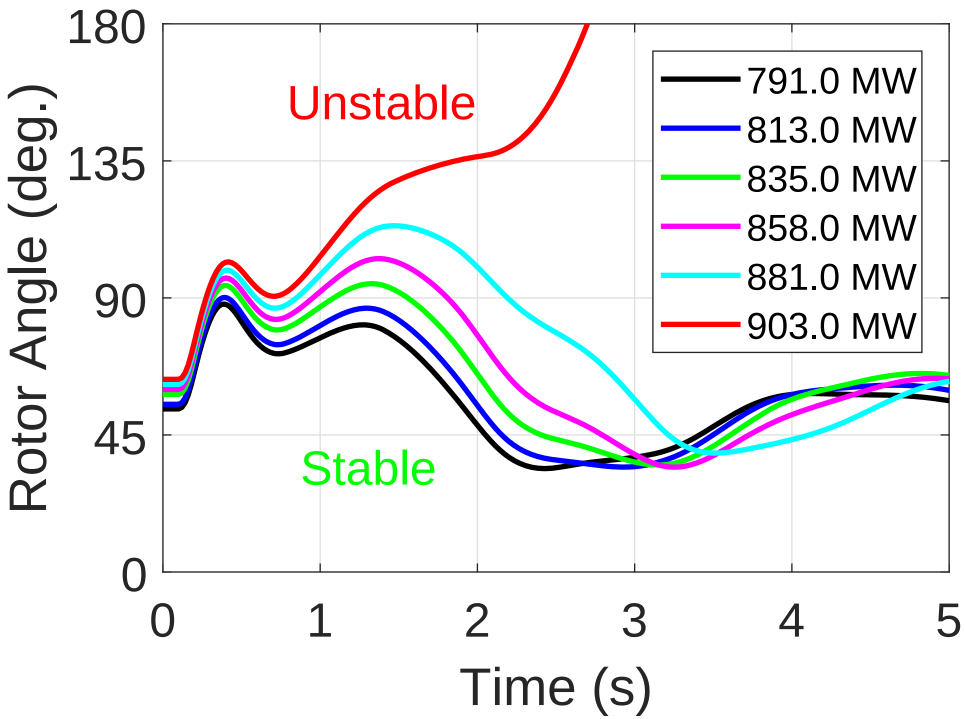




- Consider generator transferring power to a load through its step-up transformer and double-circuit transmission line (above).
- With both circuits in service load voltage decreases as power transfer increases along the pre-contingency PV curve (black).
- In the event that one of the two transmission circuits is disconnected, say following a fault, the operating point shifts from the Pre- (black) to Post-contingency (blue) PV curve.
- Initial operation at point ‘U’ is unstable – voltage will collapse.
- Initial operation at point ‘M’ is marginally stable – Post-contingency operation is at nose of PV curve
- Initial operation at point ‘S’ is stable and the post-contingency voltage is within voltage limits.

Example: Inter-area Transfer Transient Stability Limit





- What is the maximum power that can be transferred from area 1 to 2 before the system becomes transiently unstable?
- Critical contingency: Two phase to ground fault as shown. Fault cleared by primary protection opening CBs 1 & 2 in 80 and 100 ms respectively following fault.
- Transient stability simulations performed with progressively higher power transfers. Stability is indicated if the rotor-angles of all machines are bounded.
- With power transfers from 791 to 881 MW the system is transiently stable.
- With a power transfer of 903 MW the rotor-angles of synchronous generators in Area 1 increase and diverge w.r.t. to those in Area 2 indicating transient instability.

Example: Power System Damping Performance – the need for Power System Stabilizers

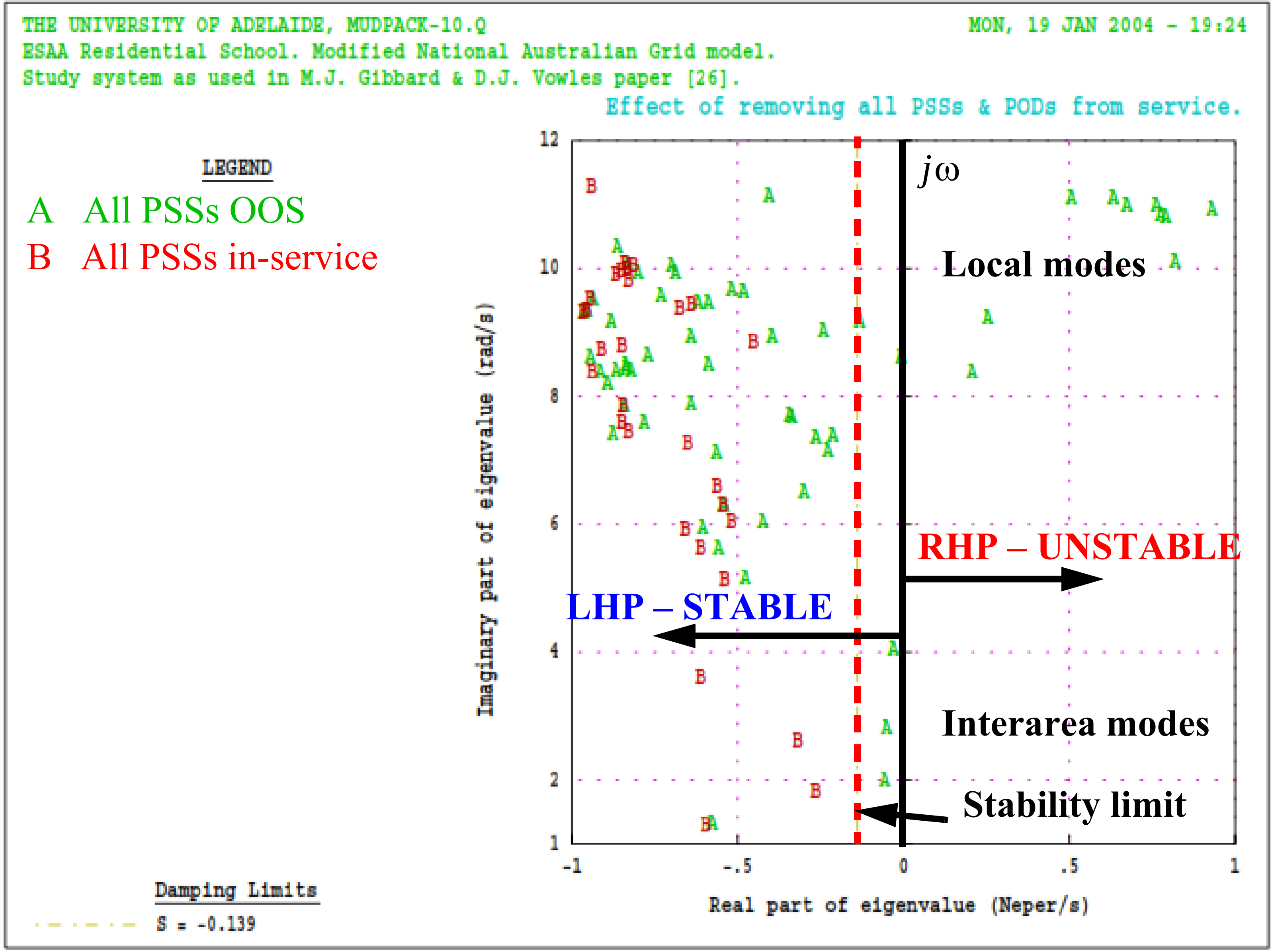
Sparse and long structure of the Australian grid with weak interconnections between its main regions means it is prone to *rotor-angle small-signal instability*. The damping problem is exacerbated by the necessity of utilizing high gain excitation systems on synchronous generators to ensure transient stability.

To ensure adequate damping specialized supplementary damping controls are fitted to the excitation system of generators and to Flexible a.c. Transmission System (FACTS) devices. In the case of synchronous generators the damping controls are referred to as Power System Stabilizers (PSSs).

A PSS is designed to introduce a torque of electromagnetic origin on the shaft of the synchronous machine to which it is fitted. The PSS is tuned such that the torque, within the frequency range of electromechanical modes of oscillation, opposes changes in rotor speed. This is a damping torque. It causes the modes (or poles) of the system which are associated with the oscillation of synchronous generator rotors to be shifted to the left in the complex s-plane thereby improving system stability.

The following figure shows the poles of a detailed model of the SE Australian Power System with (i) all PSSs removed from service; and (ii) with all PSSs in operation.

The key point is that without PSSs the system is unstable as indicated by poles in the right-half plane.


THE UNIVERSITY OF ADELAIDE, MUDPACK-10.Q
MON, 19 JAN 2004 - 19:24
ESAA Residential School. Modified National Australian Grid model.
Study system as used in M.J. Gibbard & D.J. Vowles paper [26].
Effect of removing all PSSs & PODs from service.
LEGEND
A All PSSs OOS
B All PSSs in-service
jω
Local modes
RHP – UNSTABLE
LHP – STABLE
Interarea modes
Stability limit
Imaginary part of eigenvalue (rad/s)
Real part of eigenvalue (Neper/s)
12
10
8
6
4
2
1
-1
-.5
0
.5
1
Damping Limits
S = -0.139

Rapidly emerging challenge: Reducing voltage strength

- One measure of network voltage strength at a node is its short-circuit capacity.
- The lower the short-circuit capacity the weaker the network.
- As synchronous generators are displaced in favour of asynchronous generators the short-circuit strength decreases.
- A measure of the voltage strength at a node in comparison with the size of a connected asynchronous generating plant (e.g. a wind farm) is the Short-Circuit-Ratio (SCR). The SCR is the ratio of the short-circuit capacity at the point of connection of the plant to the MVA rating of the plant.
- The higher the SCR the better.
- A SCR below three for an asynchronous plant is a cause for concern for a number of reasons including the possibility of significant voltage swings and the instability of the power-electronic-converter controls.
- Low short-circuit capacity has potentially serious implications for the operation of protection systems and may necessitate changes in protection settings and possibly protection philosophies.