AGL Electricity Knowledge Course

Melbourne, 22 October 2018

Agenda

1	**Electricity theory**	David Bartolo Head of Asset Intelligence
2	**Electricity systems**	David Bartolo Head of Asset Intelligence
3	**Keeping the lights on**	Melinda Buchanan General Manager Physical Markets

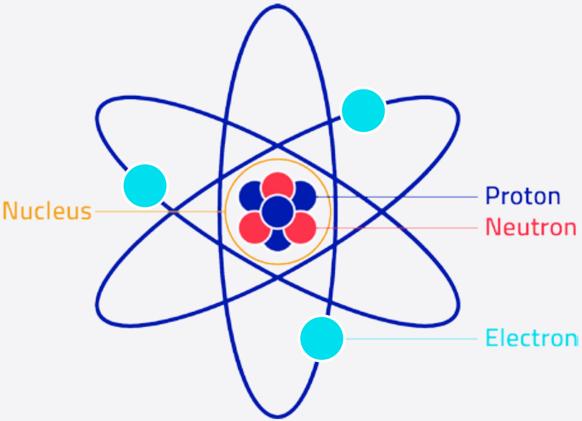
Electricity theory

- Electricity theory building blocks
- Currents – DC/AC
- Power factor theory
- Three phase circuits
- Voltage transformers

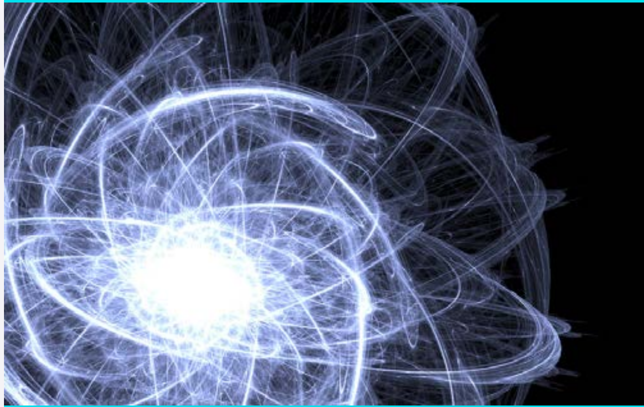
Electric Current

The movement of electric charge is known as an electric current

Current can consist of any moving charged particles, most commonly these are electrons



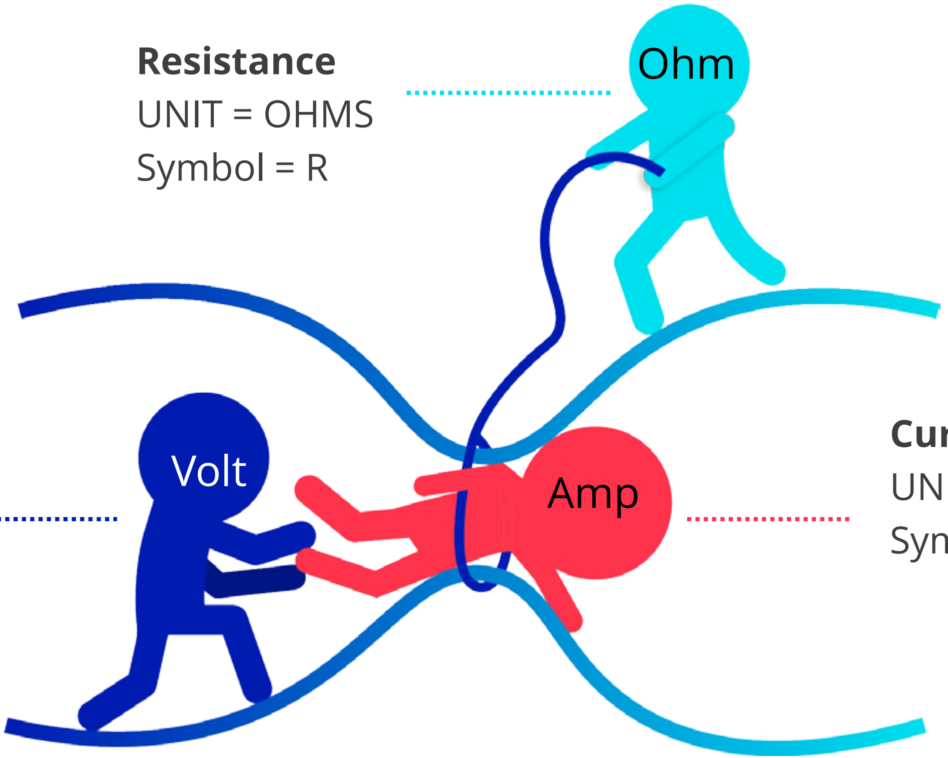
The Atom



The Electron Cloud

Voltage, Current and Resistance

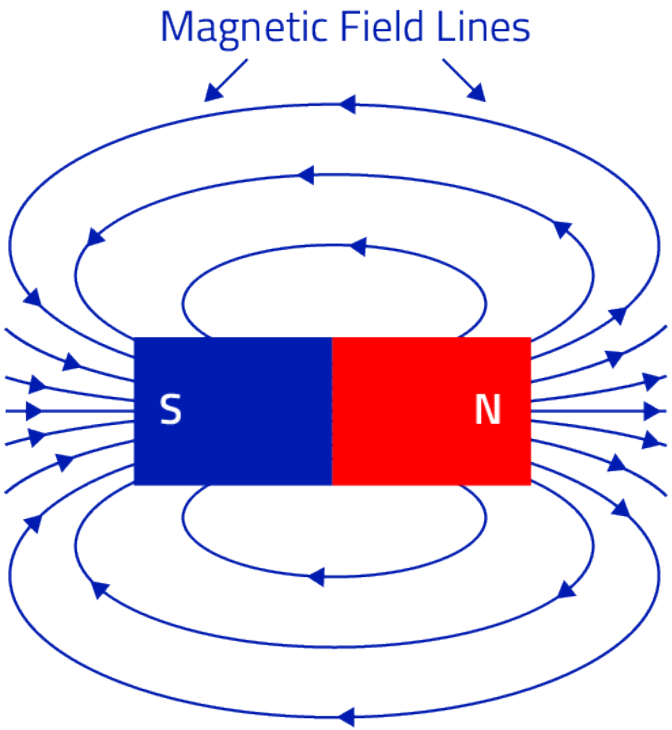
Resistance
UNIT = OHMS
Symbol = R



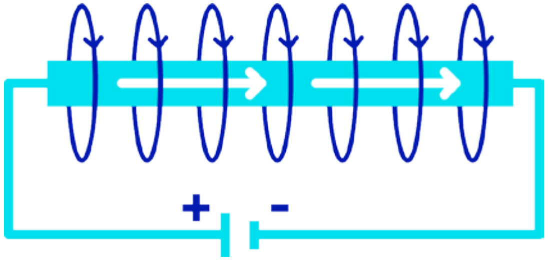
Electro Motive Force (EMF)
UNIT = Volts
Symbol = V

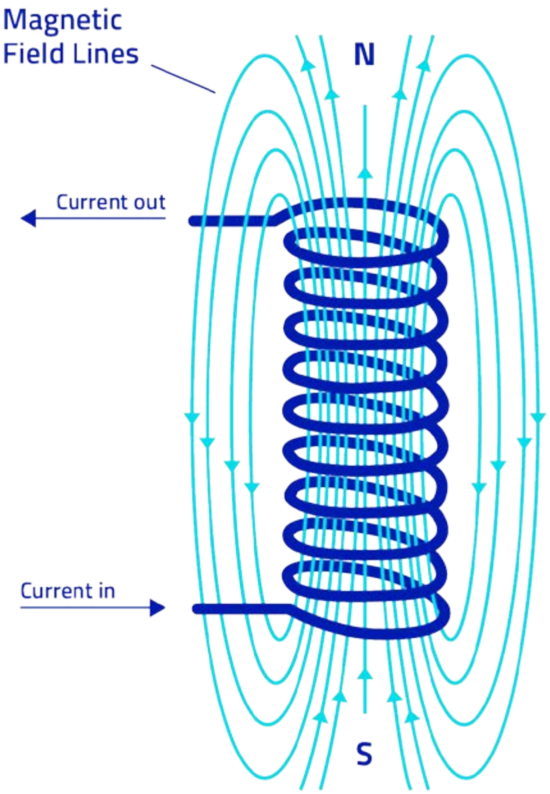
Current
UNIT = Amps
Symbol = I

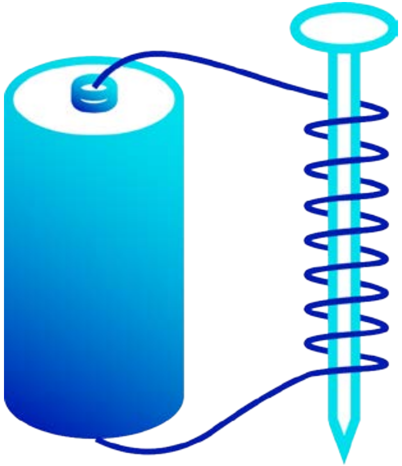
Magnetic Fields



Electromagnetism



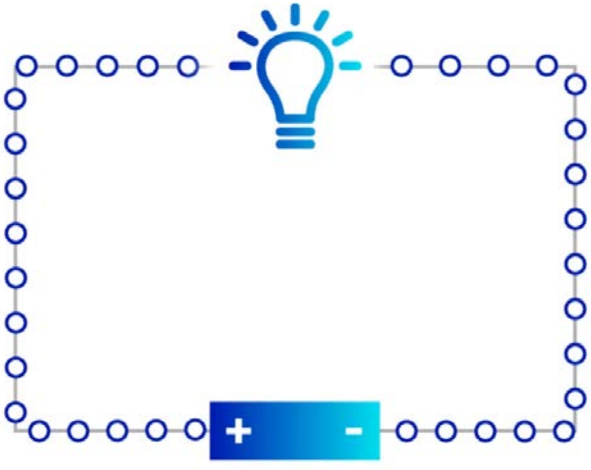




Two Types of Electricity

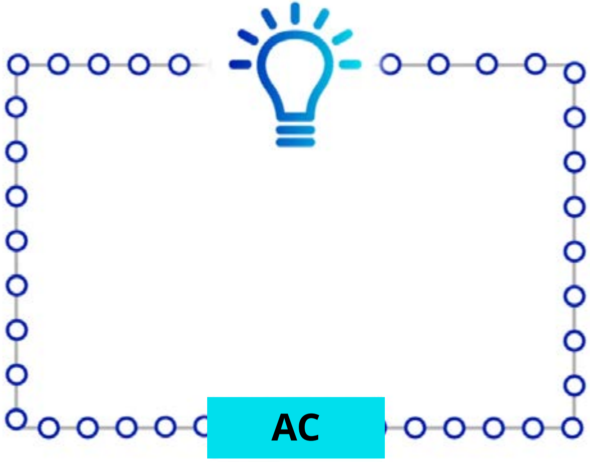
Direct Current (DC)

The electrons flow in one direction around a circuit



Alternating Current (AC)

The electrons are moving back and forth (shaking) in the circuit



War of the Currents

Edison

DC generation systems

Requires each load to have its own local generation system due to the losses involved

Tesla

AC generation systems

Allows for remote generators, however voltages need to be higher

Power Factor Theory

The resistor DC circuit

V=R x I

R= V / I

R= 2.4 OHMS

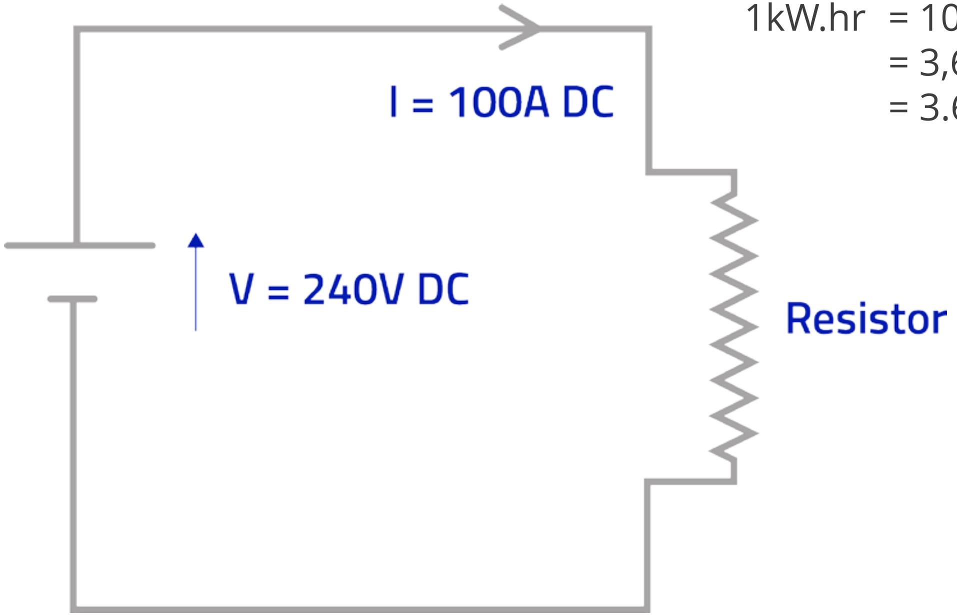
P=V x I

P= 240 x 100

P= 24,000 J/s

P= 24,000 W

P= 24 kW

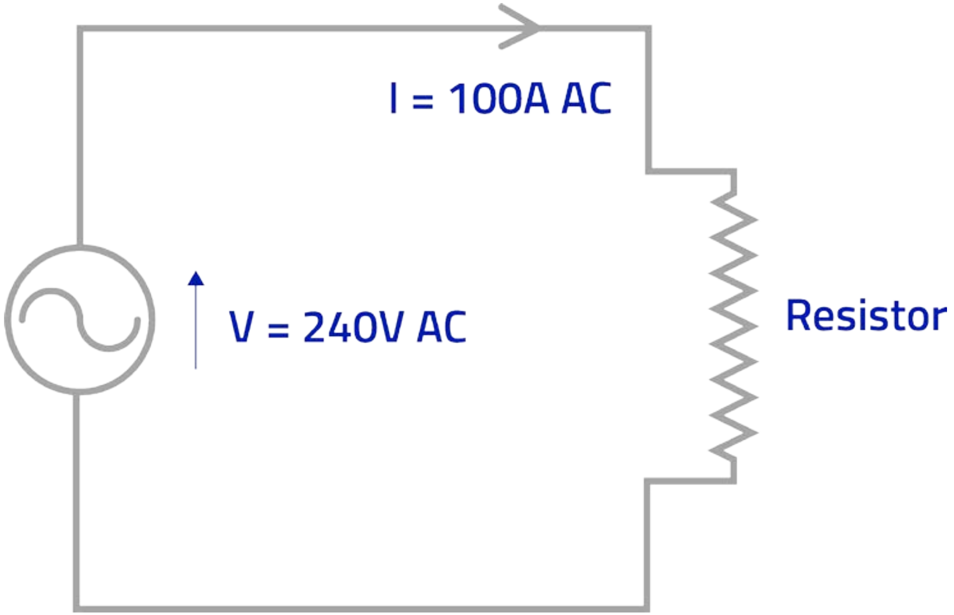


kW.hr to Joules conversion

1kW.hr = 1000 x 60 x 60 J
= 3,600,000 J
= 3.6 MJ

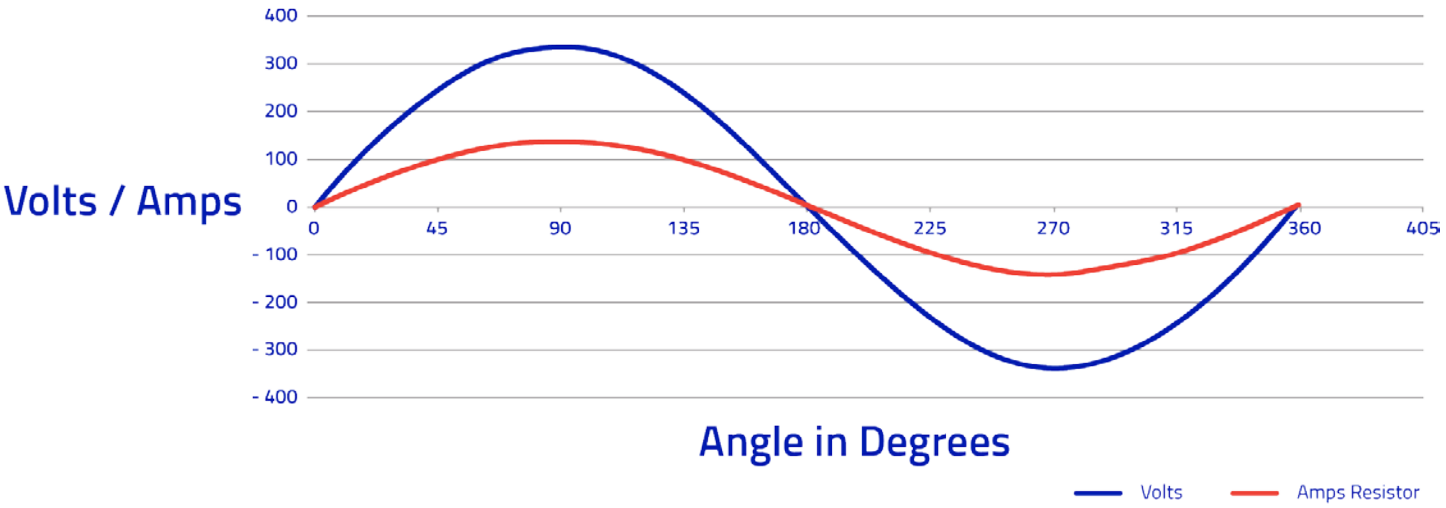
Power Factor Theory

The Resistor AC Circuit



Power Factor Theory

Resistor Volts / Amps Characteristic

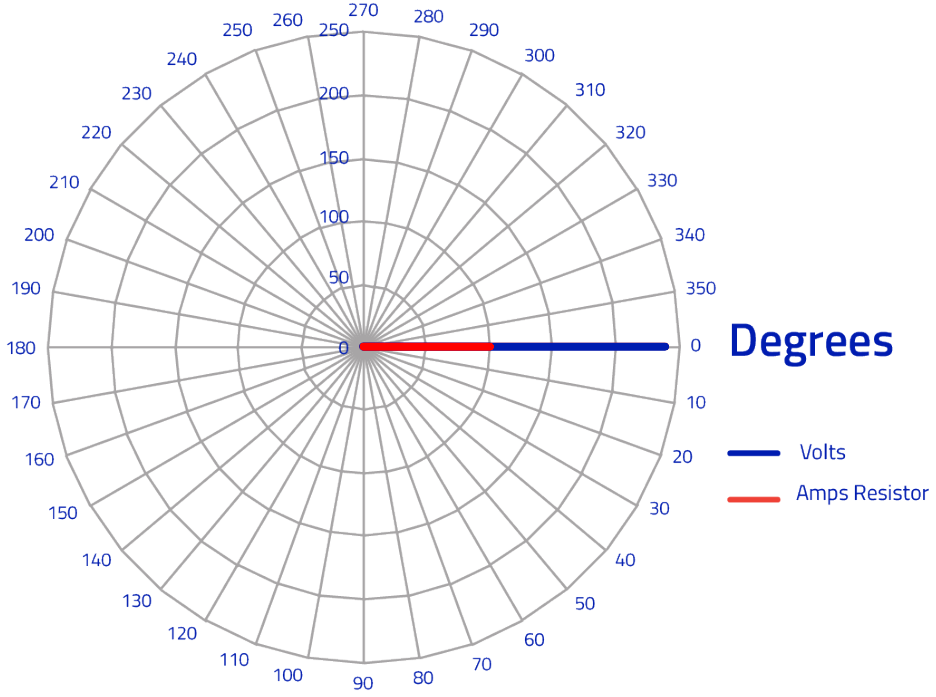


Current is in phase with voltage

Power Factor Theory

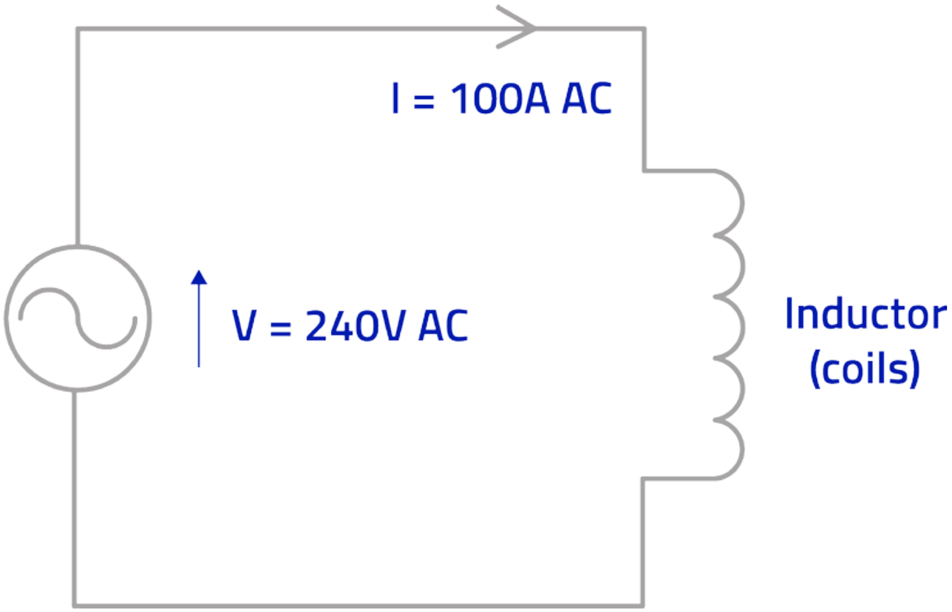
Resistor Volts / Amps Characteristic

Power Factor = Cos φ
= Cos 0°
= 1
Unity



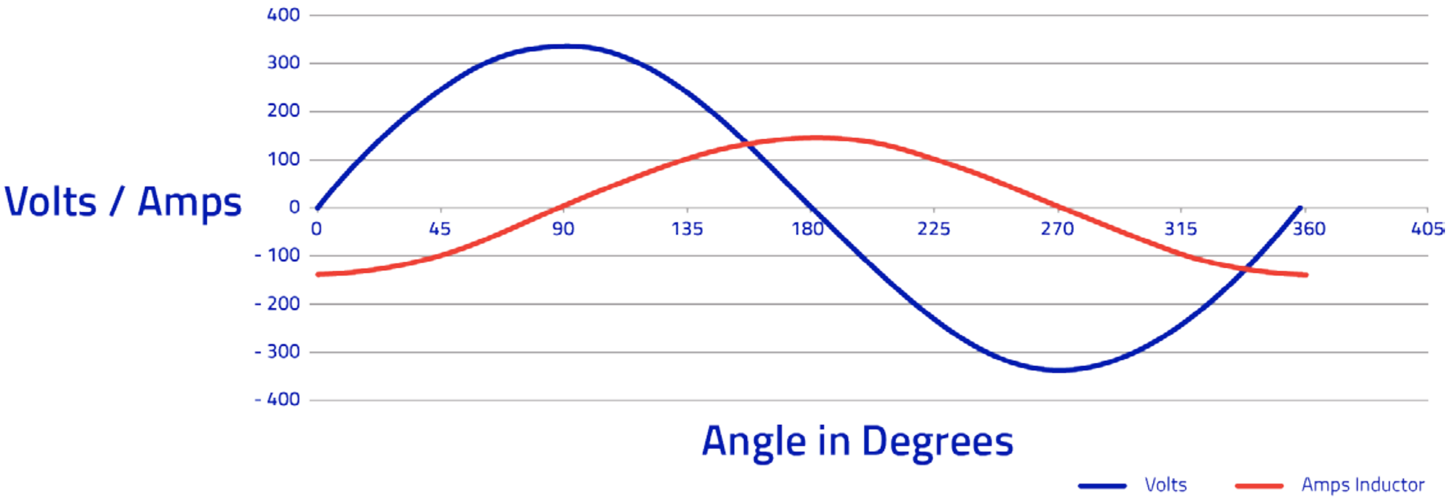
Power Factor Theory

Inductor AC Circuit



Power Factor Theory

Inductor Volts / Amps Characteristic

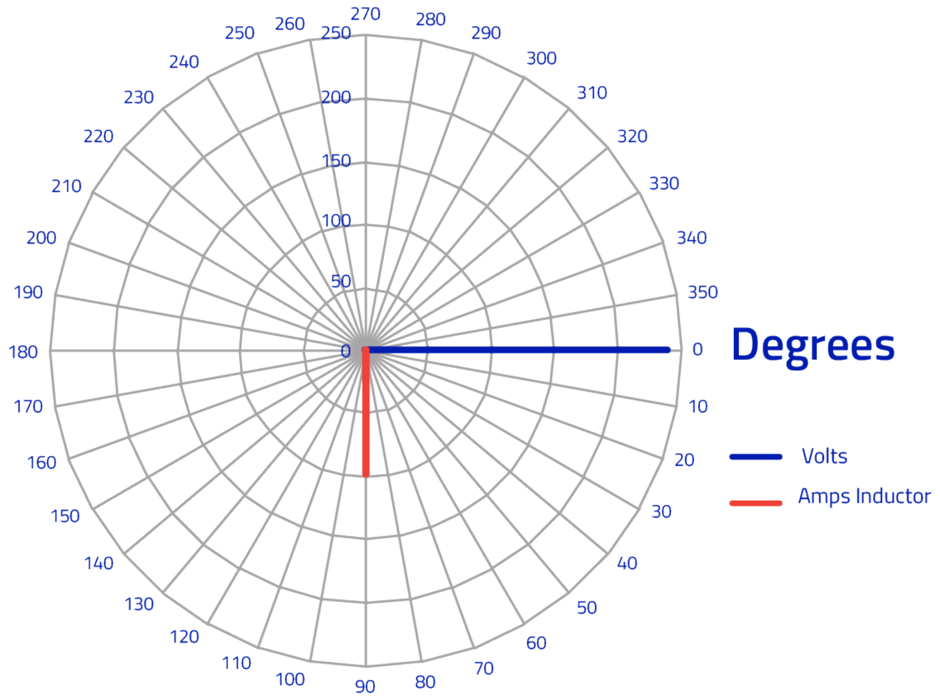


Current is lagging voltage by 90 degrees

Power Factor Theory

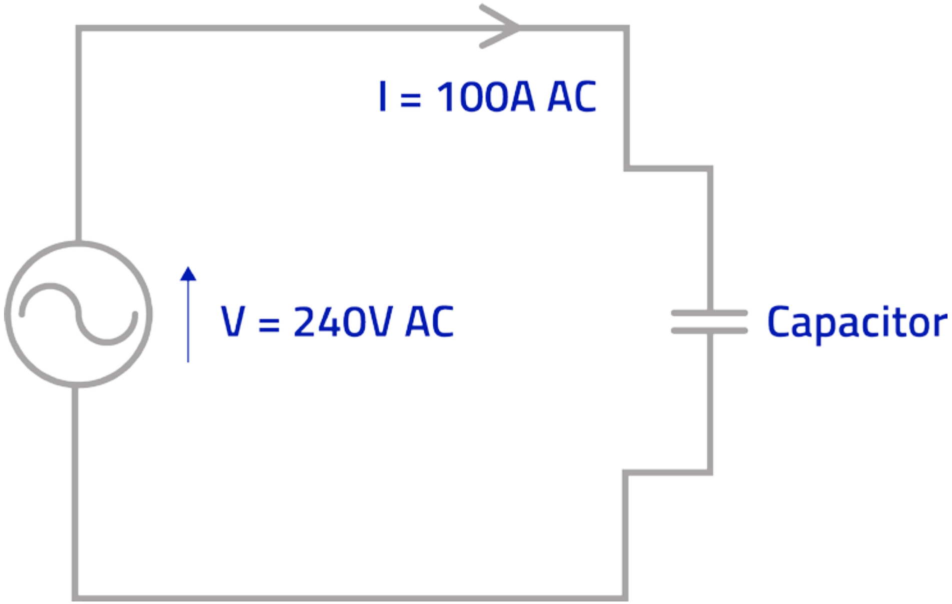
Inductor Volts / Amps Characteristic

Power Factor $= \cos \varphi$
$= \cos 90^{o}$
$= 0$
Lagging



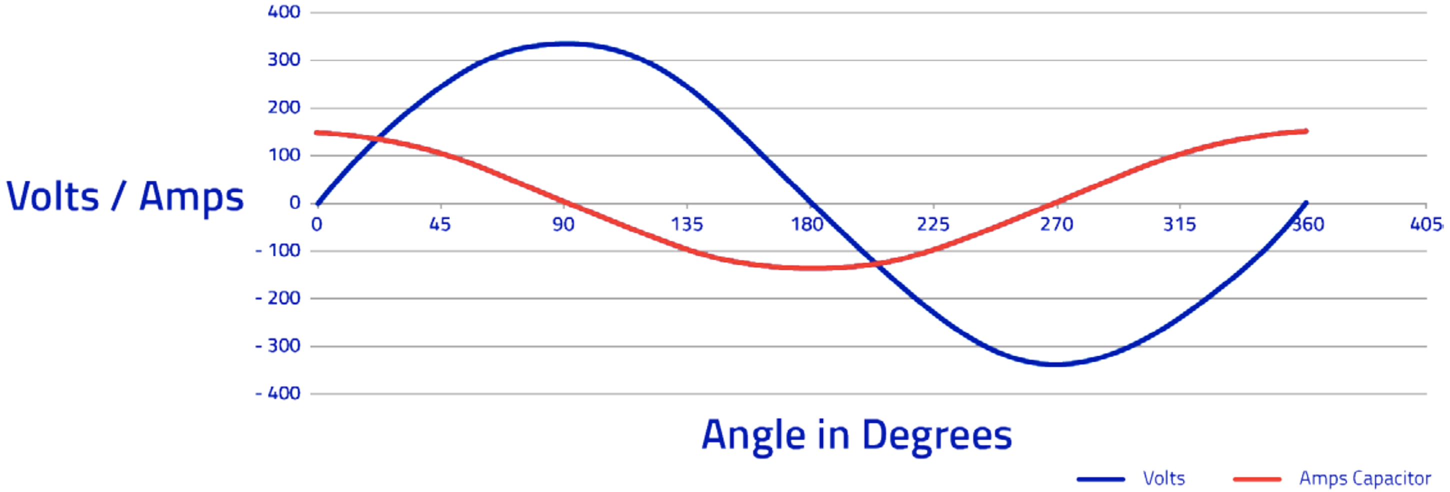
Power Factor Theory

Capacitor AC Circuit



Power factor theory

Capacitor Volts / Amps Characteristic



Current is leading voltage by 90 degrees

Power factor theory

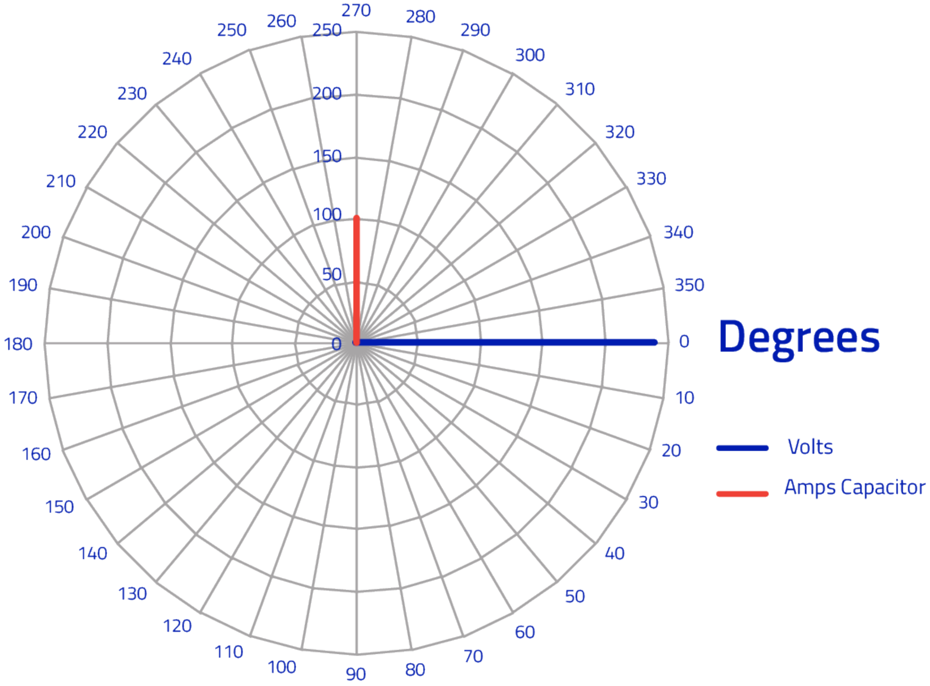
Capacitor Volts / Amps Characteristic

Power Factor = Cos φ

= Cos -90º

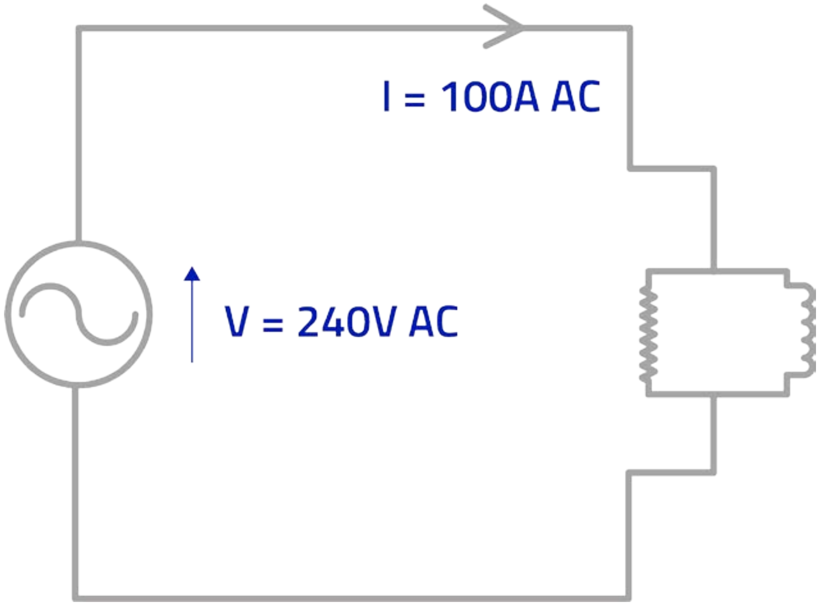
= 0

Leading



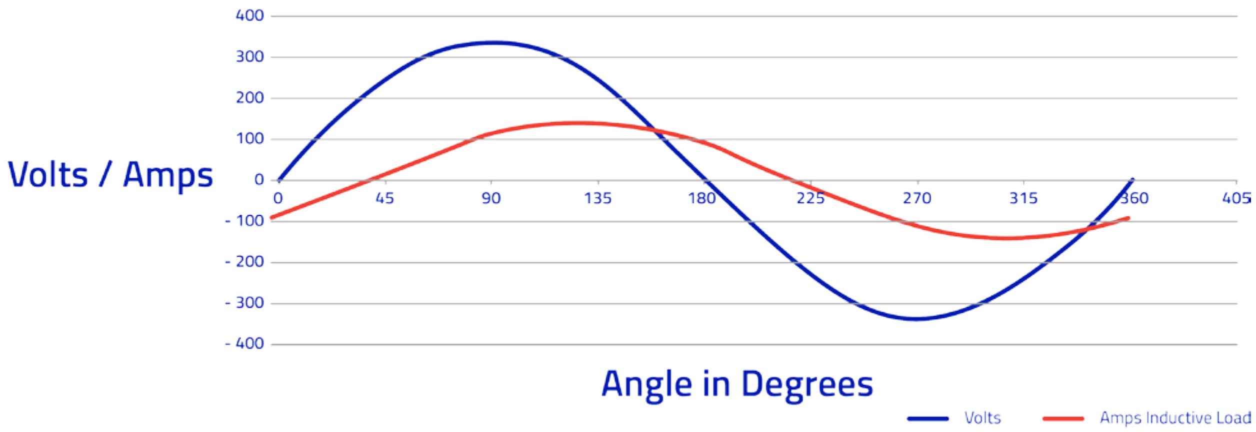
Power Factor Theory

Load Network



Power Factor Theory

Inductive Load Volts / Amps Characteristic

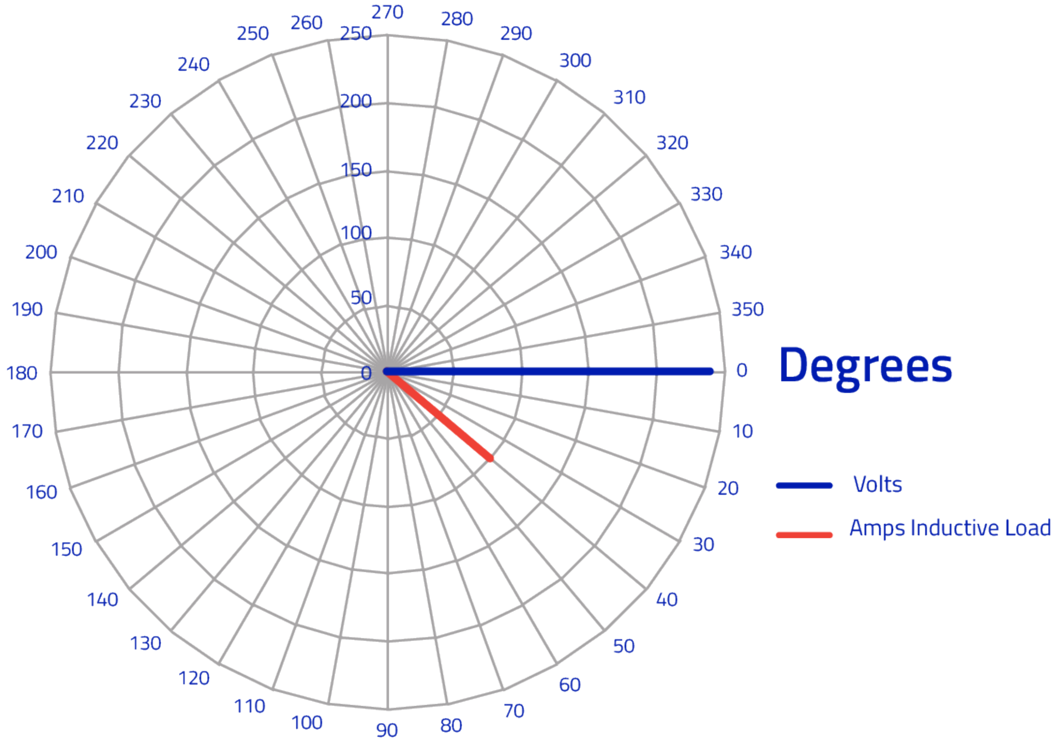


Current is lagging voltage by 40 degrees

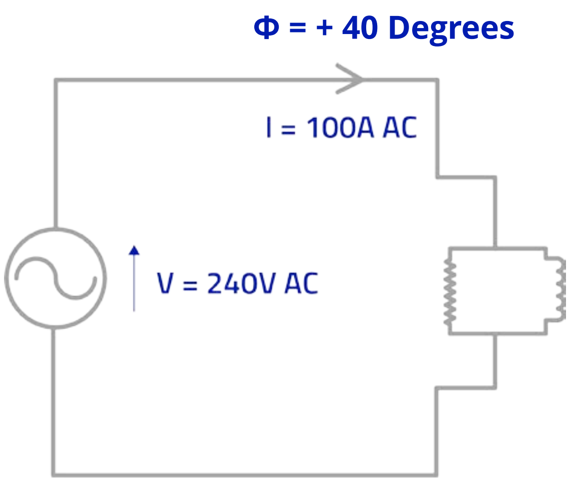
Power factor theory

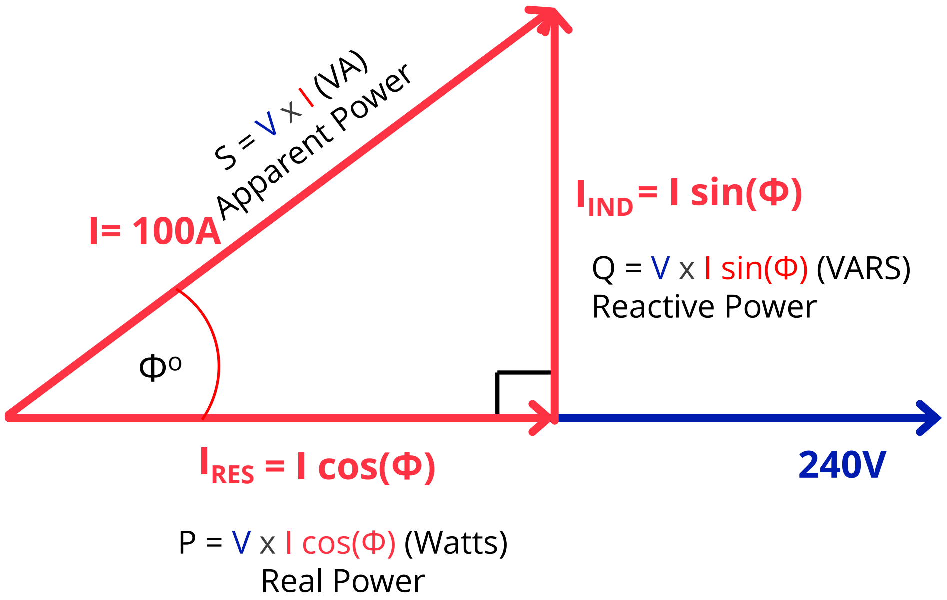
Inductive Load Volts/Amps Characteristic

Power Factor = Cos φ
= Cos 40°
= 0.766
Lagging

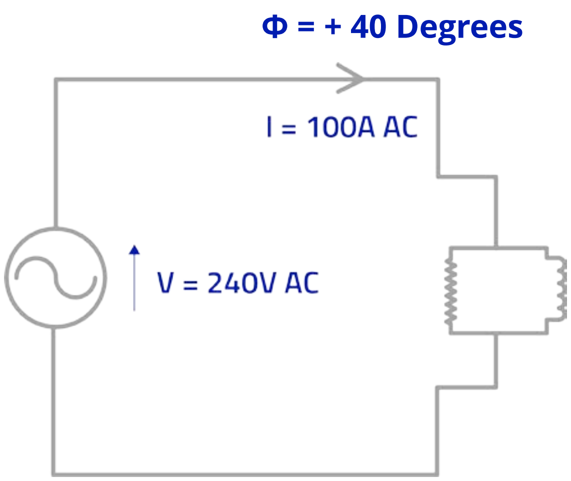


The AC Power Triangle: Derived





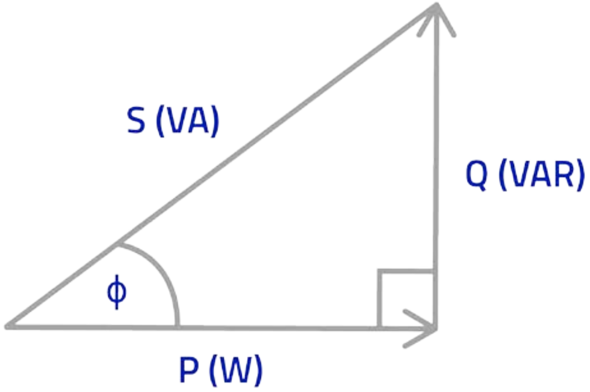
AC Power Triangle



S = Apparent Power
= V x I
= 240 x 100
= 24kVA

P = Real Power
= V x I x Cos φ
= 240 x 100 x 0.766
= 18.385 kW

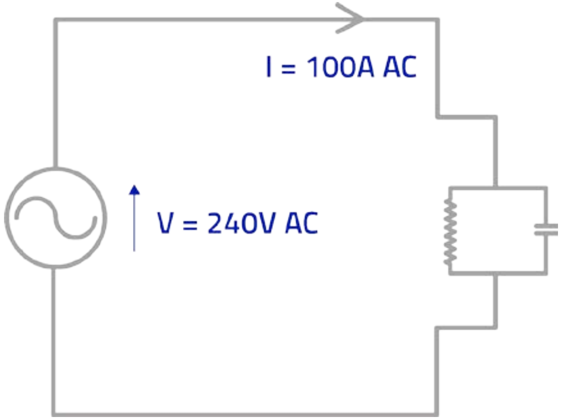
Q = Reactive Power
= V x I x Sin φ
= 240 x 100 x 0.6427
= 15.427 kVAR



Lagging system = Generator Supplying VARS
= Load Absorbing VARs

AC Power Triangle

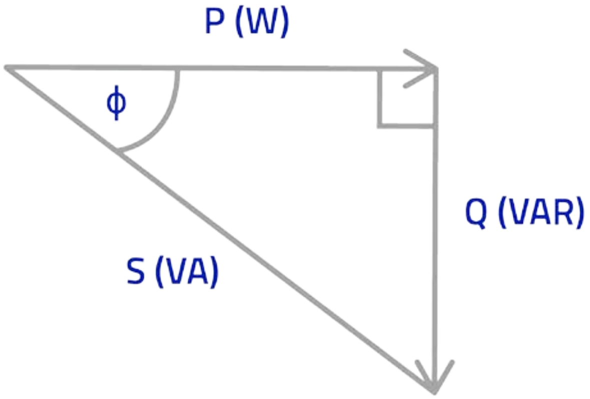
Φ = - 40 Degrees



S = Apparent Power
= V x I
= 240 x 100
= 24 kVA

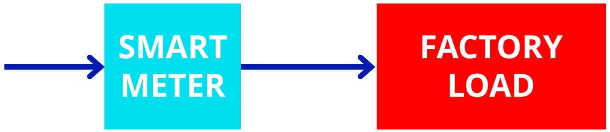
P = Real Power
= V x I x Cos φ
= 240 x 100 x 0.766
= 18.385 kW

Q = Reactive Power
= V x I x Sin φ
= 240 x 100 x -0.6427
= -15.427 kVAR

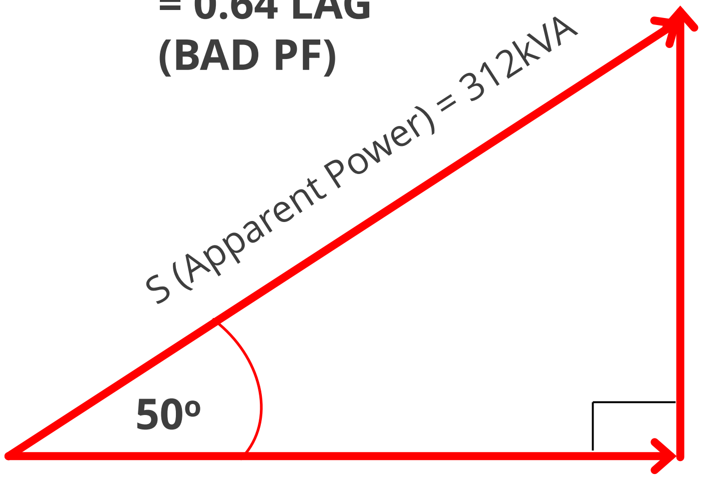


Leading system = Generator Absorbing VARS
= Load Supplying VARs

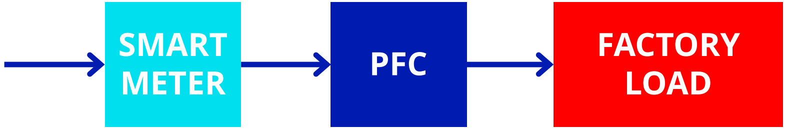
Power Factor Correction Explained



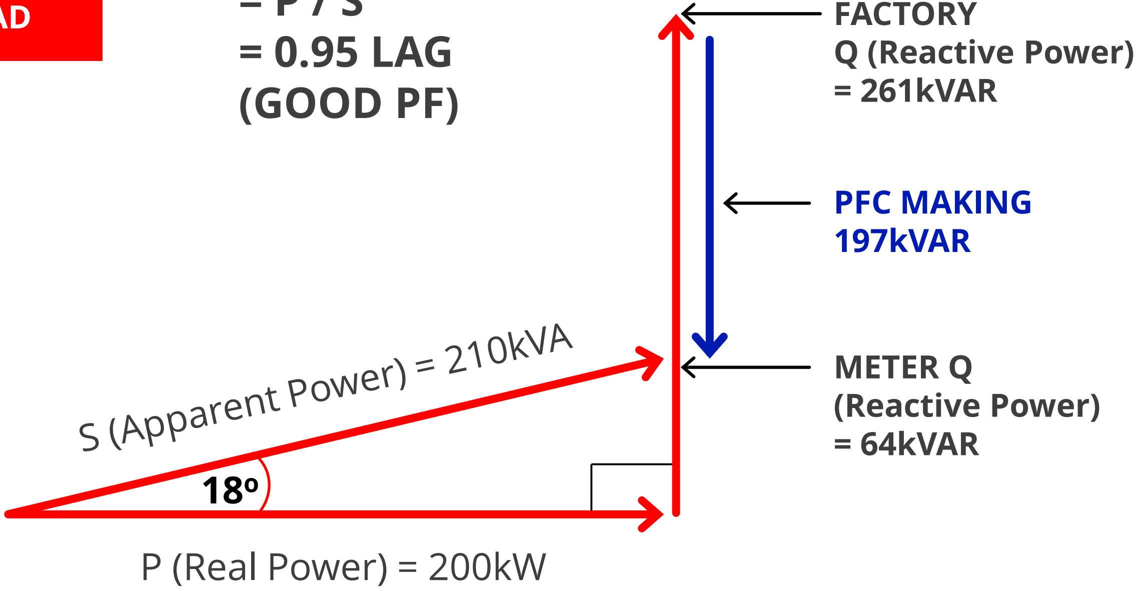
PF = COS (50º)
= P / S
= 0.64 LAG
(BAD PF)



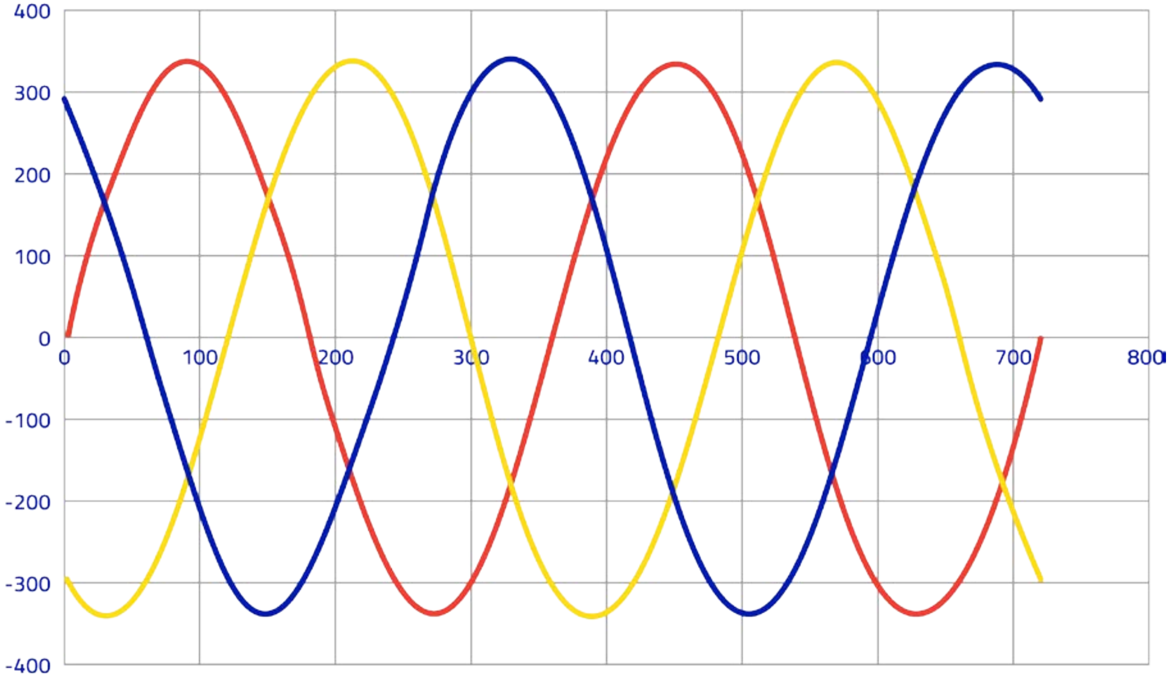
Power Factor Correction Explained



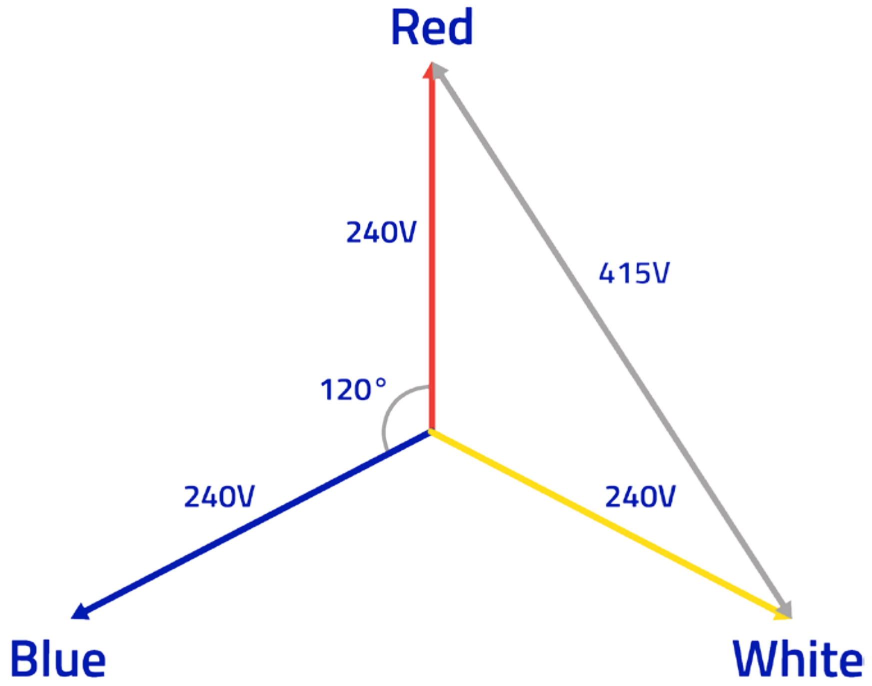
PF = COS (18°)
= P / S
= 0.95 LAG
(GOOD PF)



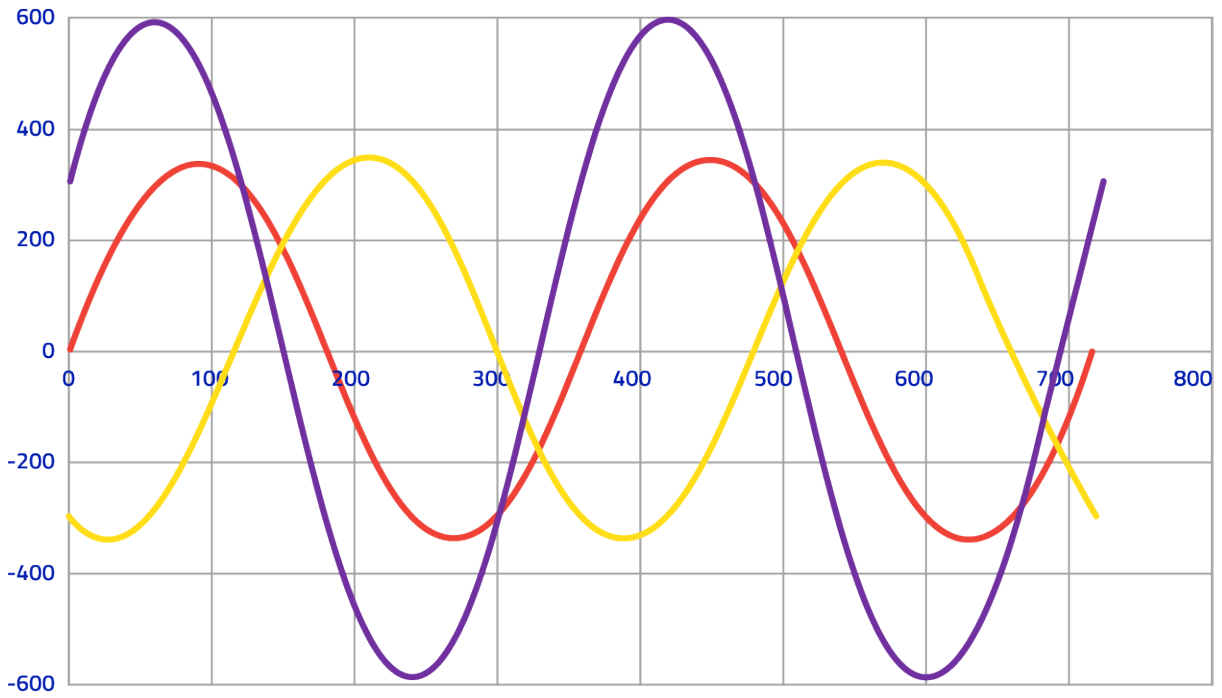
3 Phase Circuits



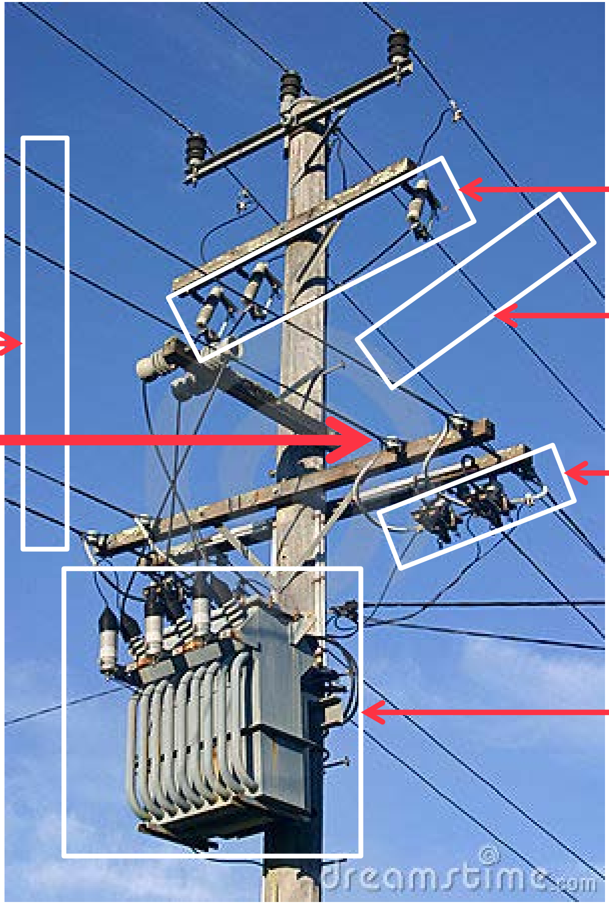
3 Phase – Vector Addition



3 Phase – Waveform Addition

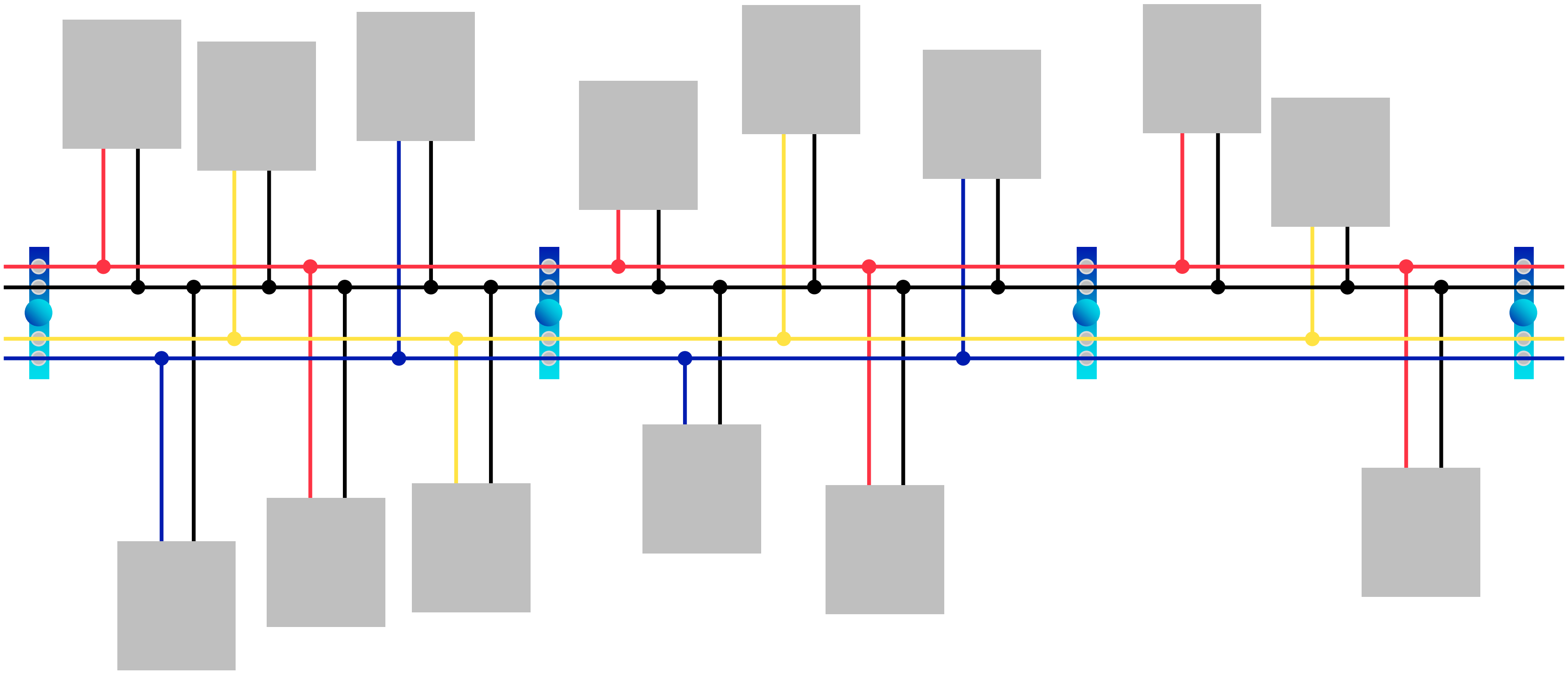


Street Power Pole

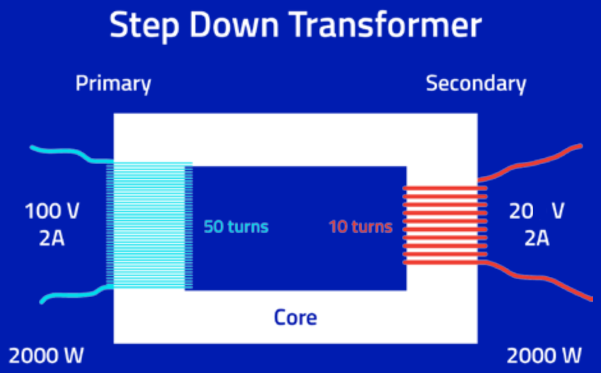


Contains both 22kV and 415V

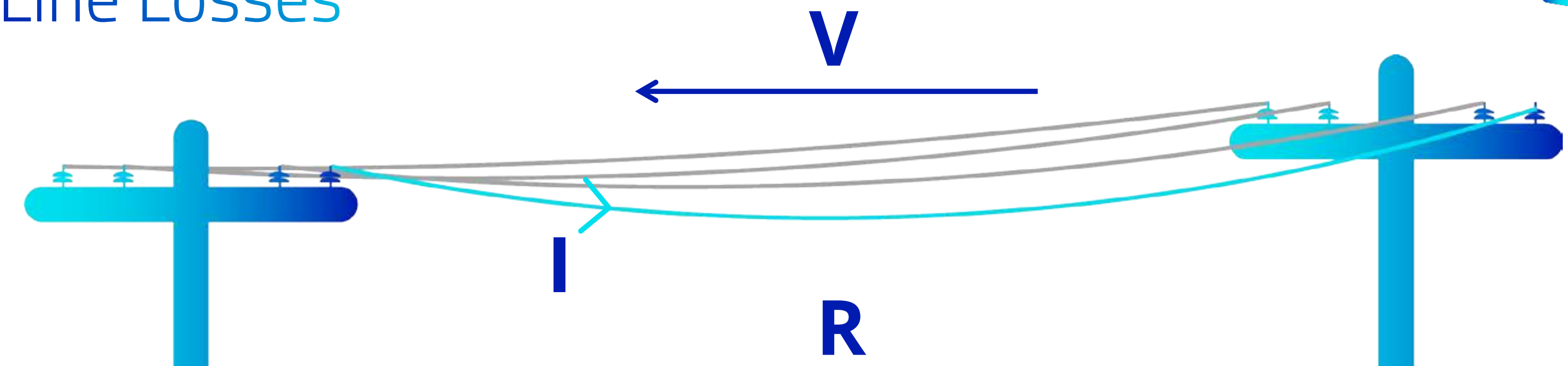
House Connections



Power Transformer



Line Losses

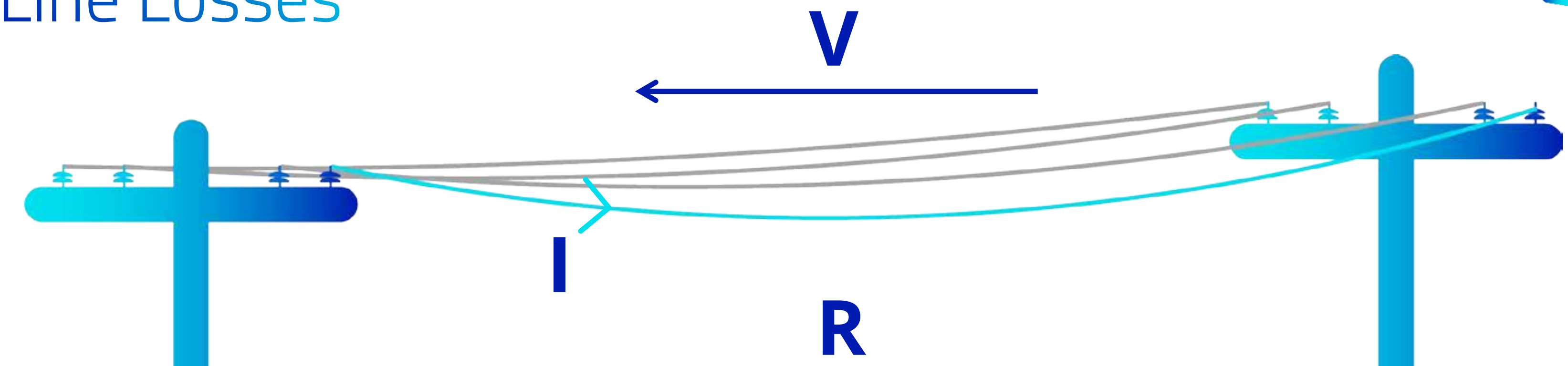


$$V_{BACK} = RI$$

$$P_{LOST} = VI$$

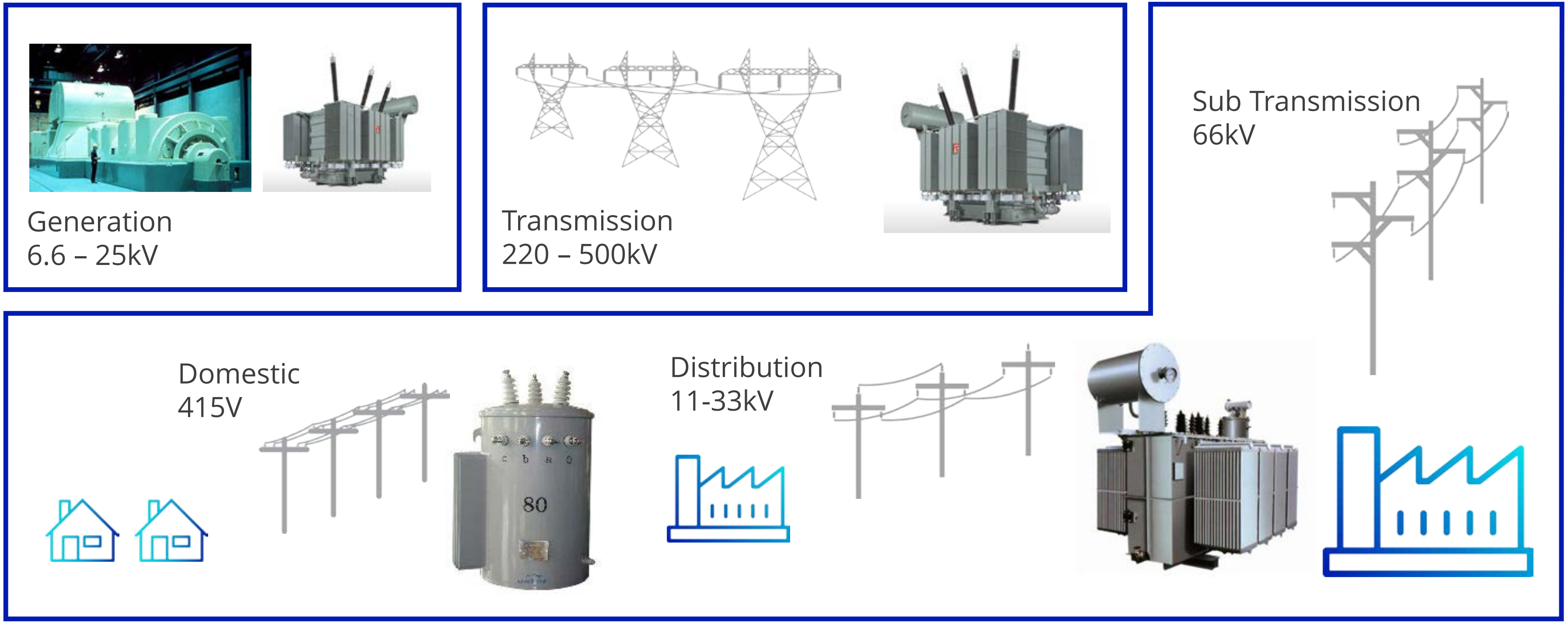
$$P_{LOST} = RI \times I = R\,I^2$$

Line Losses



- Every power line has a resistance. When current is passed down it, a power loss occurs.
- By reducing the current by a factor of 2 we reduce the power loss by a factor of 4,
  … and the easiest way to reduce the current is to increase the voltage.

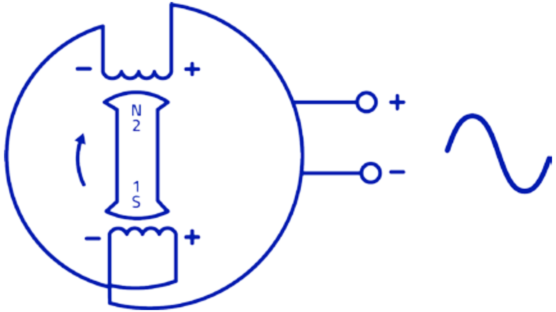
The Network

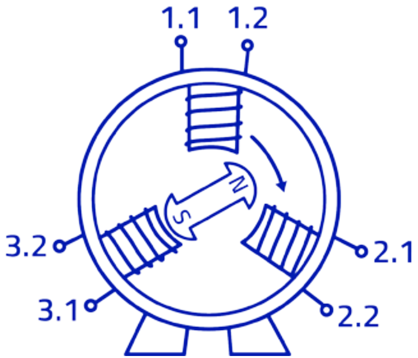

Generation
6.6 – 25kV
Transmission
220 – 500kV
Sub Transmission
66kV
Domestic
415V
80
Distribution
11-33kV

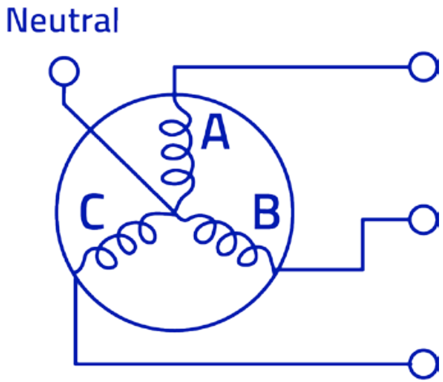
Electricity systems

- AC Generator
- Connecting to the grid
- Generator types

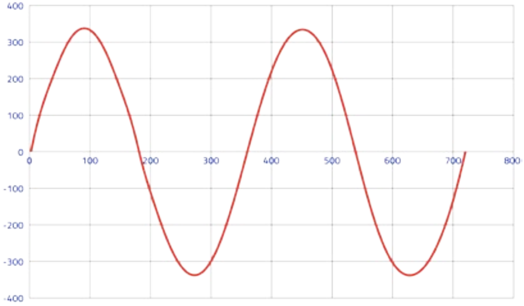
AC Generator

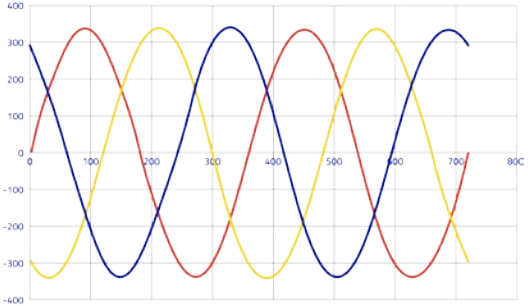




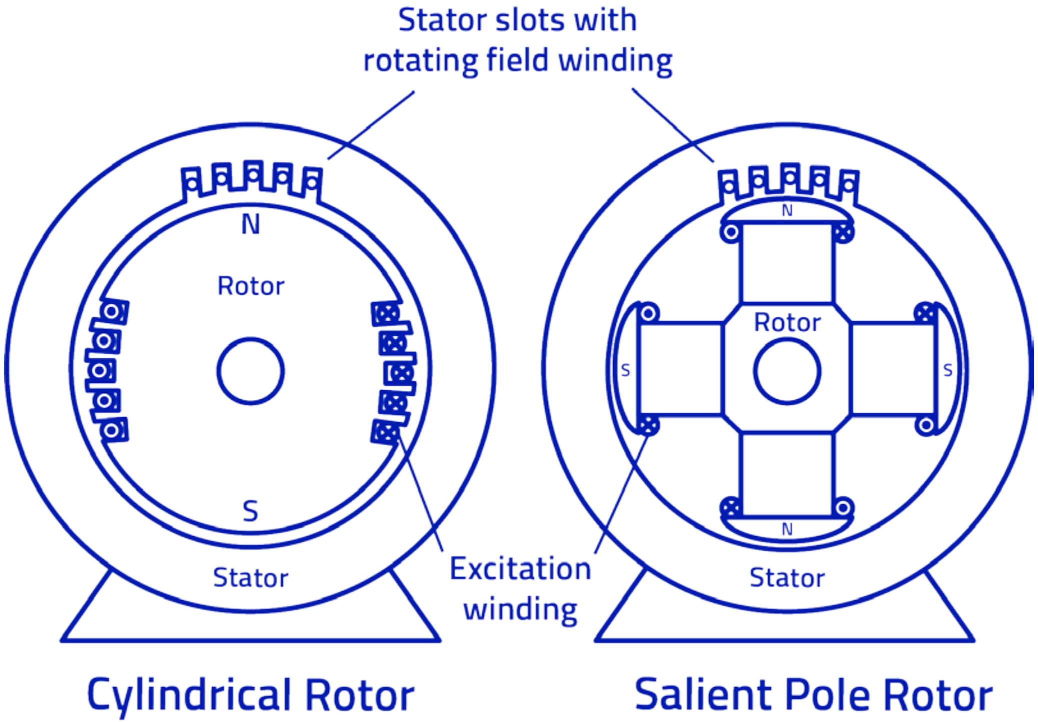


Three-Phase
WYE Connected





AC Generator Rotor Types



Synchronous Speed

$$n_{syn} = (60 \times f) / p$$

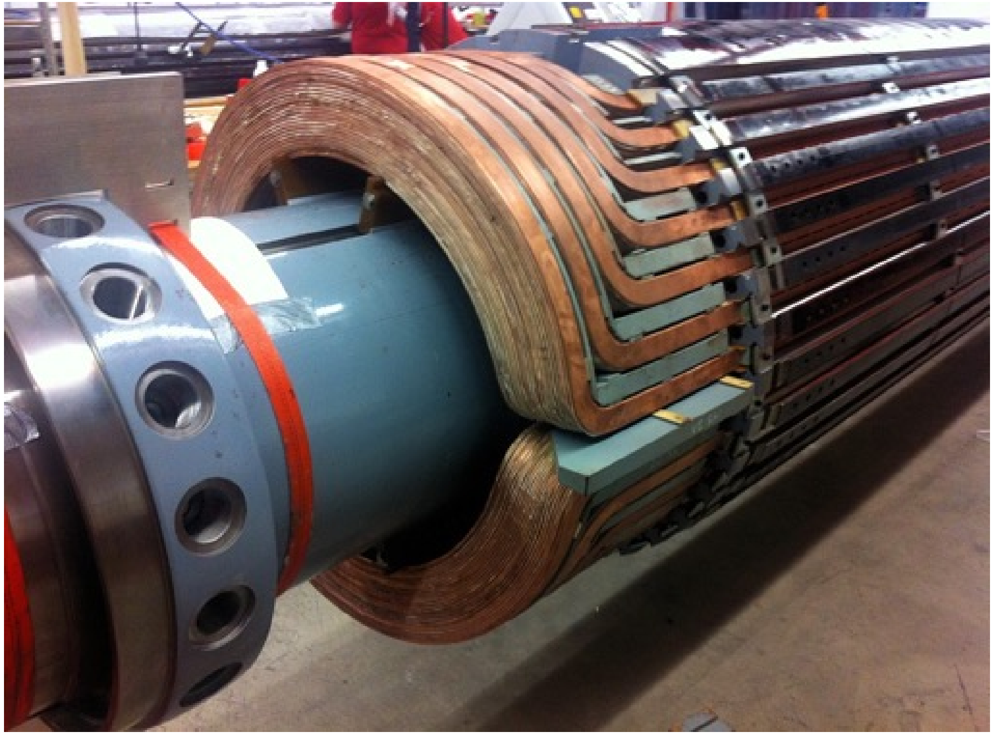
n = Rotor Speed in RPM

f = frequency of electricity generated

p = number of pole pairs

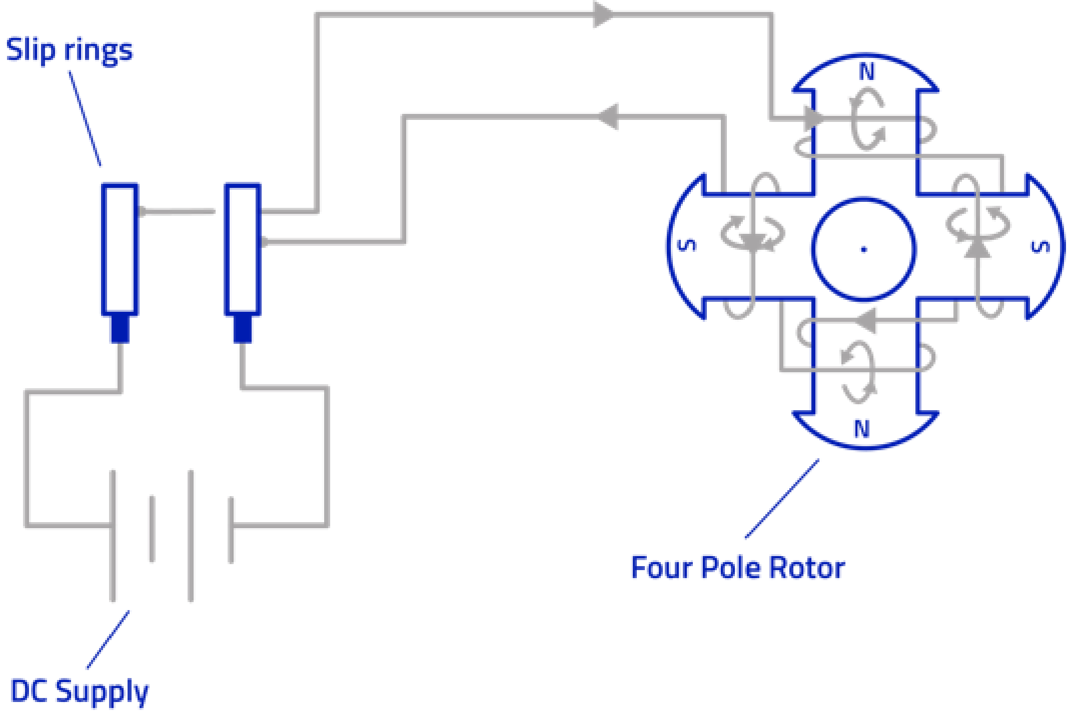
AT 50 Hz		
No of poles	P	n_{syn} (rpm)
2	1	3000.0
4	2	1500.0
6	3	1000.0
8	4	750.0
10	5	600.0
12	6	500.0
14	7	428.6
16	8	375.0
18	9	333.3
20	10	300.0
22	11	272.7
24	12	250.0
26	13	230.8
28	14	214.3
30	15	200.0
32	16	187.5
34	17	176.5
36	18	166.7
38	19	157.9
40	20	150.0
42	21	142.9
44	22	136.4
46	23	130.4
48	24	125.0
50	25	120.0

AC Generator Rotors: Cylindrical



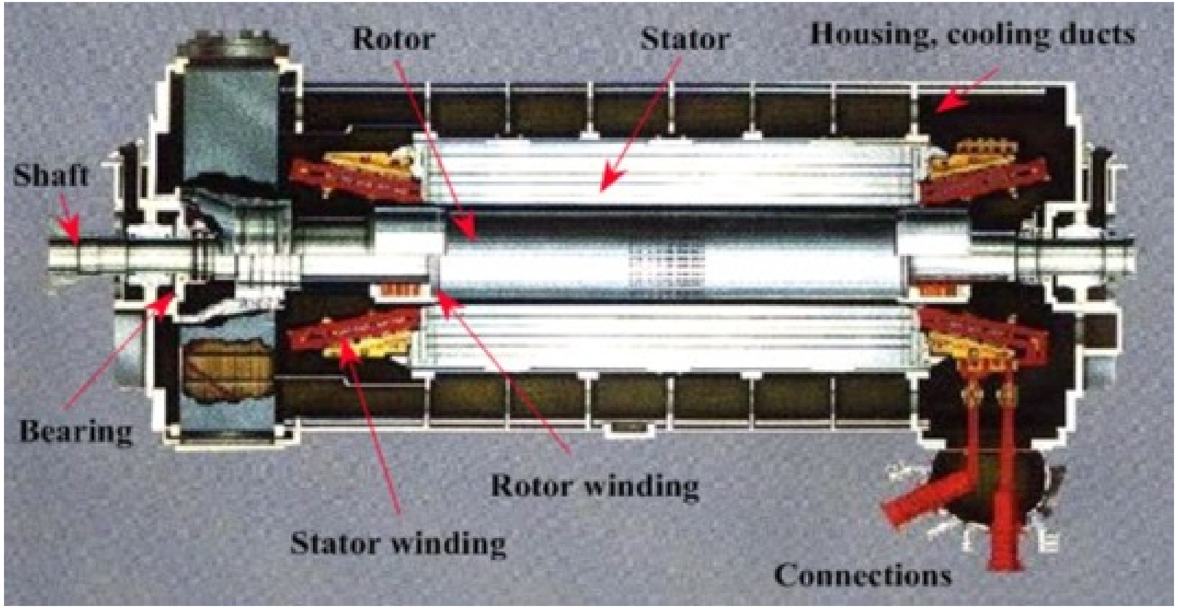
AC Generator Rotors: Salient Pole

Salient Pole Rotor



AC Generator Rotors: Salient Pole

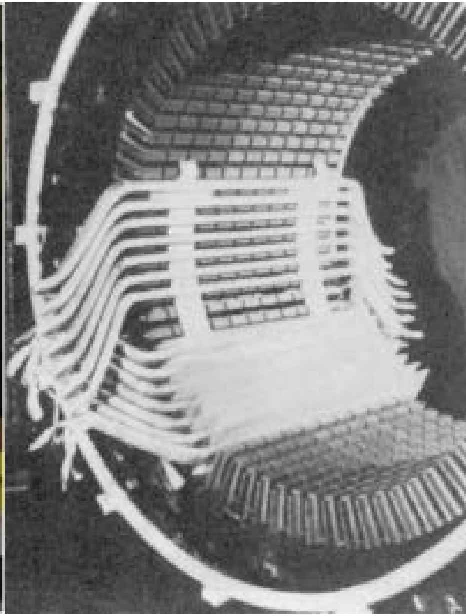
AC Generator: Round Rotor Generator



Cross-section of a large turbo generator.
(Courtesy Westinghouse)

AC Generator

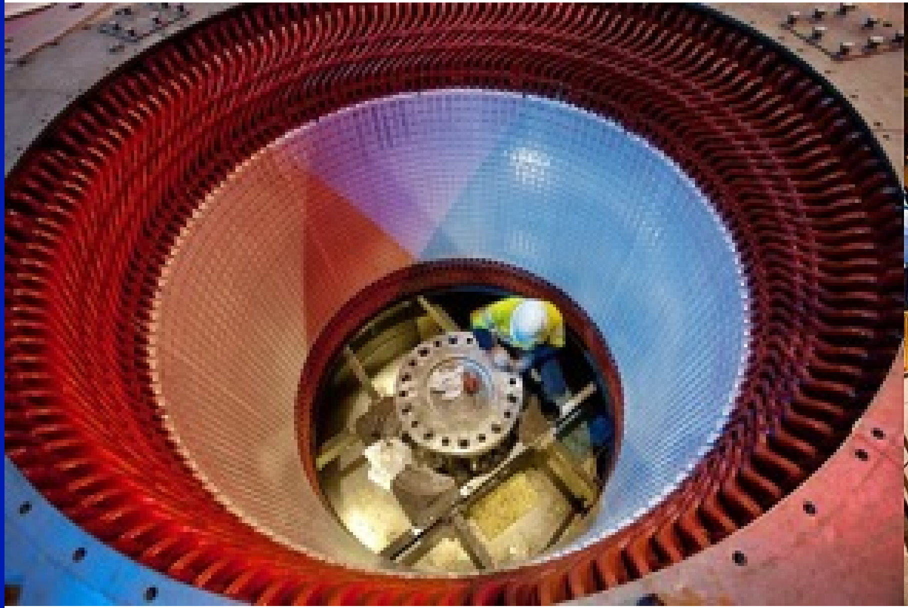
Stator Construction



AC Generator

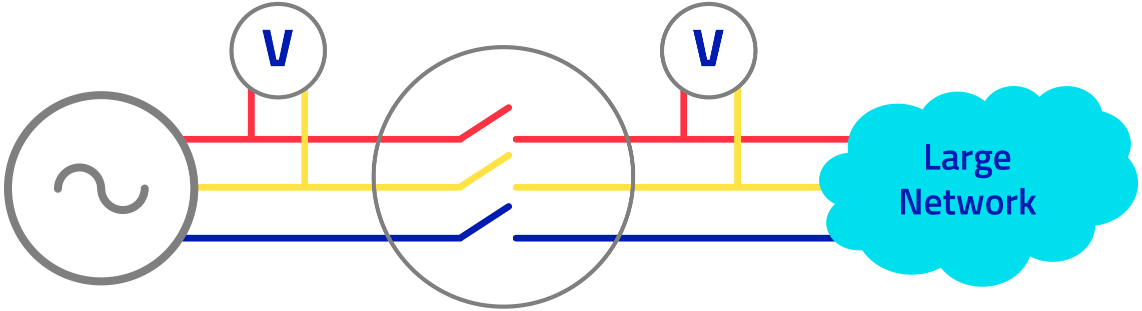
West Kiewa Power Station

18,000 kVA Salient Pole Generator and stator



Excitation System

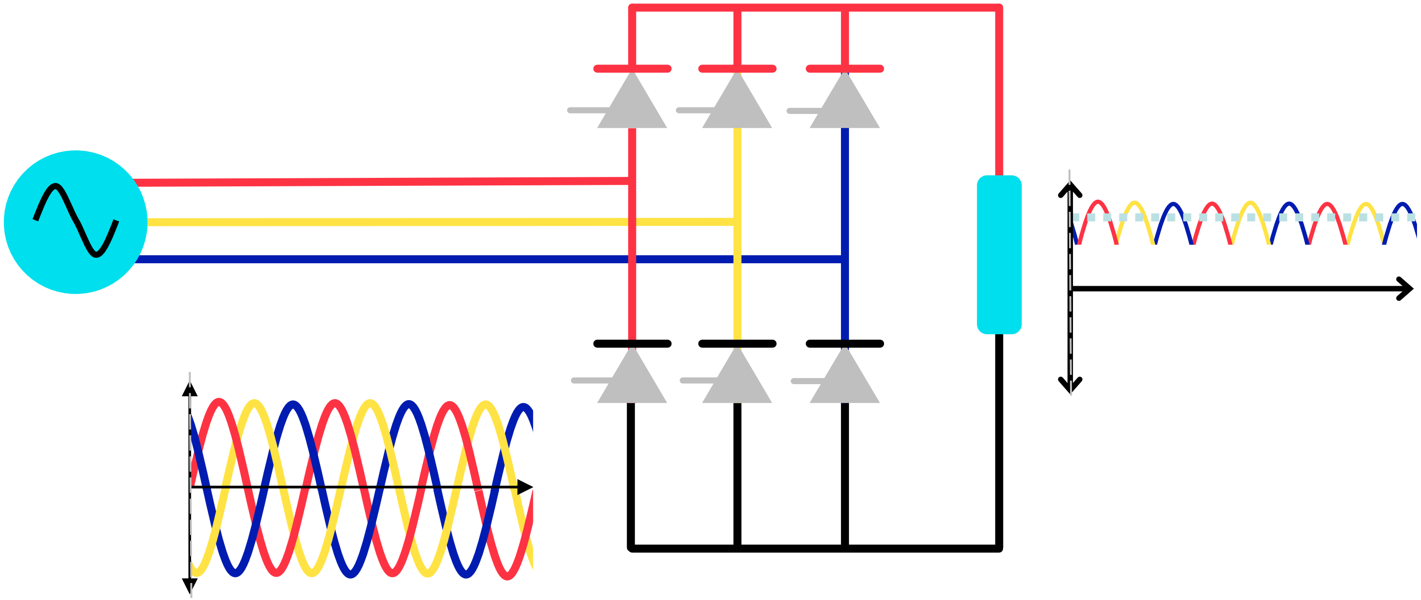
- In a Synchronous Generator the rotor pole windings need to be supplied with a variable DC current to produce the magnetic field required.
  This current is called '**Excitation Current**' or '**Field Current**'.
- The current needs to be variable to adjust
  - the stator voltage when off line (Generator Circuit Breaker OPEN), and
  - the VAR output when on line (Generator Circuit Breaker CLOSED)



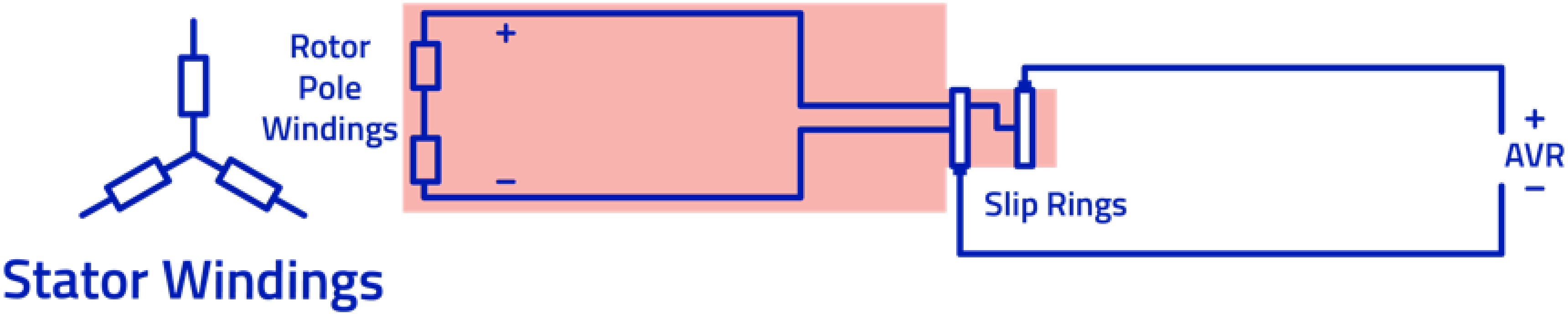
Excitation System

- The device that supplies the DC excitation current to the rotor is called the Automatic Voltage Regulator (AVR).
- The AVR contains a thyristor bridge that converts an AC supply to a variable DC output.
  The thyristors are controlled via a micro processor to achieve a desired voltage output or VAR output from the generator.
- The AVR is designed to react to a system fault by supplying more excitation current if a voltage dip (fault) is experienced.
  This helps maintain system voltage during the fault period.
  It also allows the generator to supply fault current during this period, such that protection systems (fuses and relays) can isolate and “clear” the faulted region allowing the rest of network to continue to operate.
- High fault current contribution means these generators help maintain ‘system strength’.

3 Phase Thyristor Bridge



Excitation Systems – Direct

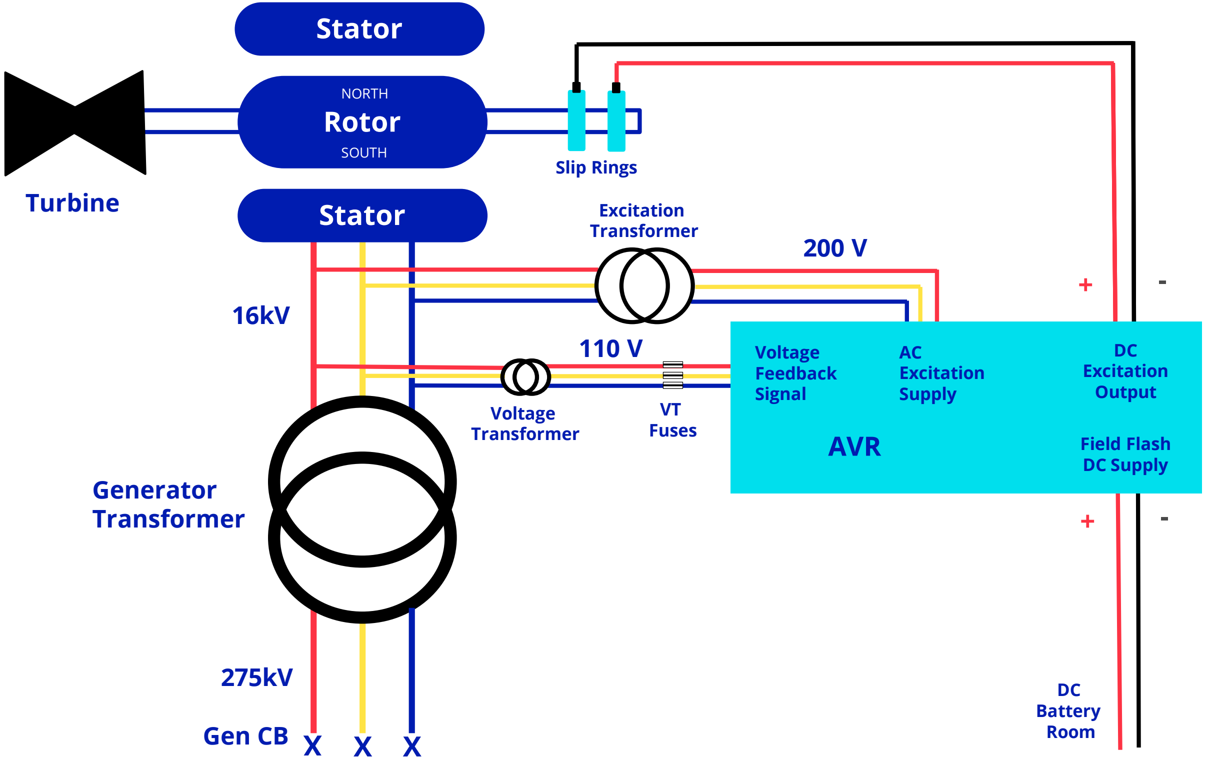


Excitation Systems – Direct

ROTOR WINDINGS

SLIP RINGS

Excitation System Including AVR



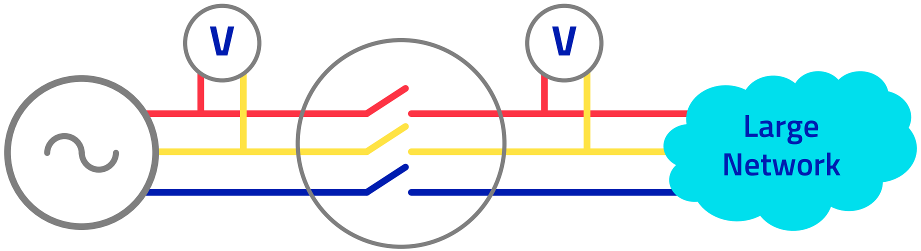
Synchronisation

Synchronising is the process of electrically connecting an additional generator to a live Network.

To do this correctly the AC voltage characteristics of the Generator need to be carefully matched to that of the 'live' network it is being connected to.

The characteristics that need to be considered are:

- Voltage magnitude (Adjusted via excitation current)
- Frequency (Adjusted via turbine speed, coarse)
- Phase (Adjusted via turbine speed, fine)



Synchronisation Panel

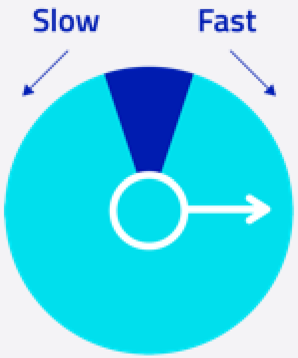
Generator Voltage (kV)

Red	16.10
White	16.12
Blue	16.13

Generator Frequency (Hz)

50.05

Synchroscope



Network Voltage (kV)

Red	16.01
White	16.03
Blue	16.02

Network Frequency (Hz)

50.00

Generator Voltage Control

Lower Raise

Generator CB Control

OPEN CLOSE

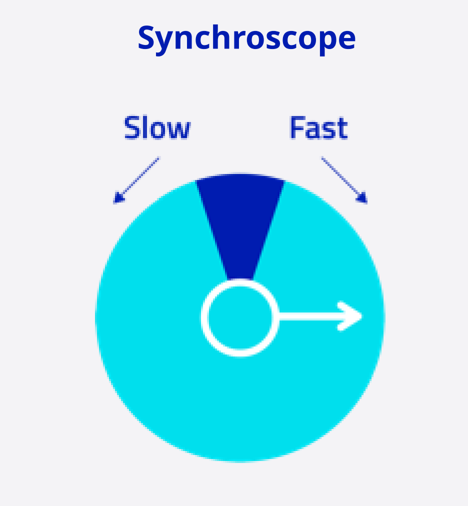
Generator Speed Control

Lower Raise

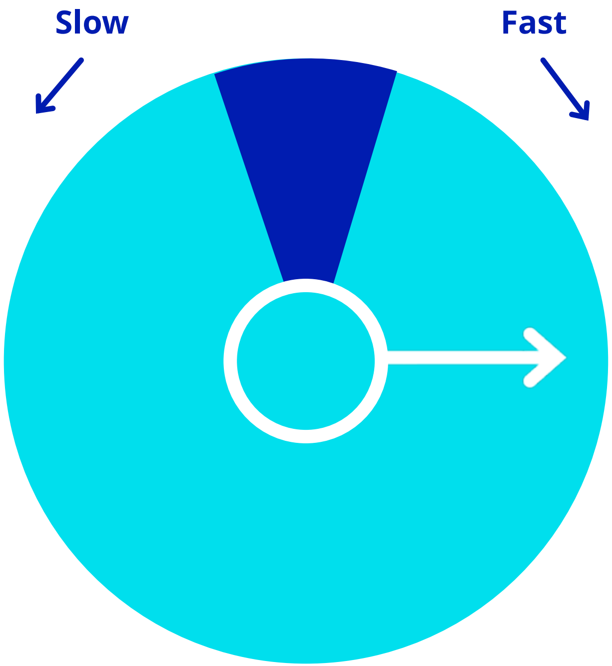
Syncroscope

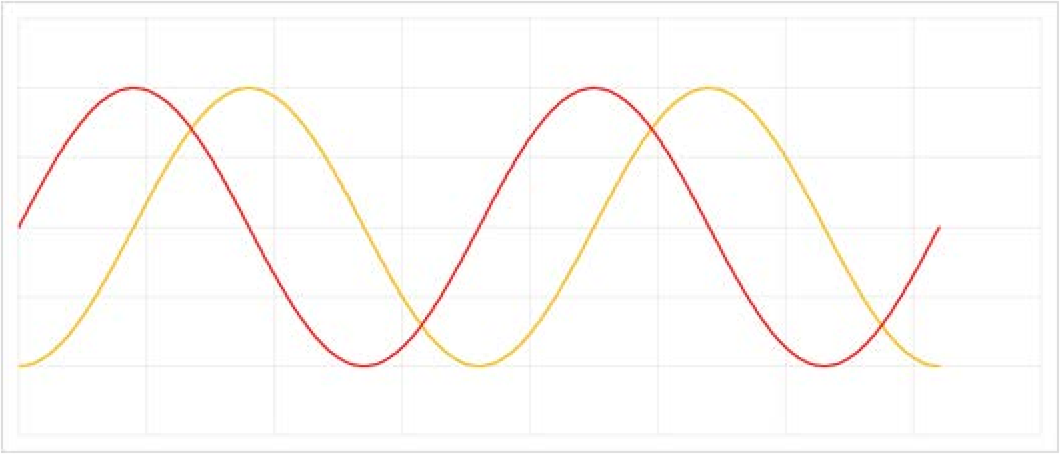
The syncroscope provides two important pieces of information

- The phase relationship between the two voltages (generator and system) and
- The speed difference between the two frequencies



Generator Out of Phase

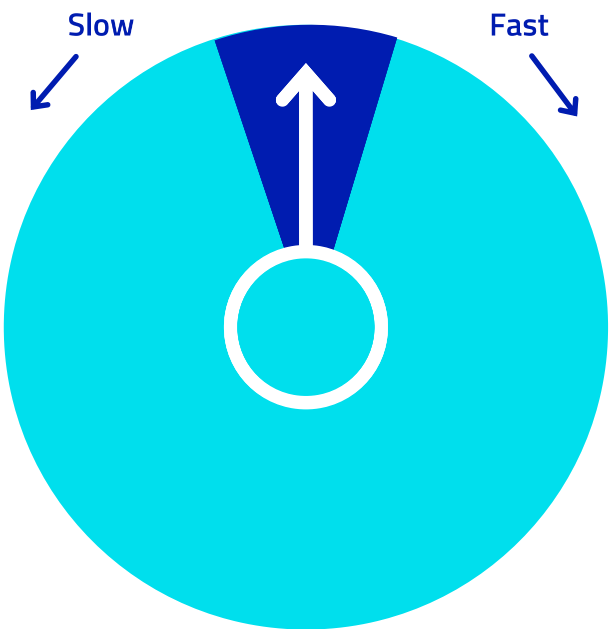




Generator at different speeds

System Frequency

50 Hz



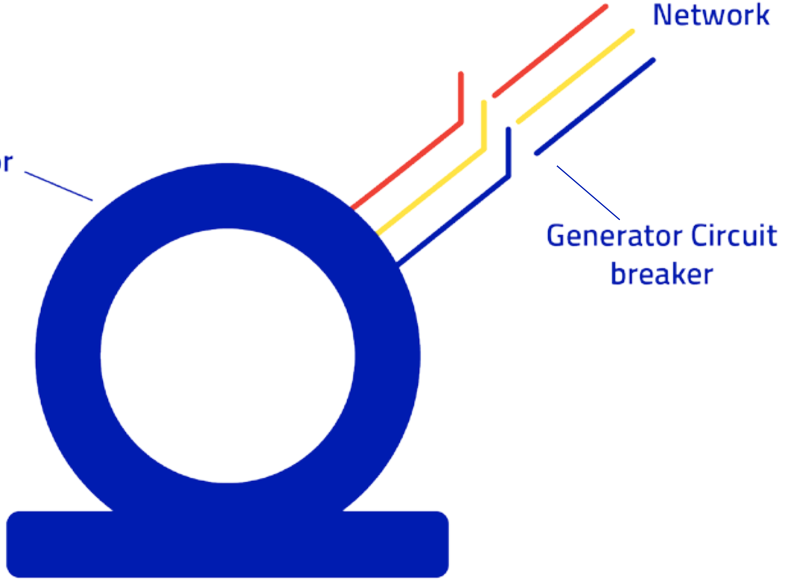
Generator Frequency

49.8 Hz

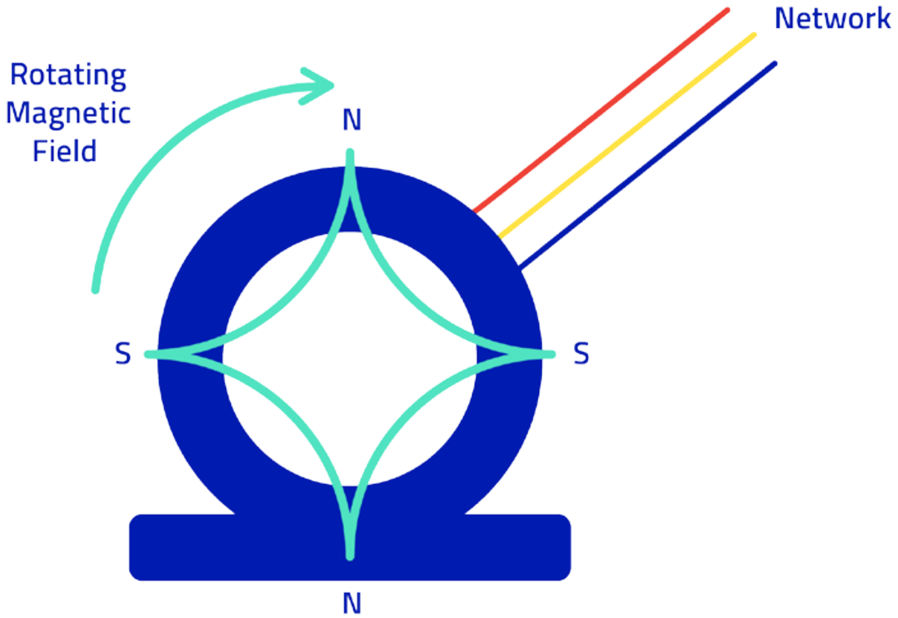
50 – 49.8 = 0.2 Hz

= 1 rotation every 5 sec Anticlockwise Direction

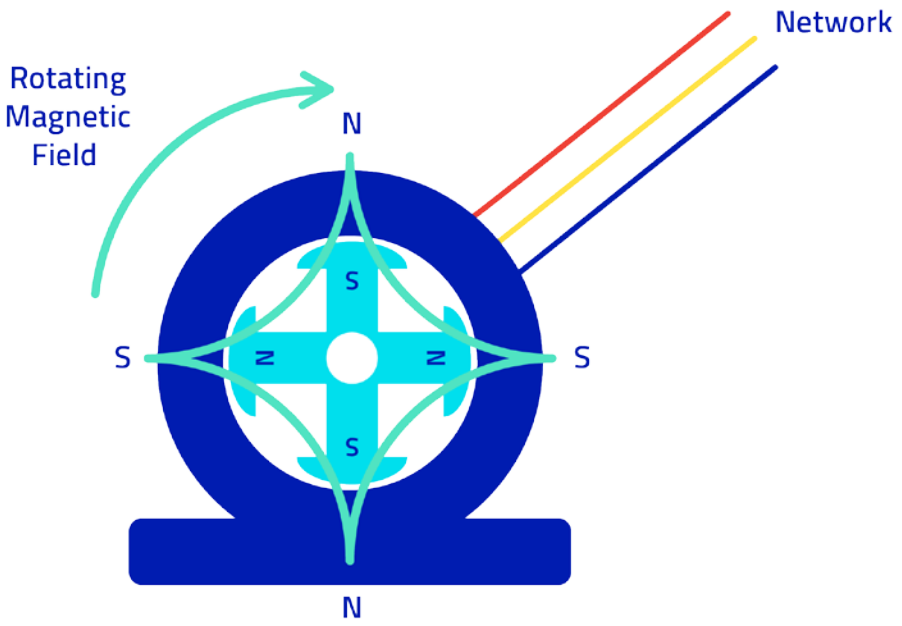
Generator Capability



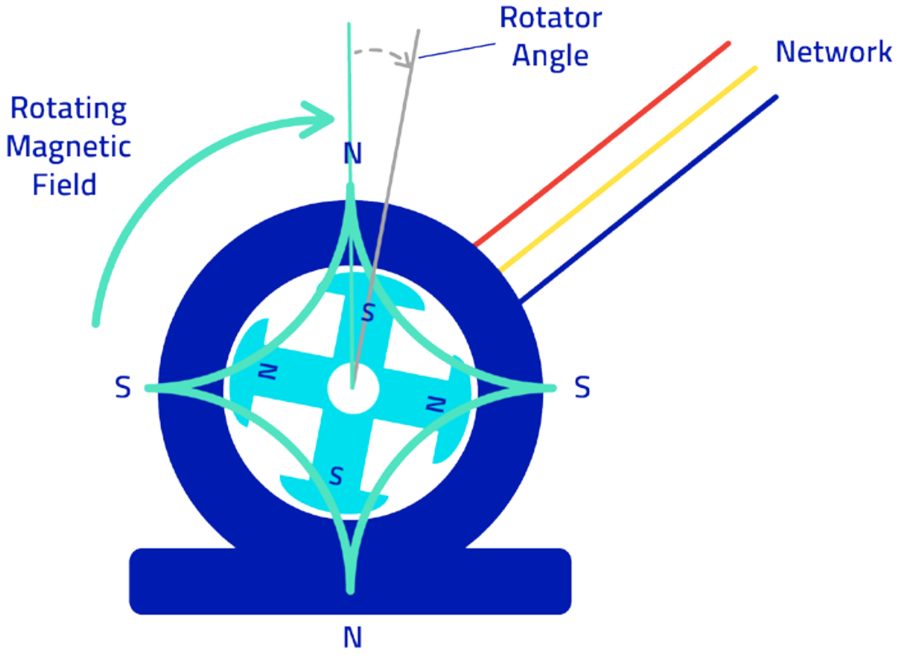
Generator Capability



Generator Capability

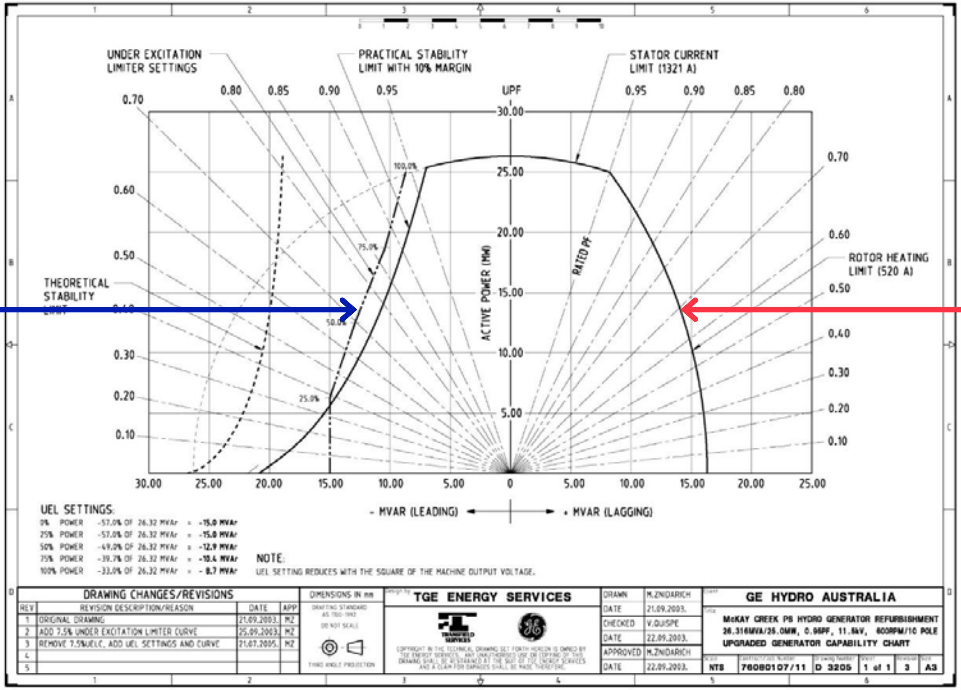


Generator Capability



Generator Capability – Limiters

Excitation Limiters are a control device that allow the machine to continue to operate in a “safe” manner. They are not classed as protection that trip the machine.

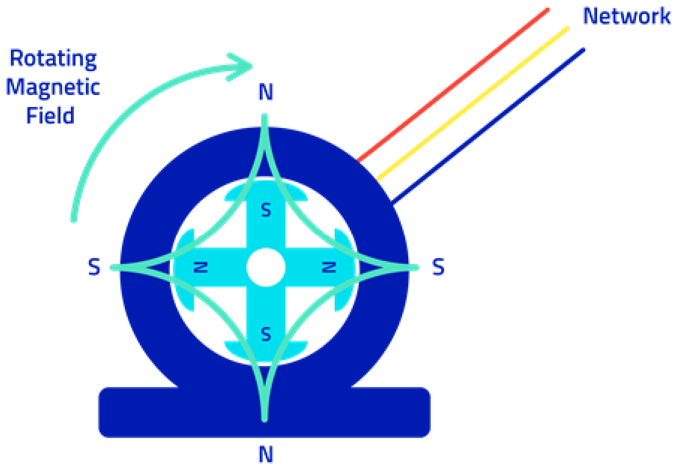


Under Excitation Limiter (UEL) is required to protect generator from a pole slip (loss of synchronisation)

The Over Excitation Limiter (OEL) is required to protect field (rotor) from overheating

System Inertia explained

- During system imbalance events, system frequency will change
  - Not enough power generation will lead to frequency drop
  - Too much power generation will lead to frequency increase
- Synchronous generators have their rotors locked in to the speed of the network when connected, as such
  - They need to be accelerated if the frequency tries to rise (absorbing power) slowing the rate of frequency change.
  - They will need decelerate if the frequency tries to fall (supplying stored power in the spinning rotor) slowing the rate of frequency change.
- Slowing the rate of frequency change is called INERTIA
- The slowing of frequency change allows the network precious time to correct the power imbalance and return to the frequency back to 50Hz



Asynchronous Generator

- Magnetic field is induced on the rotor from the stator
- The stator needs VARS to do this (capacitors supply)
- The induced rotor field slowly rotates on the rotor
- The rotor rotates up to 15% faster than the system speed at full power output. This is called the slip speed.
- These generators are ideal for wind turbines as the slip speed can increase during wind gusts avoiding damage to the blades

- Asynchronous generators:
  - offer very little inertia due to the slip characteristic
  - supply very little fault current (no AVR)
  - cannot supply VARS

Generator Control

FOR AN OPEN CIRCUIT GENERATOR (or connected to a small load)	FOR A GENERATOR CONNECTED TO A LARGE NETWORK
If excitation is increased voltage will increase	If excitation is increased VAR output will increase
If fuel flow is increased speed will increase	If fuel flow is increased Real power output will increase

AC vs DC revisited

Due to losses, DC systems required a station “every mile or so”, to provide correct voltages. At the time this was impractical.

Now, we have a large penetration of roof top solar and battery storage. These systems are DC.

These need to be converted to AC to enable connection to the grid and compatibility with household appliances.

Inverters

An inverter is used to convert DC voltage into AC voltage

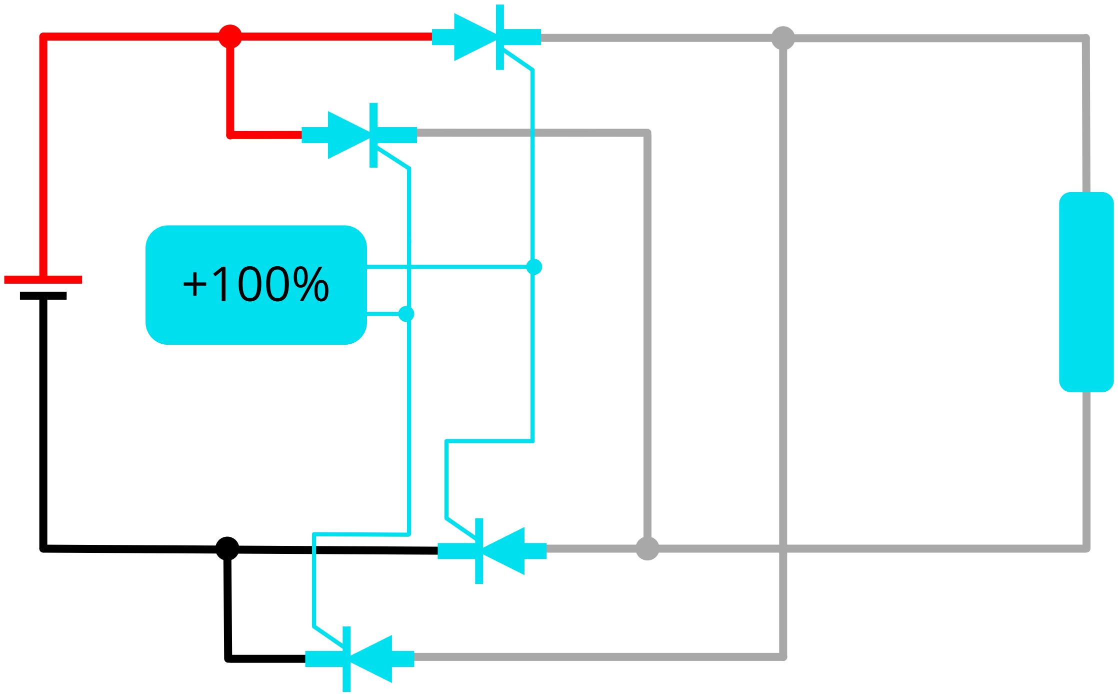
Stand Alone

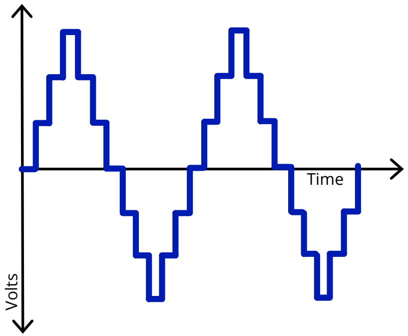
- Camping
- Remote work sites

Grid Connected

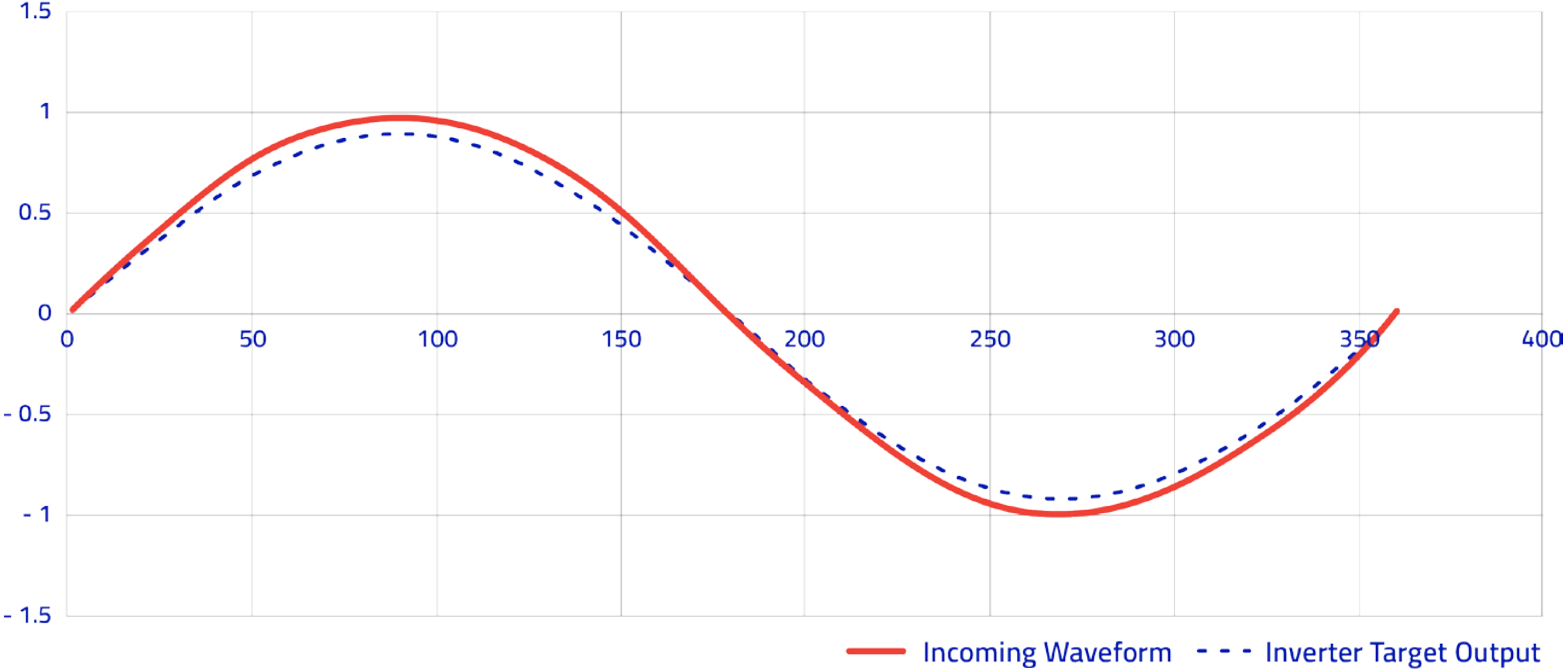
- Solar Panels
- Battery

Sin Wave Inverter





Grid Connected



Target Wave Ahead of Incoming Wave

- Power Transfer (Generate)
- No Reactive Transfer

Grid Connected

The “Virtual” Power Plant

By connecting small stand alone inverters and batteries together, and controlling them from a single controller, a larger combined virtual power supply can be created.

This enables the control of power flows contributing to the network in a even and predictable manner.

High Voltage Safety

- Voltage radiates away from the contact point of downed power lines
- Voltage levels depend on resistivity of the ground contacted
- Step potential is the voltage difference between two contact points

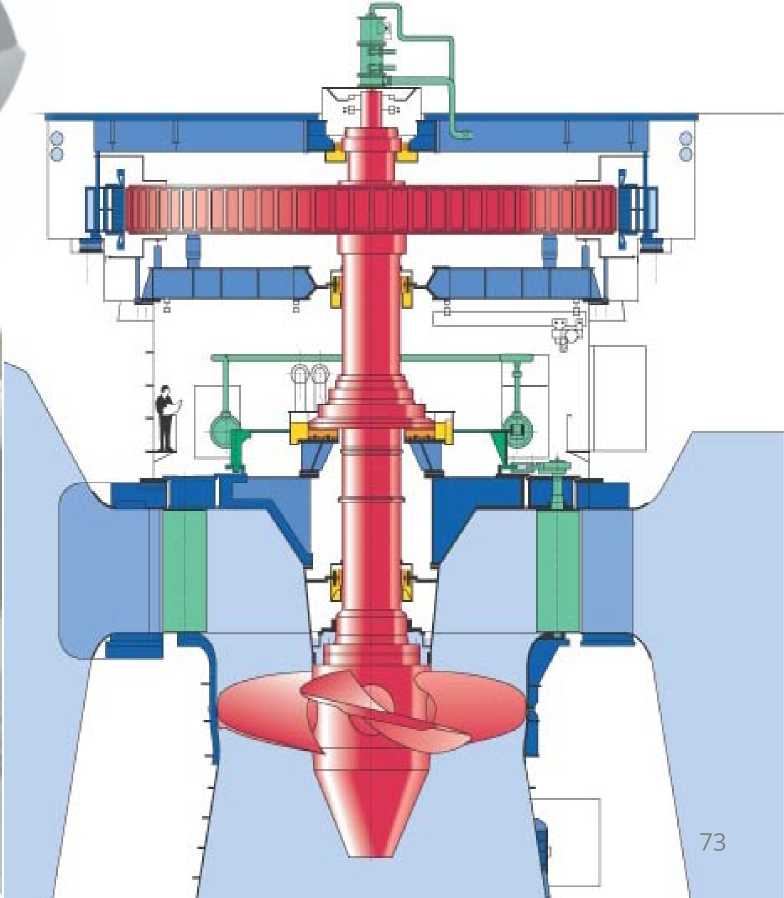
Therefore …

- Keep well clear of any downed power lines
- Be aware of “auto reclose” and lines becoming alive again without warning
- Avoid exiting a vehicle that may be in contact with a downed power line

Hydro Turbines

Kaplan Turbine

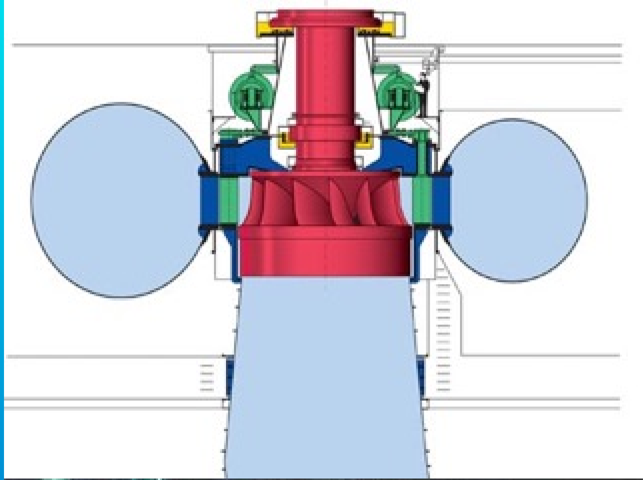
AGL generators
Yarrawonga
Banimboola

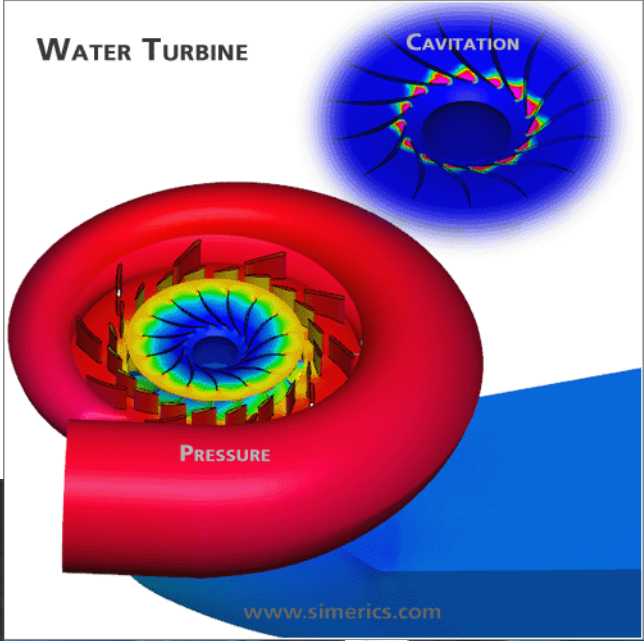


Hydro Turbines

Francis Turbine

AGL generators
Dartmouth
Eildon
West Kiewa
Clover
Copeton
Glenbawn
Pindari
Lower Rubicon
Cairn Curran

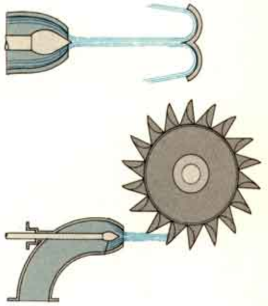


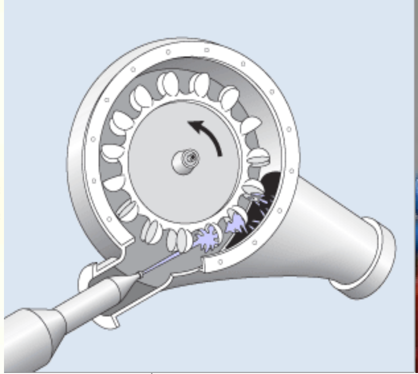


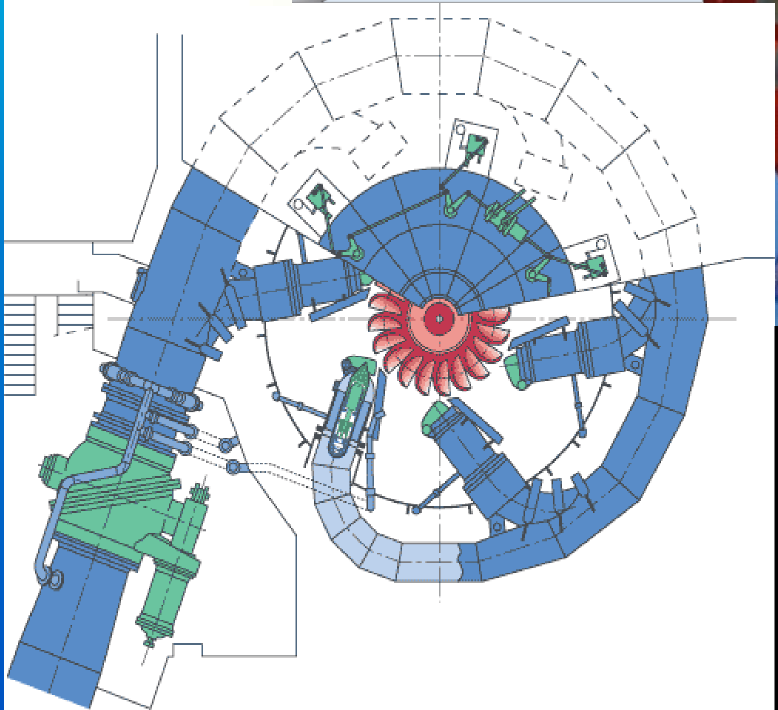
Hydro Turbines

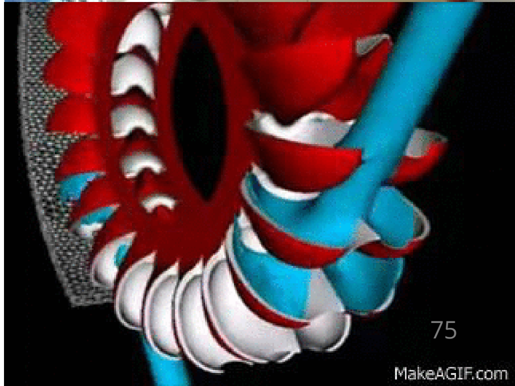
Pelton Turbine

AGL generators
McKay Creek
Rubicon
Royston



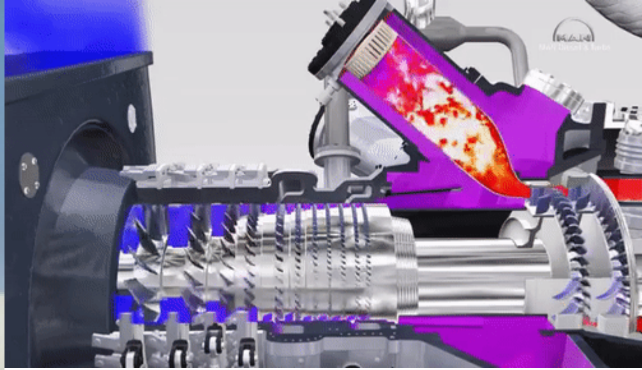


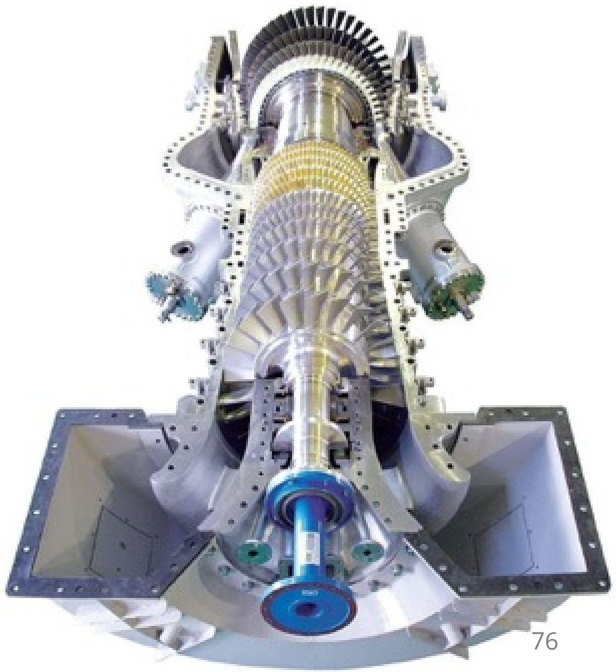




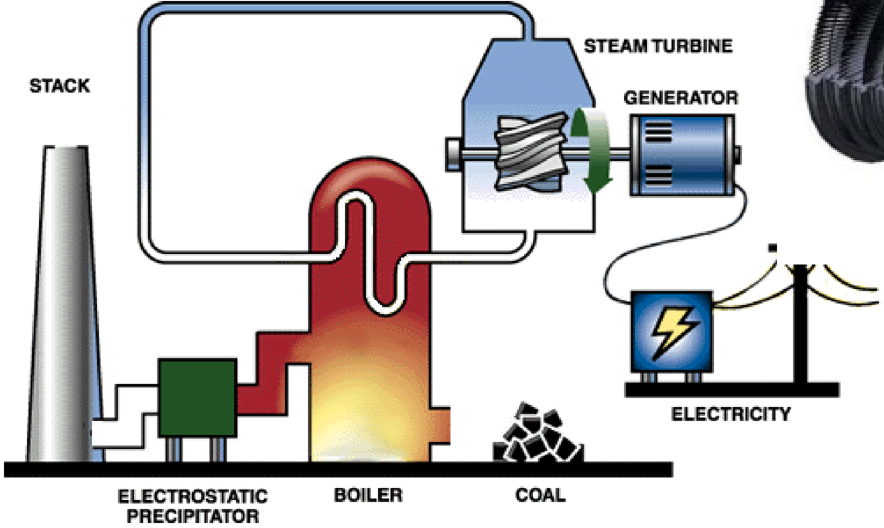
Gas Turbines

AGL generators
Somerton
Hunter Valley





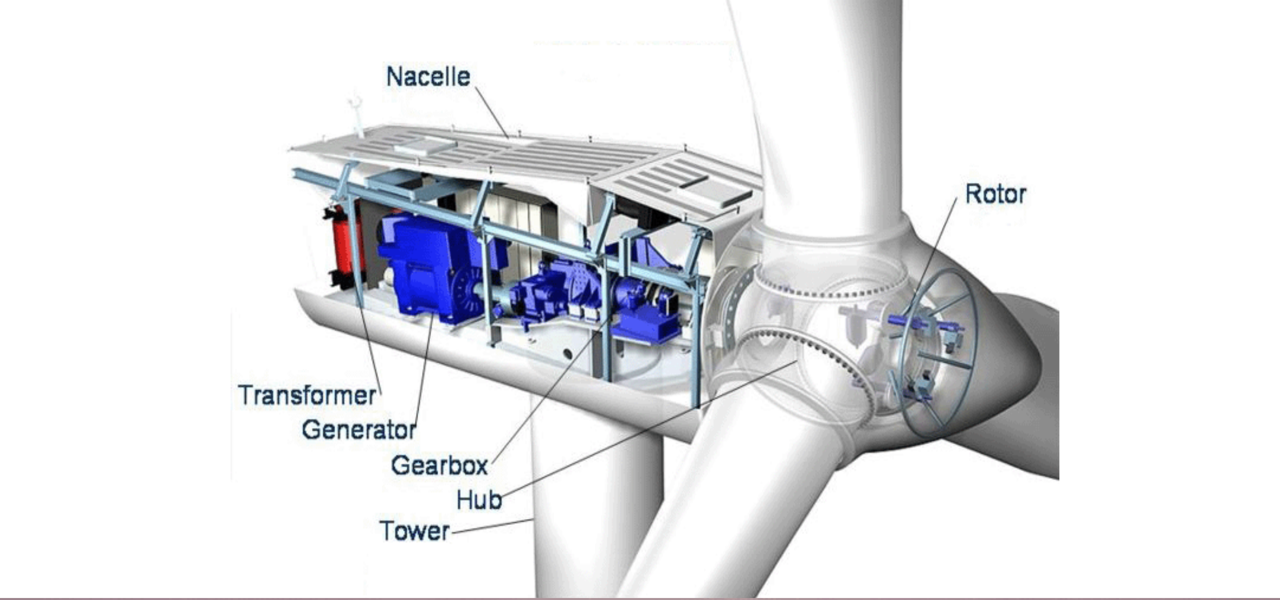
Steam Turbines



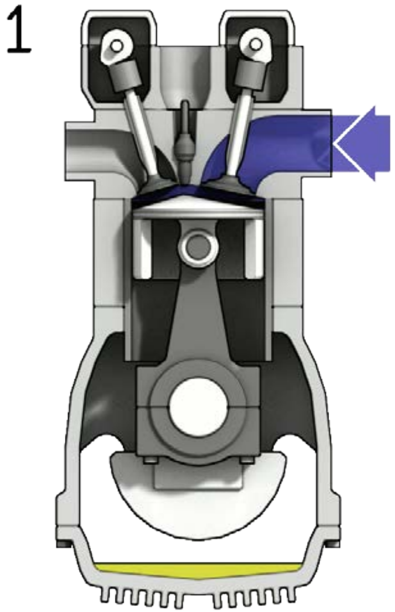
AGL generators
Bayswater
Liddell
Loy Yang A
Torrens Island A & B

Wind Turbines

AGL generators
Hallett
Hallett Hill
North Brown Hill
The Bluff
Wattle Point
Oaklands Hill
Macarthur
Silverton
Coopers Gap



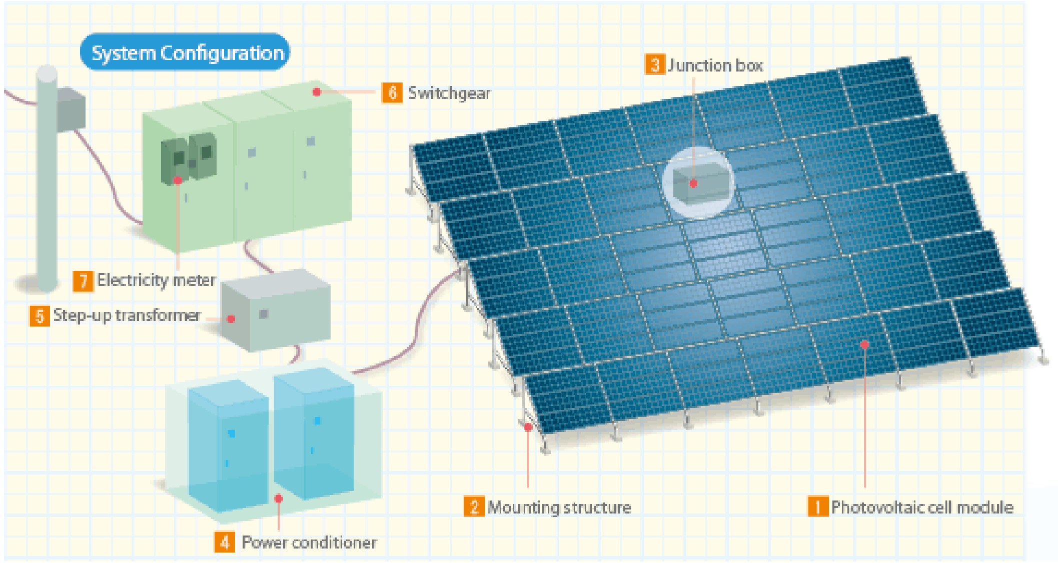
Reciprocating Engine

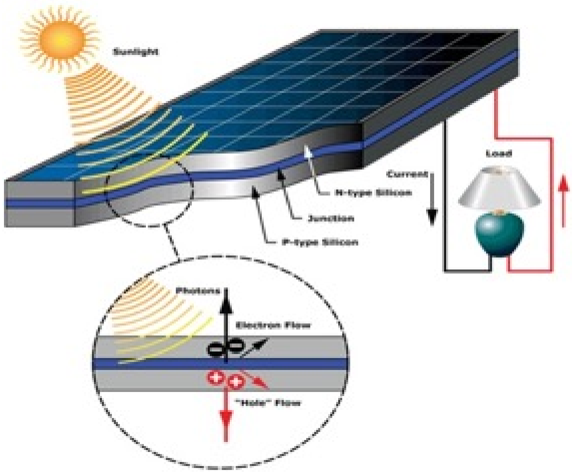


AGL generators
Barker Inlet

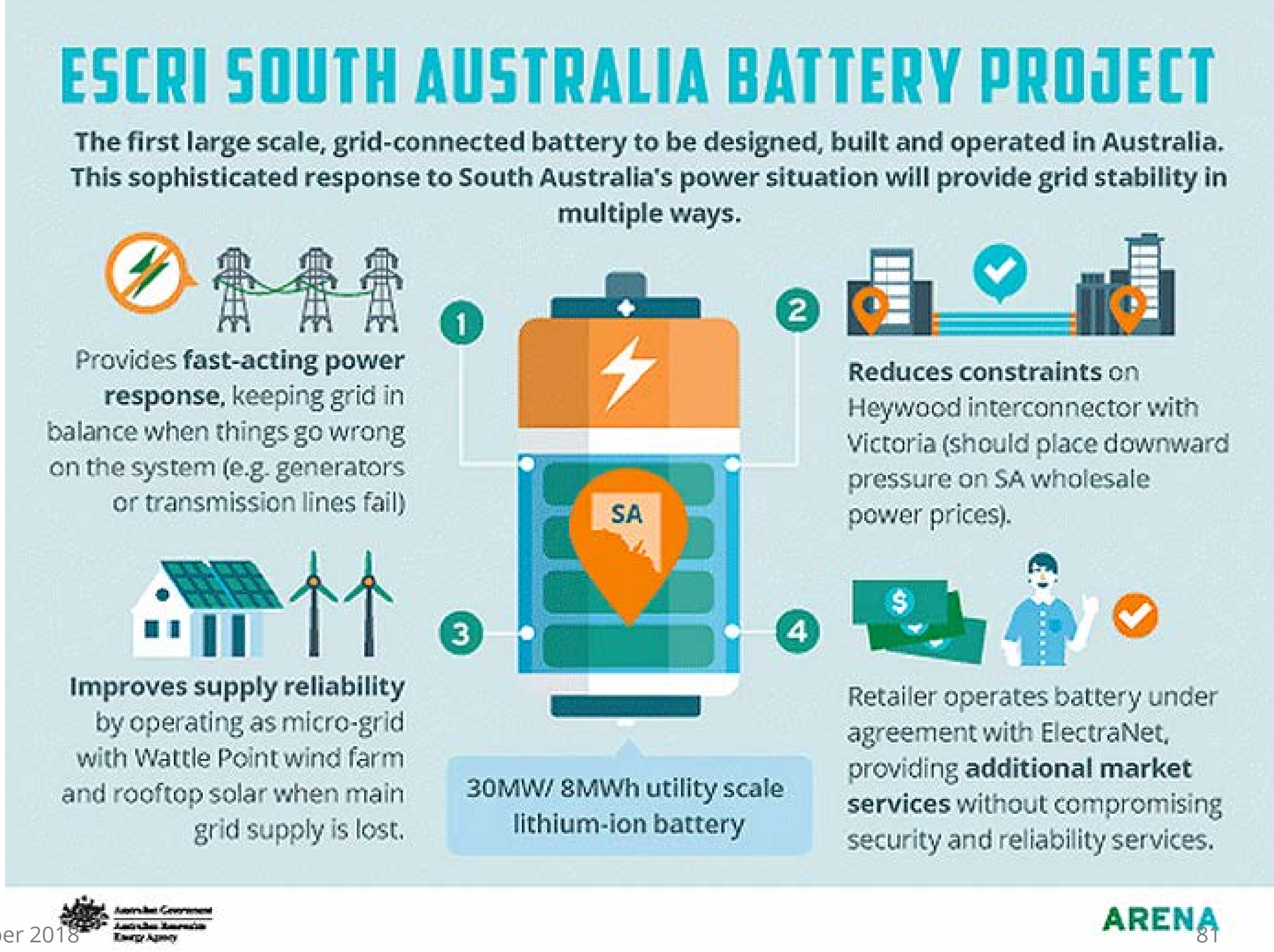
Solar Generation

AGL generators
Nyngan
Broken Hill





Battery Storage

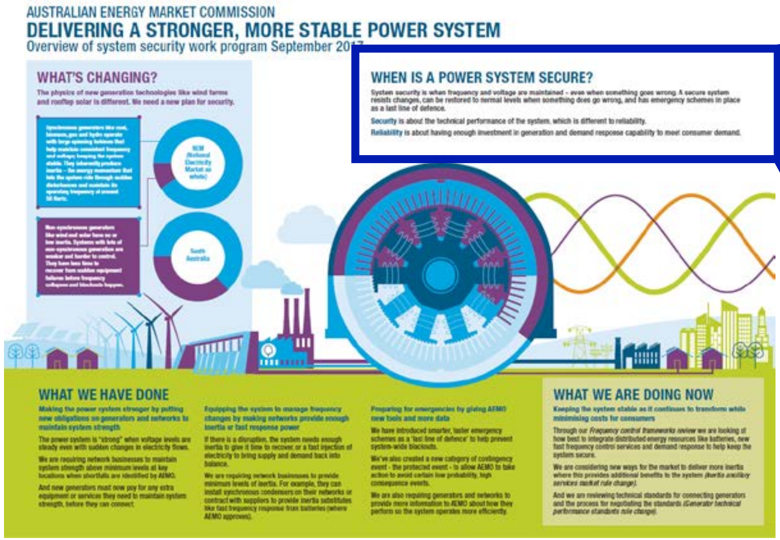


AGL generators
Dalrymple (ESCRI)

Keeping the lights on

- System security
- Market services
- System black

System security versus reliability



"System security is when frequency and voltage are maintained – even when something goes wrong.

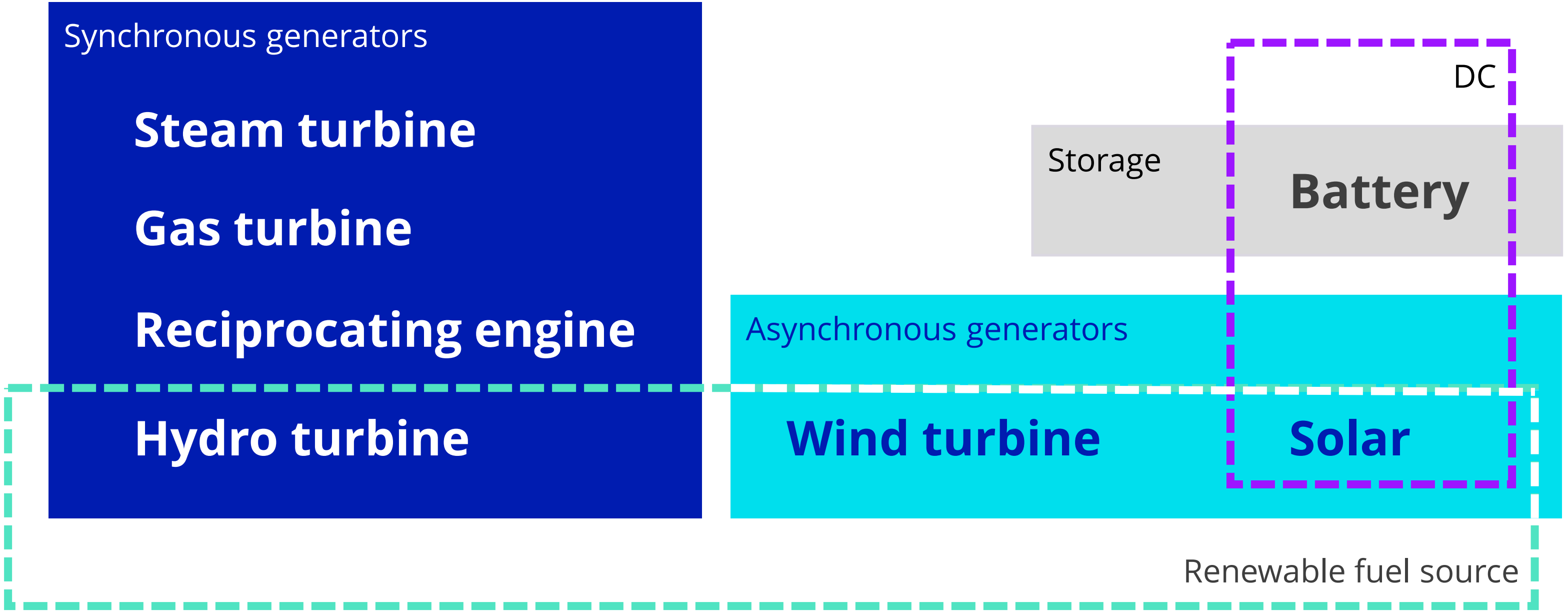
…

Reliability is about having enough investment in generation and demand response capability to meet consumer demand."

Australian Energy Market Commission

Source: AEMC Factsheet
https://www.aemc.gov.au/sites/default/files/content/25c19111-ae51-42f5-b0d2-ea4bb0a684b9/Infographic-2.PDF

Types of generators



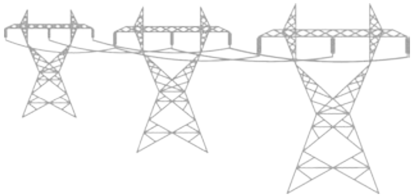
Minimum inertia and system strength

System inertia and fault levels are reducing:

- Retirement of synchronous generators and motors
- Increase in asynchronous generators and motors

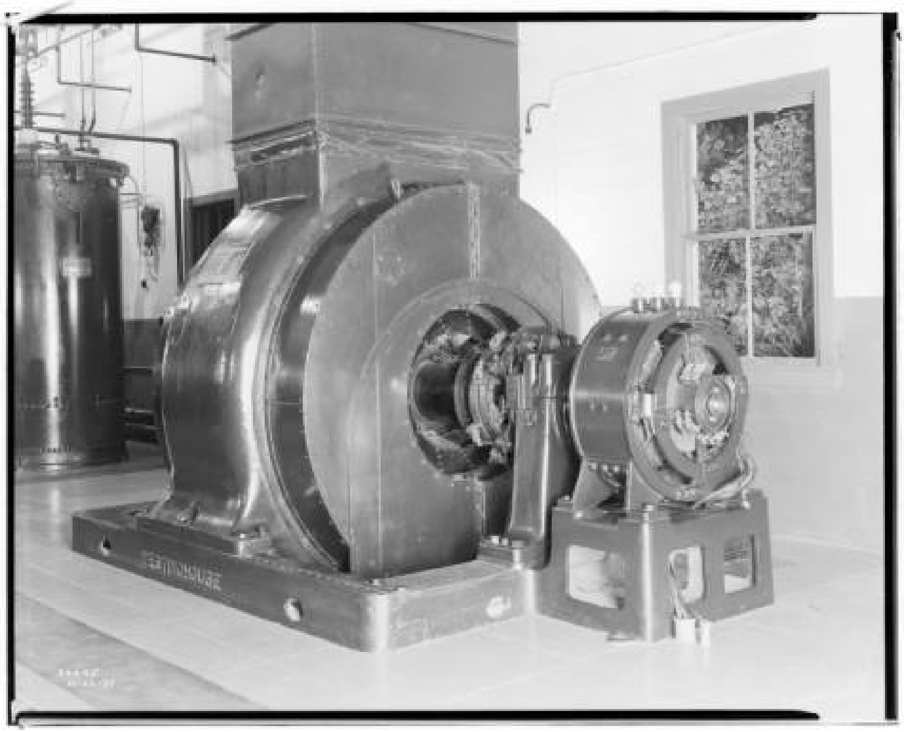
New market rules:

- Transmission Network Service Providers responsible for providing minimum levels of inertia and system strength in their networks
- New generators must “do no harm” to system security
- Enhanced generator and network information provided to AEMO



Synchronous condenser recap

- Back to the future!
- Synchronous condenser is a generator that has no turbine (driving force) behind it
- Speed is regulated by the network (50Hz)
- Takes energy from the grid to overcome frictional and electrical losses
- Some hydro machines can operate in this mode
- Supplies inertia, voltage control and fault current



Source: Southern California Edison collection, The Huntington Library, San Marino, California.

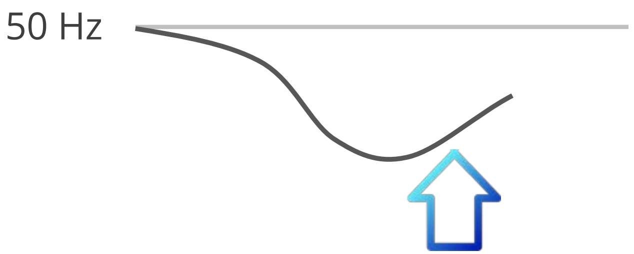
South Australian case study: interim solutions

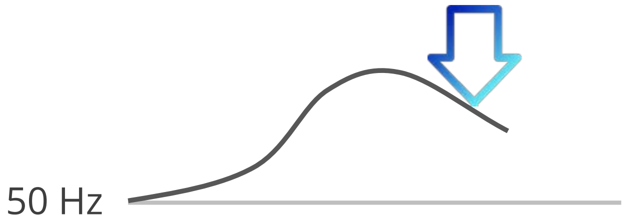
AEMO Transfer limit advice – South Australia System Strength September 2018
https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Congestion-Information/2018/Transfer-Limit-Advice---South-Australian-System-Strength.pdf

Frequency control ancillary services (FCAS)

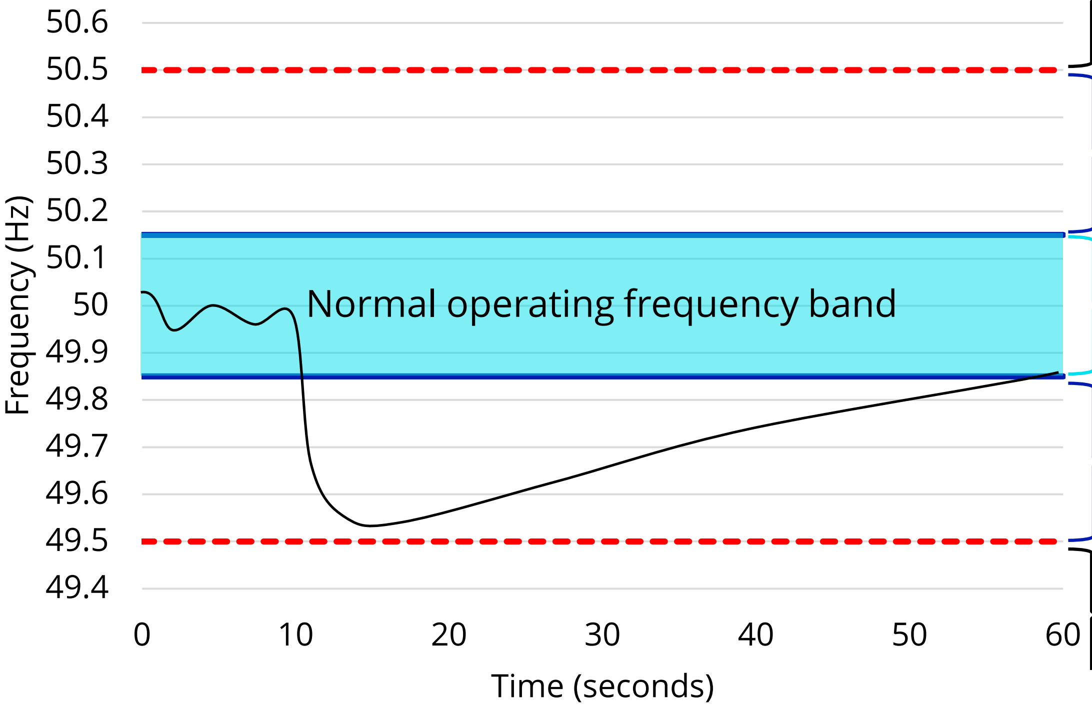
Raise services help to raise the frequency:
- Used if the frequency drops below 50Hz
- Generators lift output
- Loads reduce consumption

Lower services help to lower the frequency:
- Used if the frequency rises above 50Hz
- Generators reduce output
- Loads increase consumption





FCAS: Regulation and Contingency



Emergency frequency control schemes

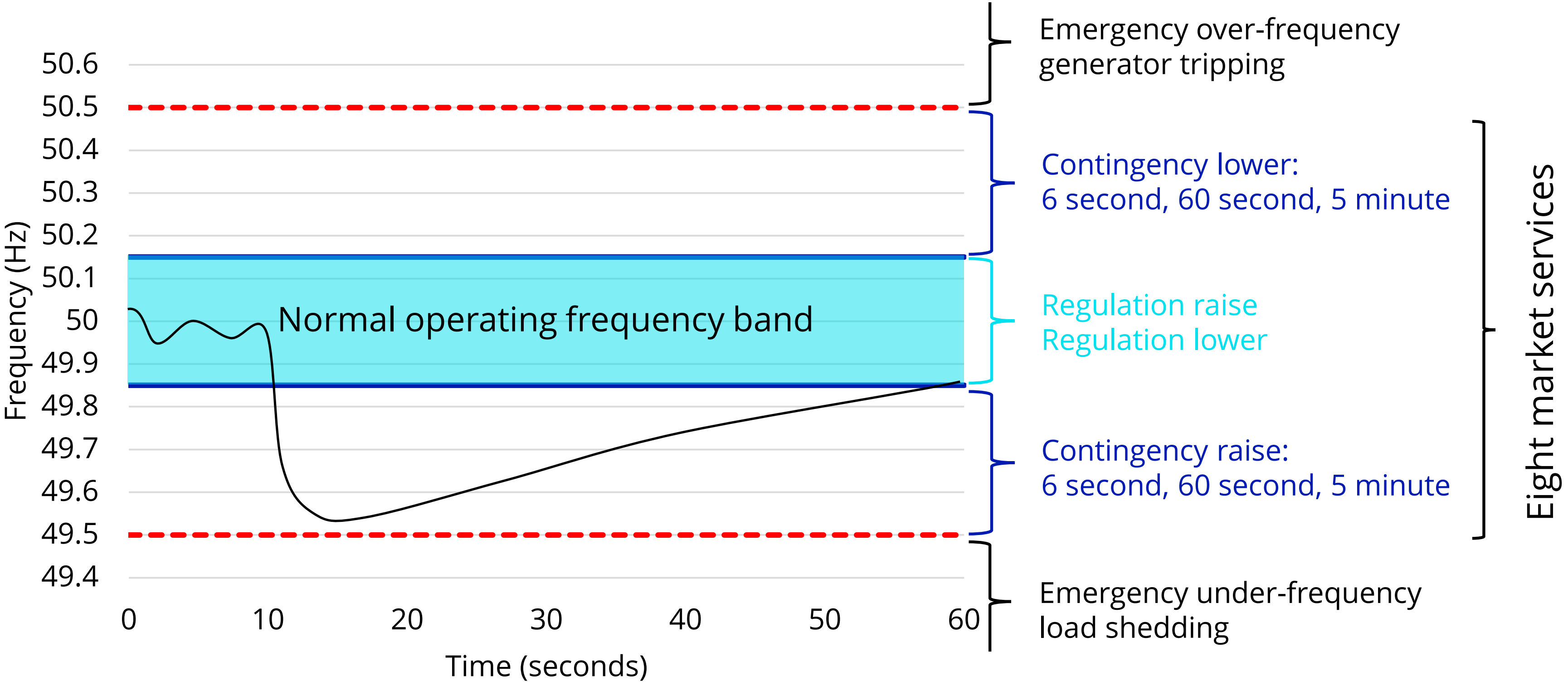
Contingency services help to control the frequency within the Contingency Operating Band

Regulation services help to control the frequency within the Normal Operating Frequency Band

Contingency services help to control the frequency within the Contingency Operating Band

Emergency frequency control schemes

FCAS: Eight market services



Market versus non-market services

Service	Source	Provision
Energy	Market	**Market participants:** - Generators - Customers - batteries
Frequency control ancillary services (FCAS)	**8 markets for:** - Regulation raise - Regulation lower - Contingency raise (6 second, 60 second, 5 minute) - Contingency lower (6 second, 60 second, 5 minute)	
System strength	Non-market	**Transmission network service providers**
Inertia	Non-market	
Fast Frequency Response	Non-market	

AGL generation fleet

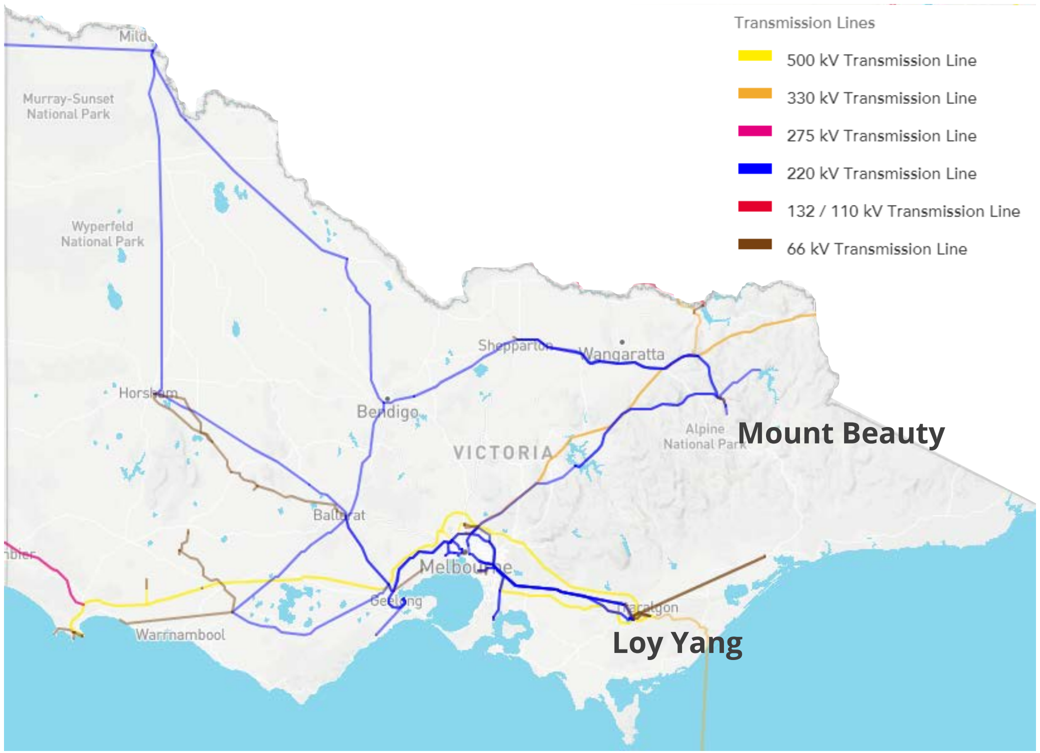
Dalrymple battery

System black discussion

August 2003 – North East America

Satellite view of the 'system black'

System black training



Source: AEMO

Conclusion

In conclusion...

1

The electricity system is a highly integrated and complex machine

2

The Australian electricity system is undergoing great transition, raising new challenges for system security

3

The industry is working hard to address these challenges and deliver a smooth transition

Contact

James Hall
General Manager, Capital Markets
Phone: +61 2 9921 2789
Mobile: +61 401 524 645
Email: jbhall@agl.com.au

Chris Kotsaris
Senior Manager, Investor Relations
Phone: +61 2 9921 2256
Mobile: +61 402 060 508
Email: ckotsaris@agl.com.au

Blathnaid Byrne
Group Treasurer
Phone: +61 2 9921 2255
Mobile: +61 424 644 947
Email: bbyrne@agl.com.au

agl.com.au

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