CIGRE ANC Seminar

"The impact of power electronics on network performance and capability"

9th November 2017 to 10th November 2017

University of Queensland – St Lucia Campus, Building 78, Room 343

In this program, the presentations are grouped into the following four topics:

- ***Topic 1 – Frequency***
- ***Topic 2 – Voltage***
- ***Topic 3 – Power Quality***
- ***Topic 4 – Power System Security and Generator Grid Connections***

PROGRAM - Day One: 9th November 2017

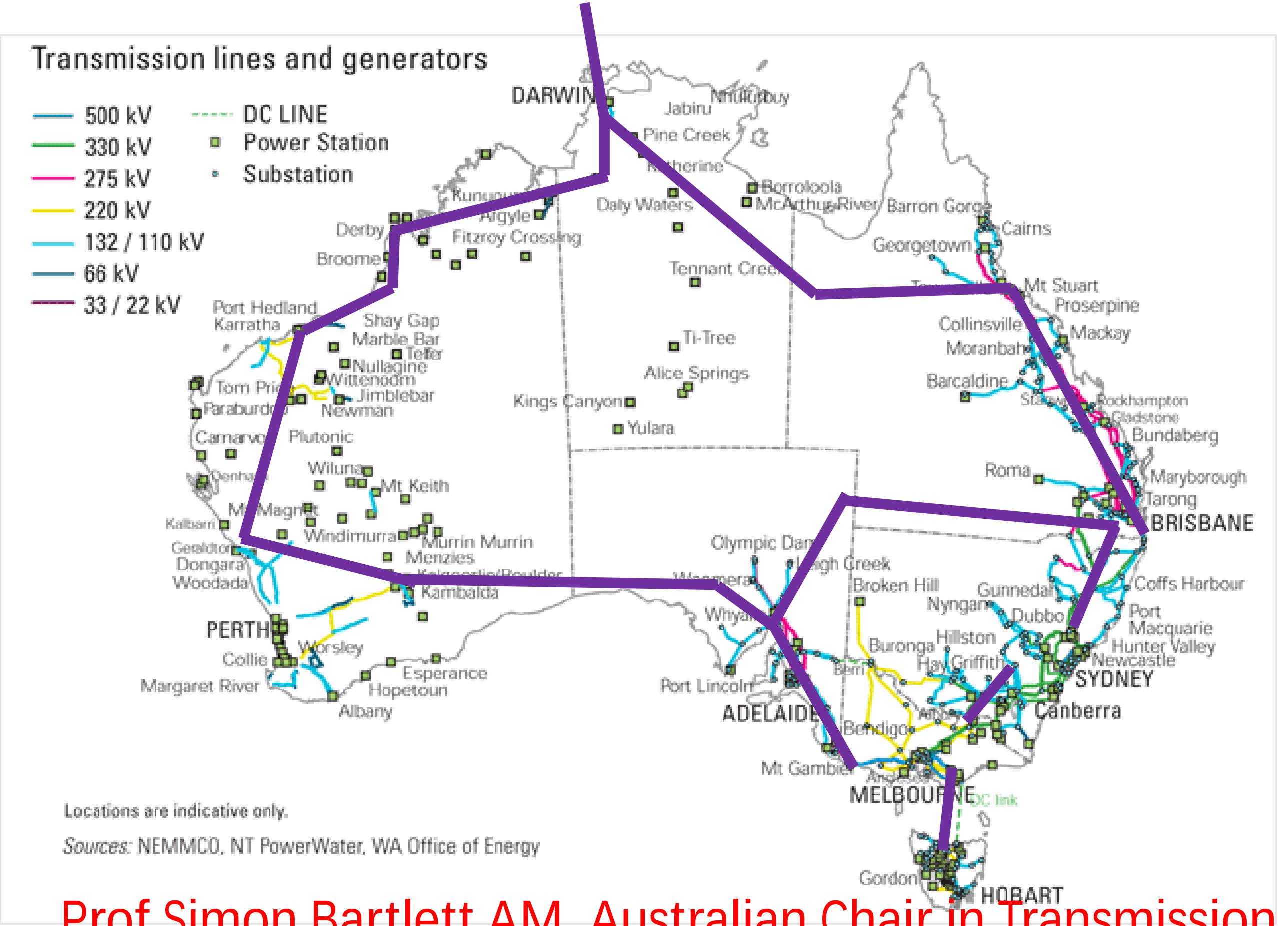
Start Time	Finish Time	Title	Presenter
9:00AM	9:30AM	Welcome and Keynote speaker	Simon Bartlett University of Queensland
Frequency			
9:30AM	10:00AM	Comparison of FFR and inertial energy.	Marian Piekutowski (Hydro Tasmania)
10:00AM	10:30AM	SVC Plus FS presentation.	Volker Hild (Siemens)
10:30AM	11:00AM	Break	
11:00AM	11:30AM	Impact of a STATCOM with the frequency stabiliser capability (400MWs) on frequency control in the Tasmanian power system.	Marian Piekutowski (Hydro Tasmania)
Voltage			
11:30AM	12:00PM	Use of STATCOMS to assist with providing network support given the change in generation patterns, technologies and the increase in renewables.	Colin Wood (ABB)
12:00PM	1:00PM	Lunch	
1:00PM	1:30PM	South Australia Blackout – September 28, 2016 D-VAR STATCOM Performance	John Wright-Smith (American Superconductor)
1:30PM	2:00PM	Implementing STATCOMS to improve voltage profile of electricity distribution network with high levels of renewables.	Yateendra Mishra (QUT)
2:00PM	2:30PM	D-VArs for wind farm connections.	John Wright-Smith (American Superconductor)
2:30PM	3:00PM	Break	
Tutorial Sessions			
3:00PM	4:00PM	Connection of Wind Farms to Weak AC Networks.	Mark Davies (TasNetworks)
4:00PM	5:00PM	Power system operation with high penetration of non-synchronous generation.	Babak Badrzadeh (AEMO)
5:30PM	8:30PM	Evening dinner/networking event - at UQ	

“The impact of power electronics on network performance and capability”

PROGRAM - Day Two: 10th November 2017

Start Time	Finish Time	Title	Presenter
Power Quality			
9:00AM	9:30AM	Modular multilevel converters: The key power electronics technology for high power network applications.	Georgios Konstantinou (UNSW)
9:30AM	10:00AM	Harmonic resonance issues related to the installation of new SVC Plus unit in Queensland – observations and applied mitigations	Rizah Memisevic (Powerlink)
10:00AM	10:30AM	*Harmonic allocation issues for renewable generation connected to sub-transmission systems*	Vic Gosbell (UOW) and Chandana Herath (Essential Energy)
10:30AM	11:00AM	Break	
11:00AM	11:30AM	The impact on network harmonics following the transition from DC to AC locomotives in one area of Queensland – Analysis and test results that justified disconnection of harmonic filters.	Igor Perin (Aurizon)
Power System Security – Grid Connections			
11:30AM	12:00PM	Impact of non-synchronous generation on the operation of protection relays.	Babak Badrzadeh (AEMO)
12:00PM	1:00PM	Lunch	
1:00PM	1:30PM	Managing ‘system strength’ in Tasmania. How fault levels and inertia are currently managed in real time and the impacts of recent Rule changes.	Andrew Halley (TasNetworks)
1:30PM	2:00PM	The role of VSC HVDC systems in connecting renewable energy projects	Les Brand (Amplitude Consultants) / Nalin Pahalawaththa (TransGrid)
2:00PM	2:30PM	National Electricity Market (NEM) impacts of recent power station closures – The potential role of capacity markets going forward.	Dr Robert Barr (Electric Power Consulting)
2:30PM	3:00PM	Break	
Panel Discussion and Closing			
3:00PM	4:30PM	**Panel Topic:** “How must the Australian power system evolve and change to prepare for a future of 100% renewable energy and storage”.	Chair: Jenny Riesz (AEMO) Panel session members (5)
4:30PM	4:45PM	Closing	C4/B4 Panel Conveners

Australian Grid of the Future



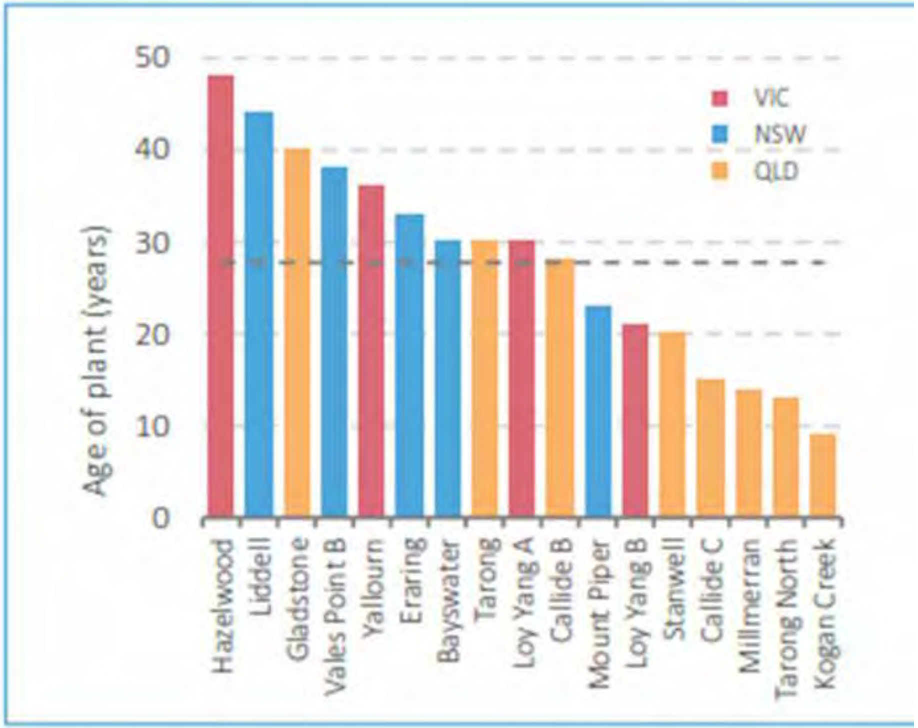
Prof Simon Bartlett AM, Australian Chair in Transmission

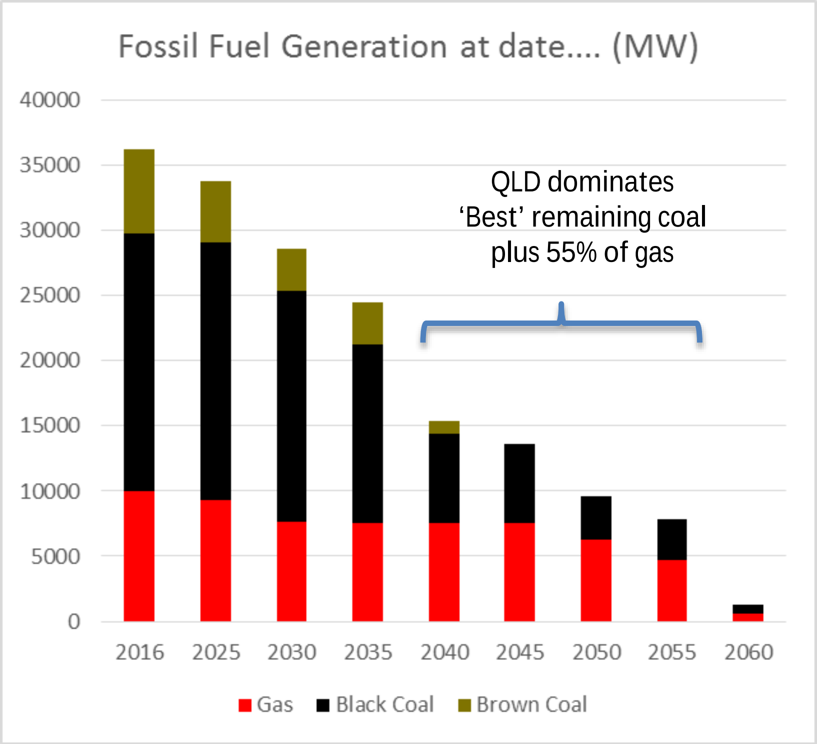
Overview of Presentation

- Reliability and Security without Coal
- Strategic Development of the National Power System
- Mesh the NEM + pumped hydro + best use of coal/gas
- Queensland’s undeveloped hydro pumped storage sites
- Global interconnections using HCDC VSC technology
- Visions for Australia’s new interconnectors

Security and Reliability without Coal ?

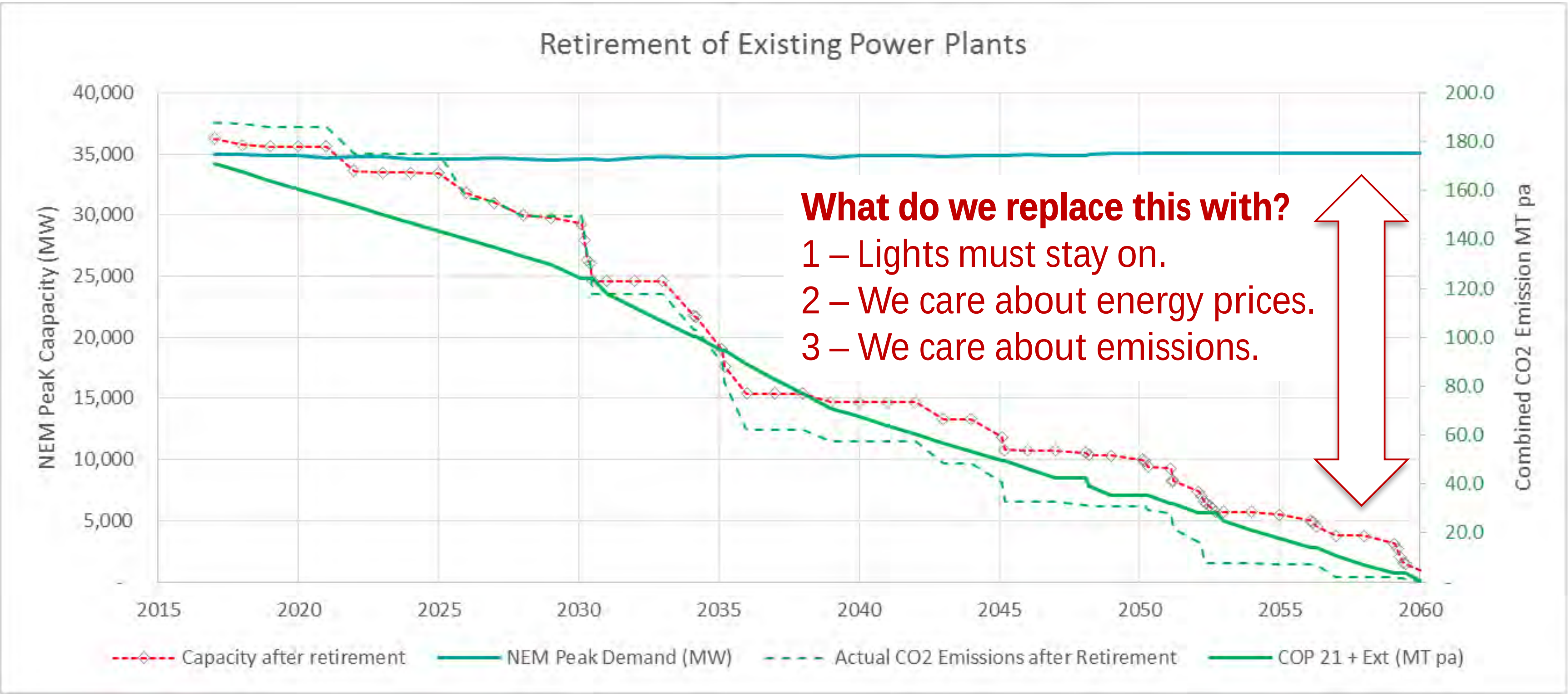
We have a mixed coal-fired fleet – everything retires eventually





Security and Reliability without Coal ?

Retirement – reducing NEM emissions but … what about the lights ?



Security and Reliability without Coal ?

So ...

Is there a clever combination of replacement options ?

Security and Affordability without Coal ?

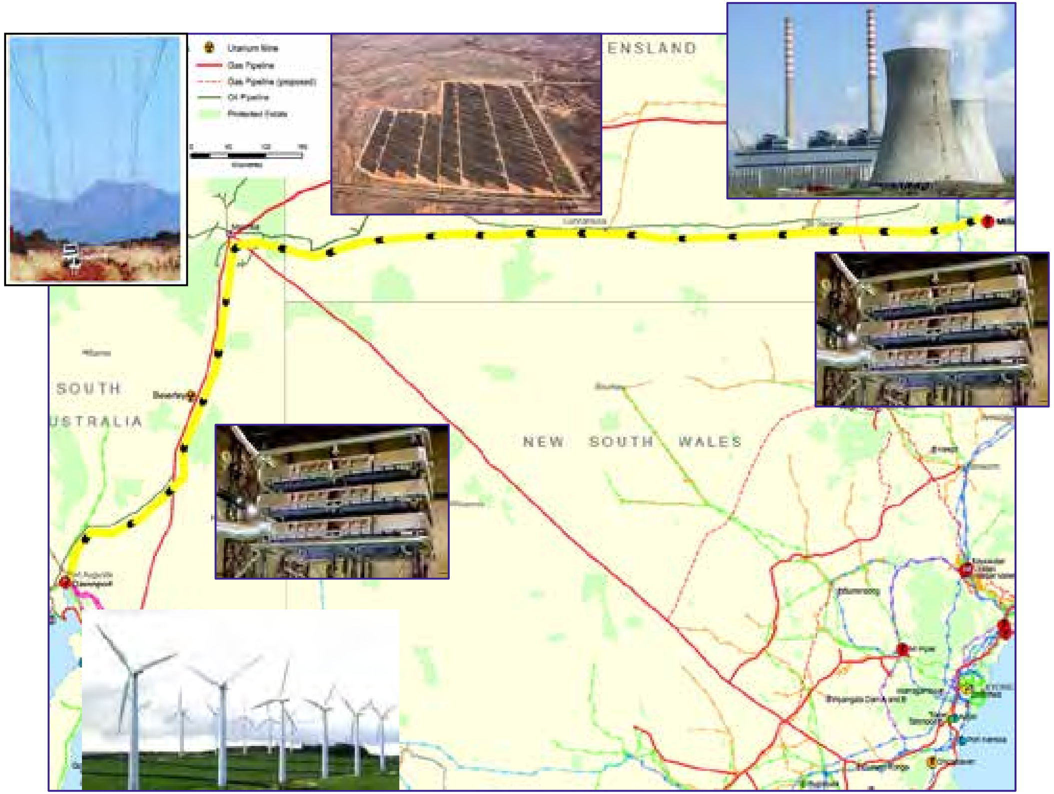
Hydro & pumped storage: "dancing partner" for wind and solar

- **Reliable and Secure**
  - ü *Stable*: high synchronous inertia and fast frequency response
  - ü *Flexible*: dispatch and load following capability
  - ü *Back-up Storage*: large scale for excess solar
- **Affordable**
  - ü *Cheap*: 1/10th the cost of battery storage (in $/MWh)
  - ü *Long Lasting*: 10 x the life of batteries
  - ü *Low Cost*: lowest cost delivery of new ancillary services
- **Clean – Low CO_2**
  - ü *But not zero impact*

ARC-Mesh – the key enabler

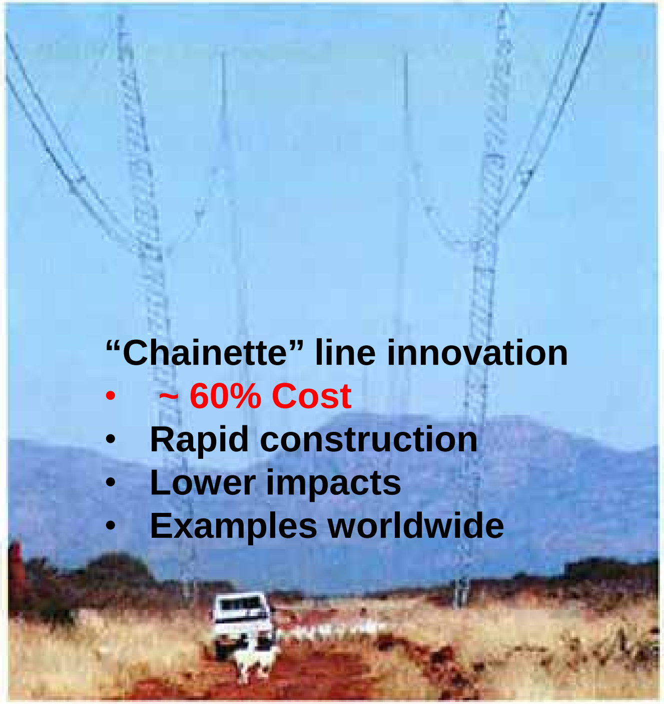
(*Australian Renewable Connector - Meshing the NEM*)

feasibility study underway by ARC-Mesh



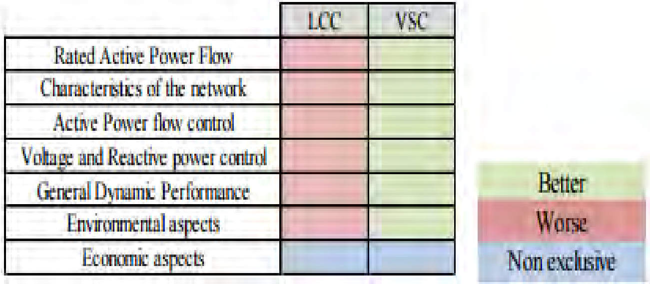
- ü *Interconnector*: privately funded
- ü *Modern Techology*: HVDC VSC
- ü *Low Cost*: innovative line design
- ü *Price Stability*: in SA and Qld
- ü *Security*: for SA power system
- ü *Low environmental impact*: (not zero)
- ü *Quick*: short construction time

ARCMesh



"Chainette" line innovation

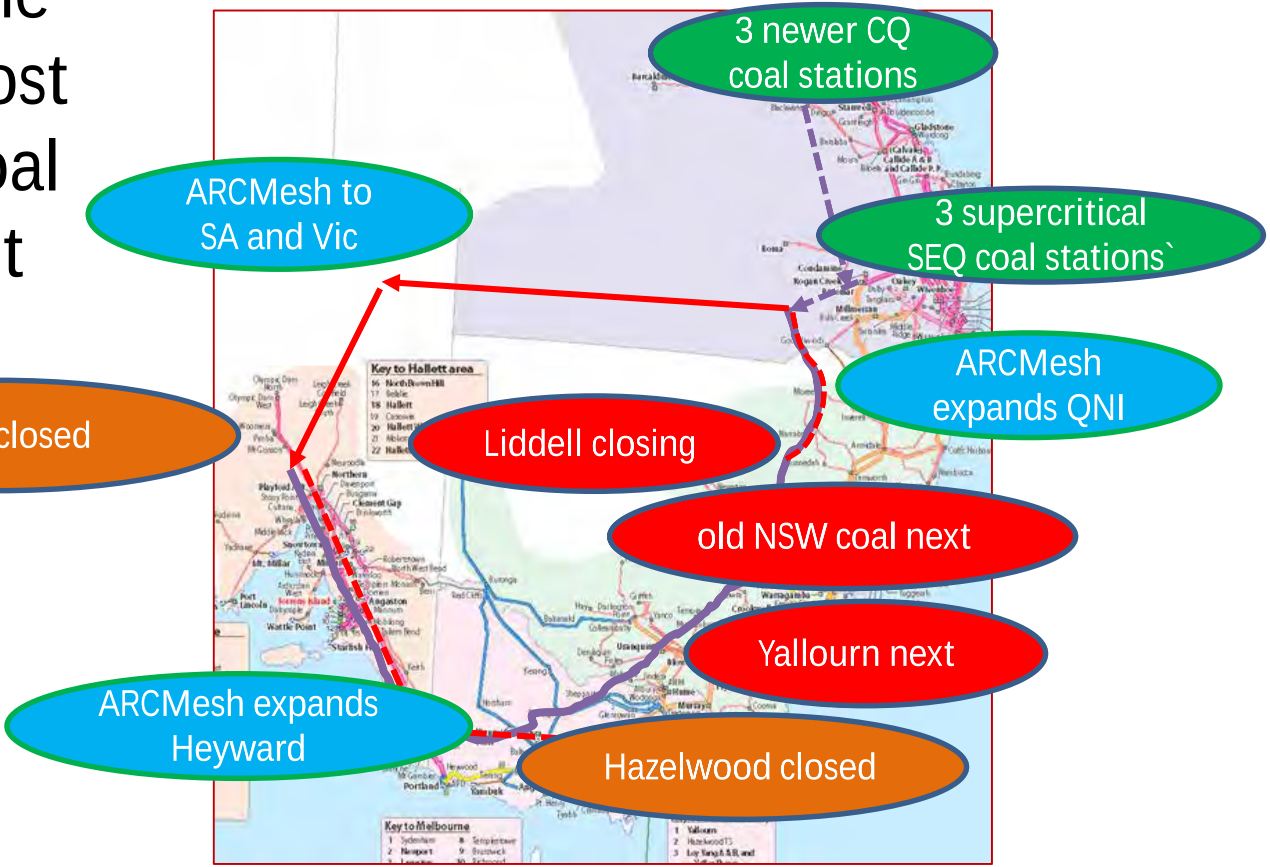
- ~ 60% Cost
- Rapid construction
- Lower impacts
- Examples worldwide



	Direct route	Strategic route
Transmission Lines	$ 815m	$800m
Easements	$ 85m	$ 80m
Converters stations	$500m	$500m
HVAC connection costs	$20m	$20m
TOTAL COST	$1,420m	$1,400m

Affordability as Australia transitions from coal?

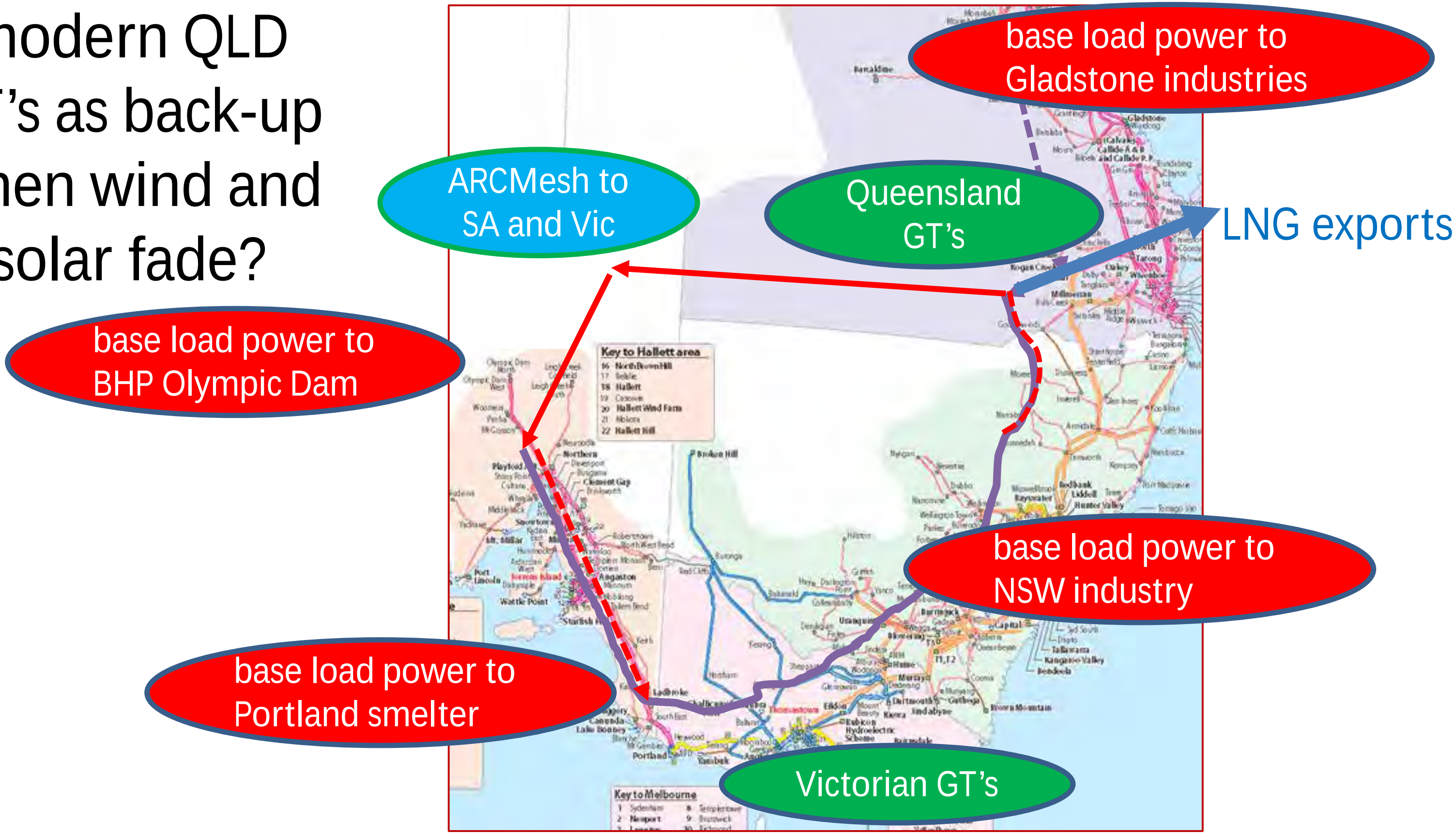
QLD has the newest, most efficient coal fired fleet



Affordability and Security without Coal ?

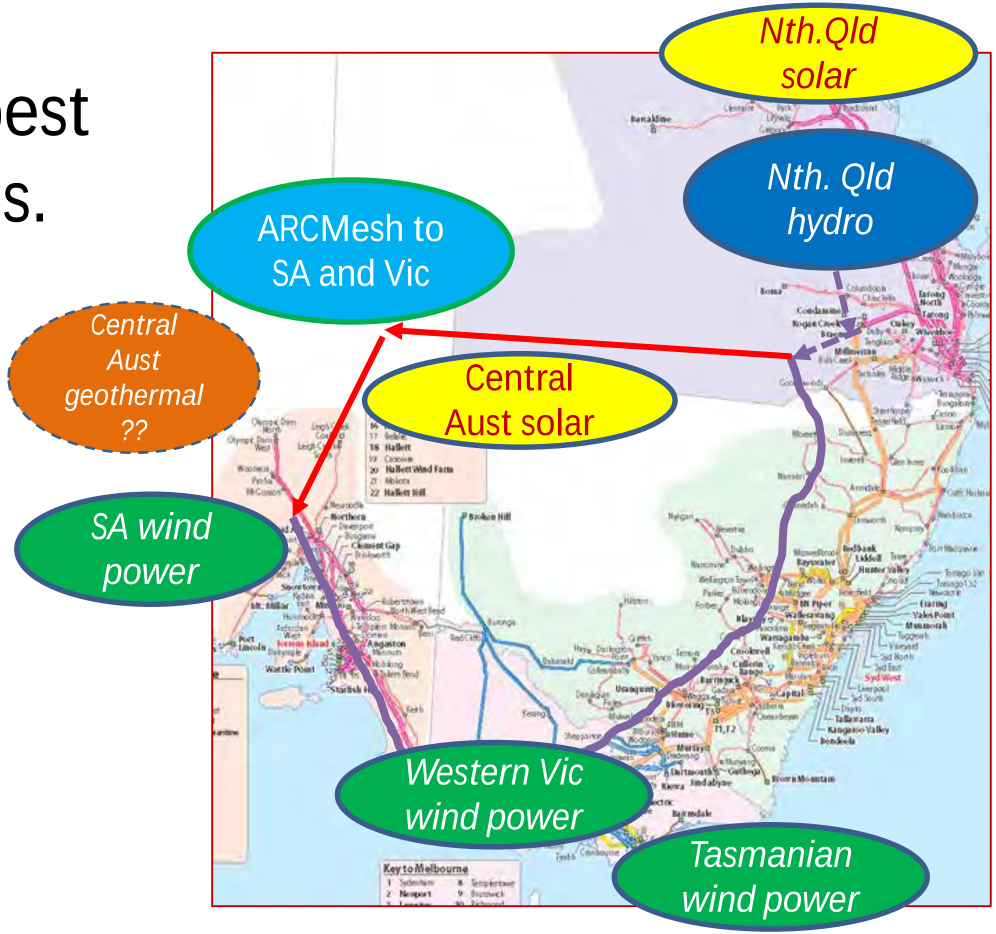
AND ...

modern QLD GT's as back-up when wind and solar fade?



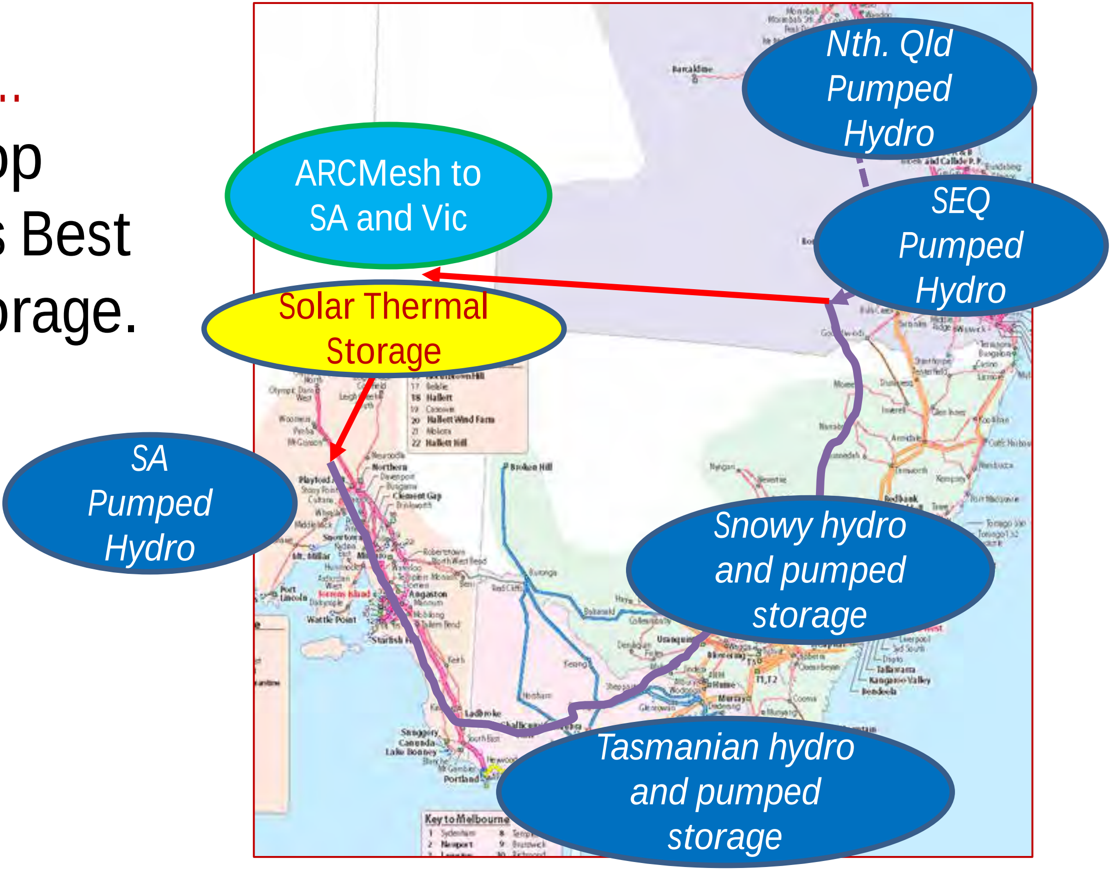
AND ... Sustainability and Affordability without Coal ?

develop Australia's best renewables.



Security, affordability and sustainability without Coal ?

AND ...
Develop Australia's Best Energy Storage.



Security, Affordability and Sustainability without Coal ?

A Smart Combination for Replacements ? ... It's an 'AND' not an 'OR' solution

- Newest, most efficient coal in fleet to ~2050 (Queensland)

plus

- Best use of modern flexible gas (mostly in Queensland)

plus

- *ARC Mesh – turn the NEM spine into a proper grid ... the key enabler*

plus

- Develop best renewables

plus

- Develop best energy storage (hydro pumped storage)

Energy Storage Needs

- Astralia will need lots of energy storage in a 50% renewables scenario to
  - avoid spilling excess solar PV and windpower energy (especially NQ)
  - cover longer duration lulls in wind or solar activity

- Hydro pumped storage – low-cost, large storage, long life, synchronous generation and inertia, flexible, proven

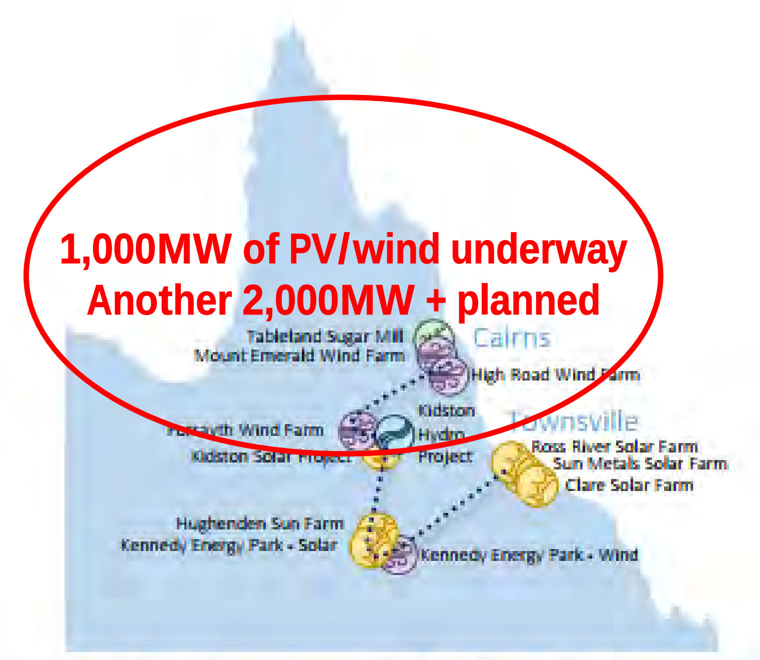
- Queensland's energy storage needs
  - ~ 2,000MW storage capacity
  - with 10 to 20 hours energy storage
  - located in NQ and SEQ regions

Qld Govt NQ Energy Plan

- NQ peak load only 1,100MW
- already ~200MW of hydro & 600MW gas/oil
- >1,000MW of NQ renewables underway
- NQ self sufficient when renewables run

- NQ hub to attract another 2,000MW?
- NQ-CQ-SQ transmission grid long and weak
- CQ has 4,600MW coal fired generation

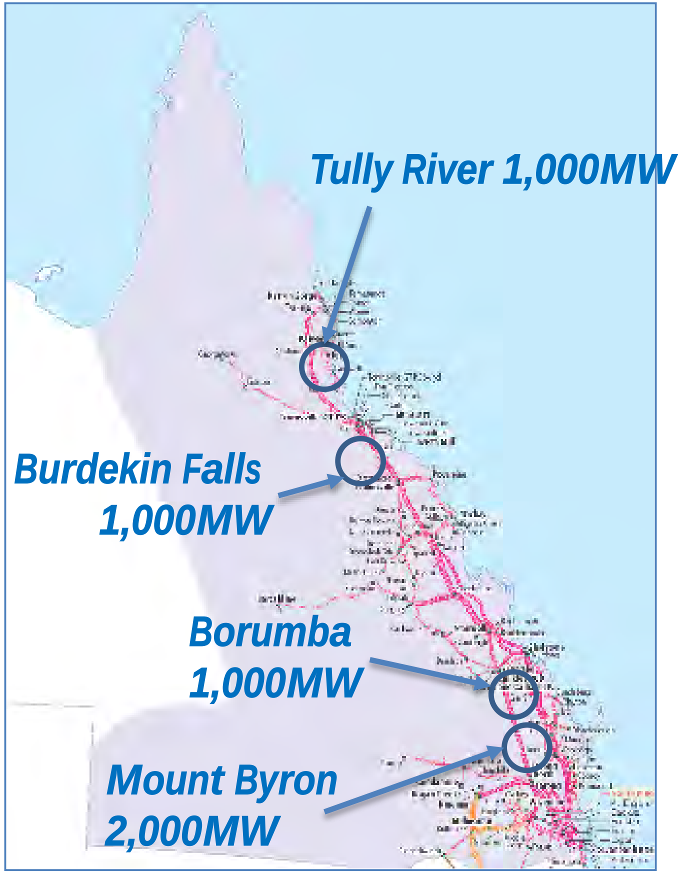
need ~1,000MW of pumped storage in NQ



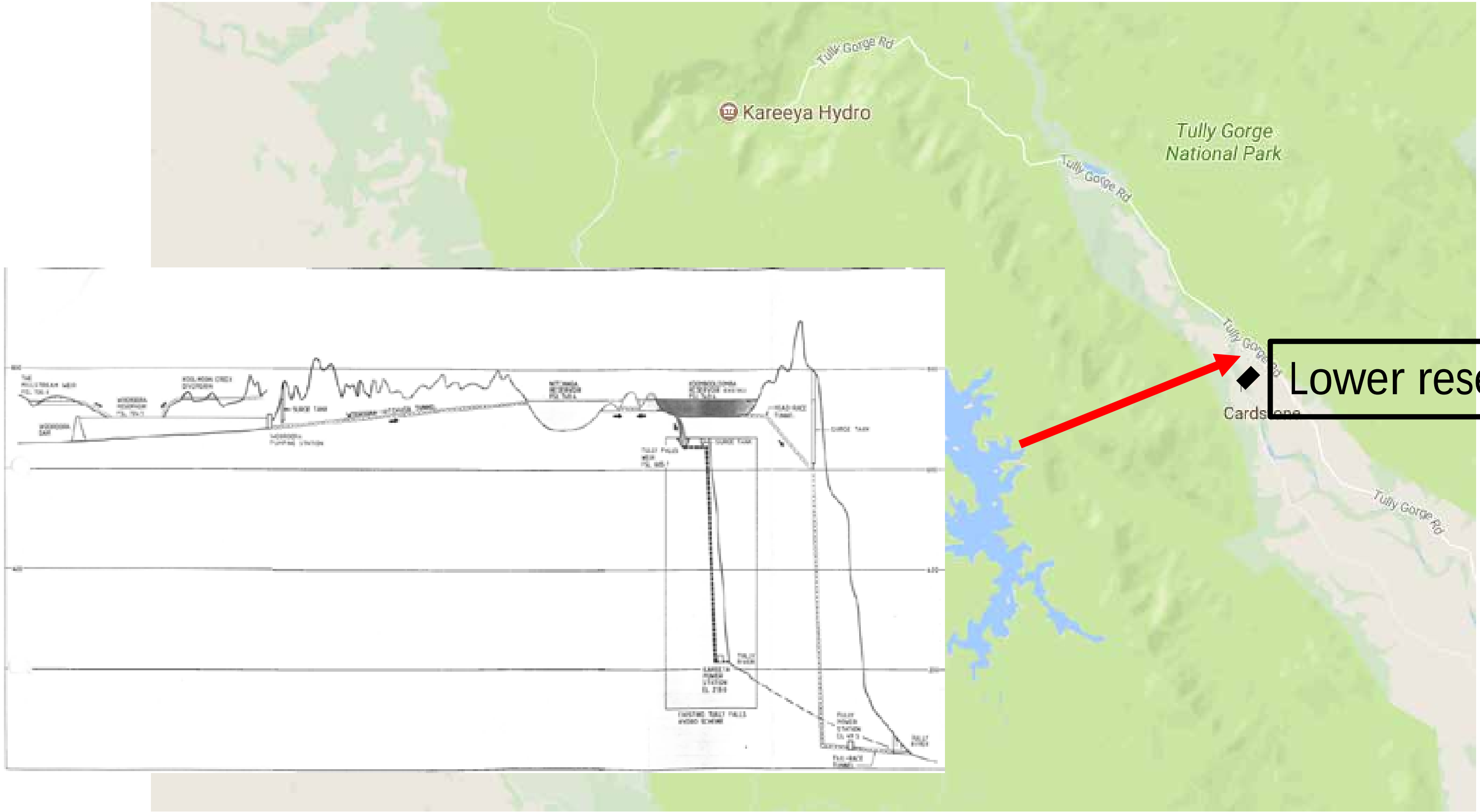
Indicative transmission path in North Queensland

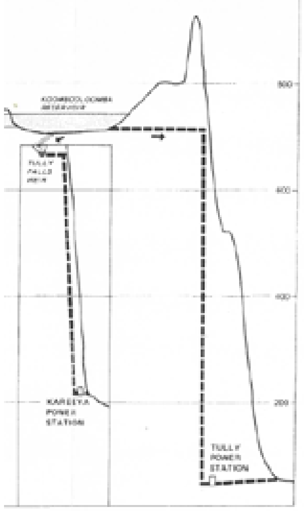
Where are Queensland's pumped storage sites?

- ü *Rigorous screening:* by SECQ 1980's
- ü *Large capacity:* energy storage
- ü *Low cost, high response*: high hydraulic head
- ü *Reserved sites*: for future development
- ü *Low Impact*: (not zero)
- ü *Existing dams:* or off-stream reservoirs
- ü *Infrastructure*: close by



Tully Millstream pumped storage scheme

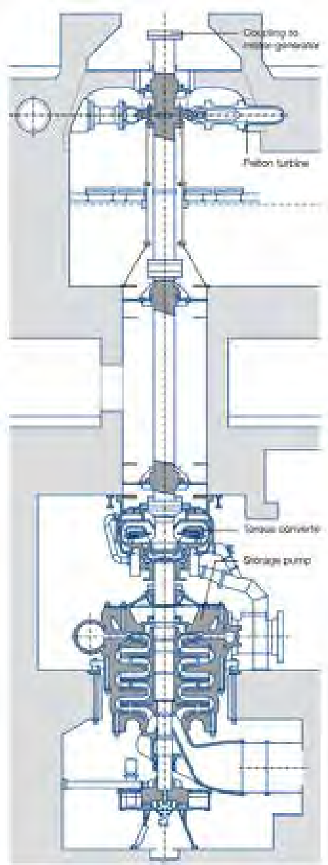


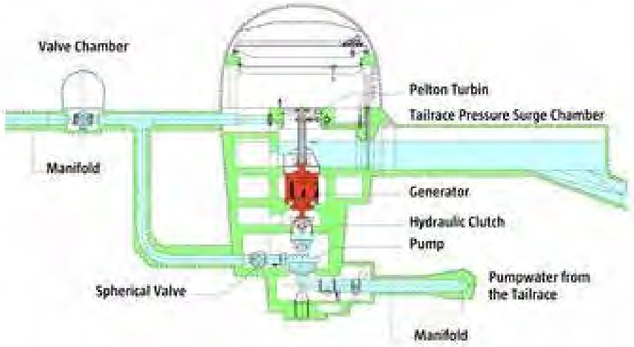


Lower resevoir

Designed for flexibility and rapid response

Course of the pressure water tunnel at the Kops II pumped storage power station (Fig.: Vorarlberger Illwerke)

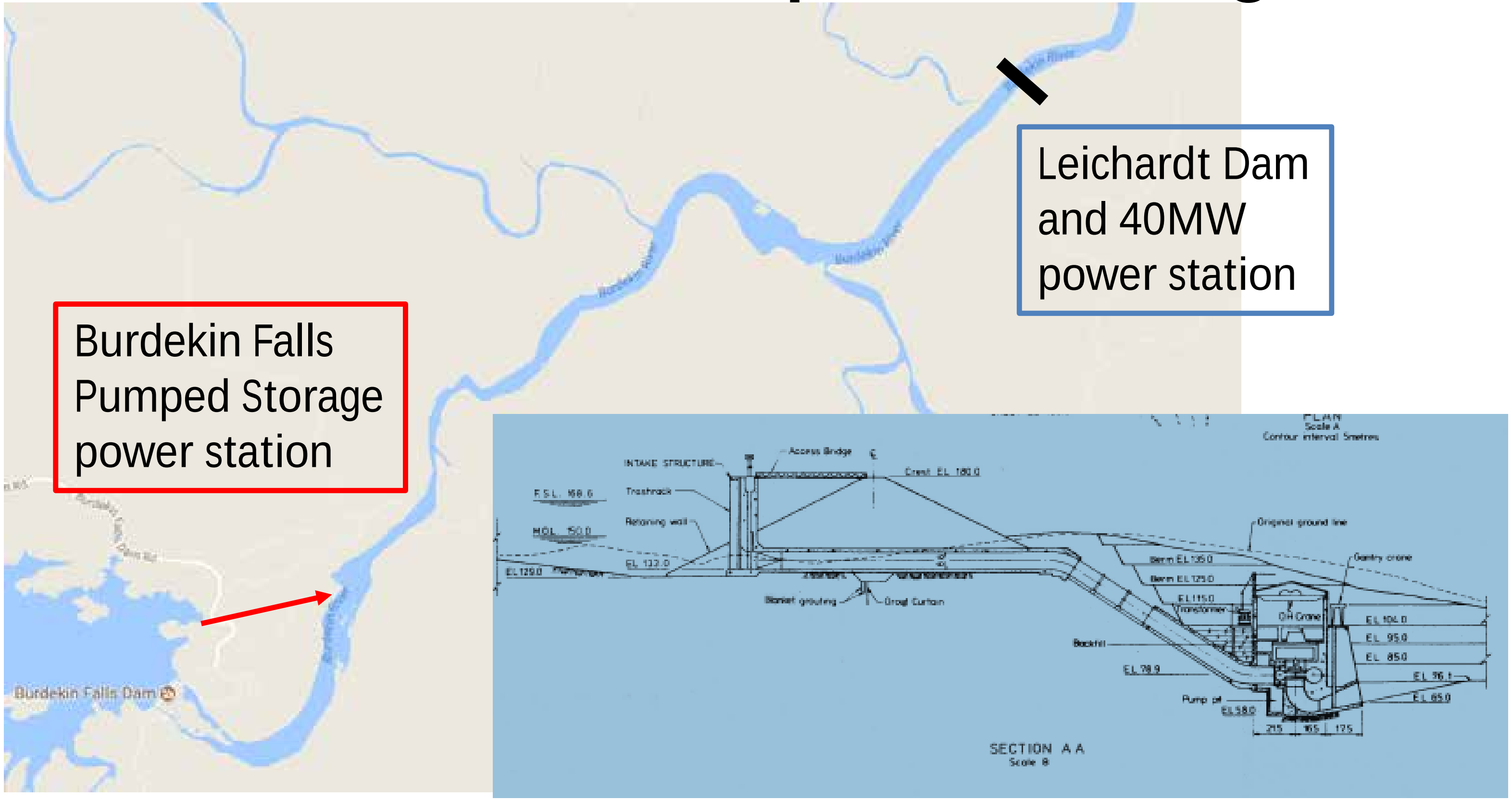


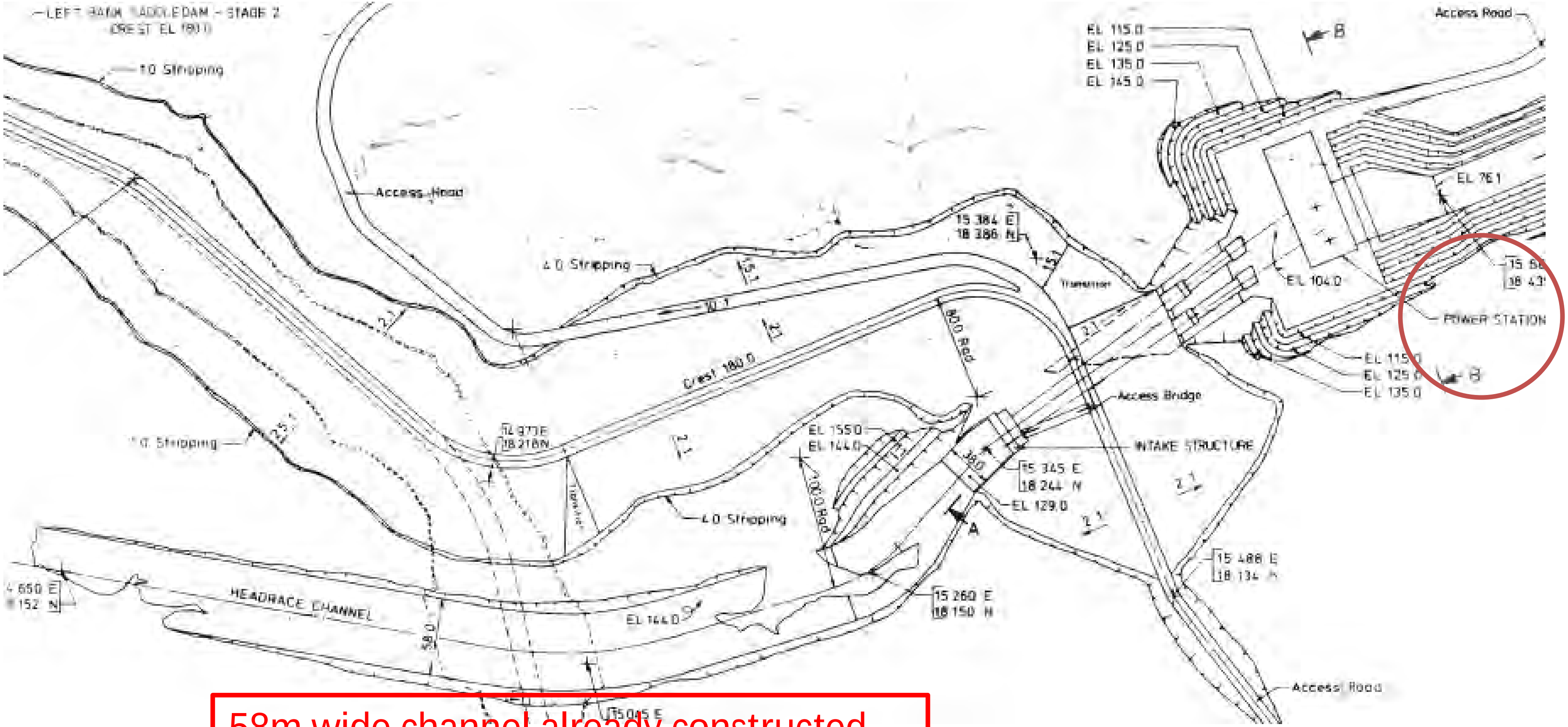


Tully River Options and Costs

Option	Capacity (MW)	Energy (Gwh pa)	$million
Tully Millstream (T-M)	600MW hydro	1,000 Gwh pa	$1,000m
Tully Cardwell	600MW p/s	600 Gwh pa	$850m
Tully Cardwell	1,000MW p/s	625 Gwh pa	$1,100m
Tully Millstream	1,000MW p/s	1,050 Gwh pa	$1,300m

Burdekin Falls Pumped Storage



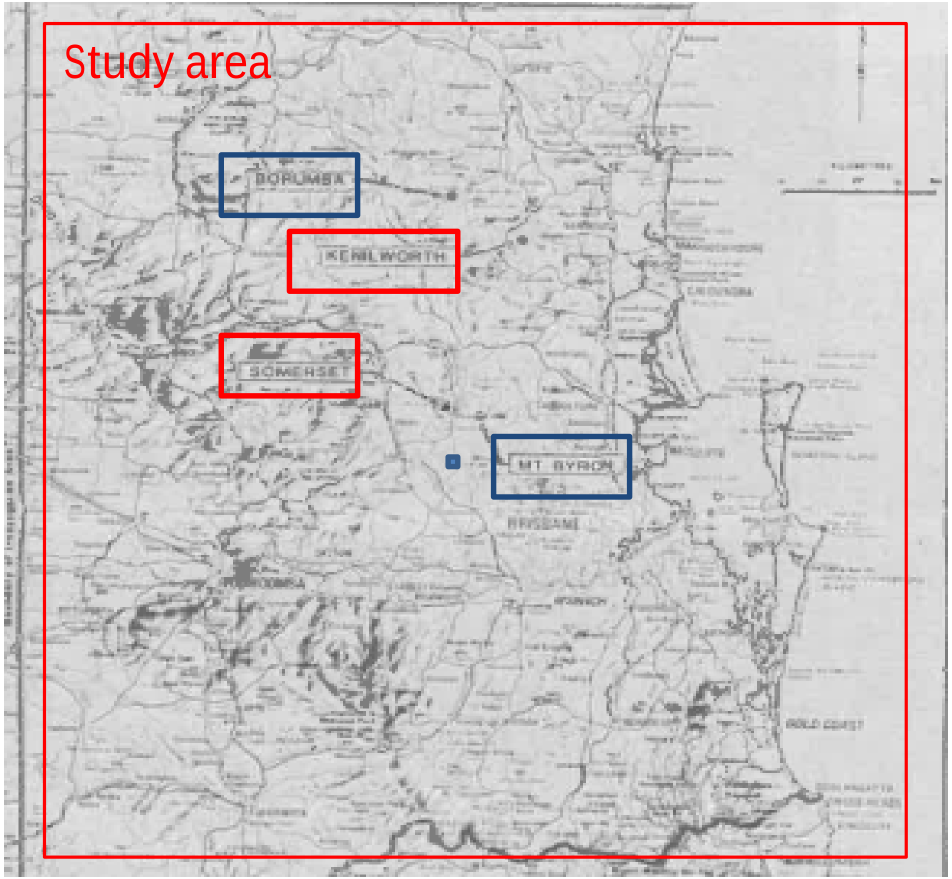


58m wide channel already constructed for 1,500MW power station

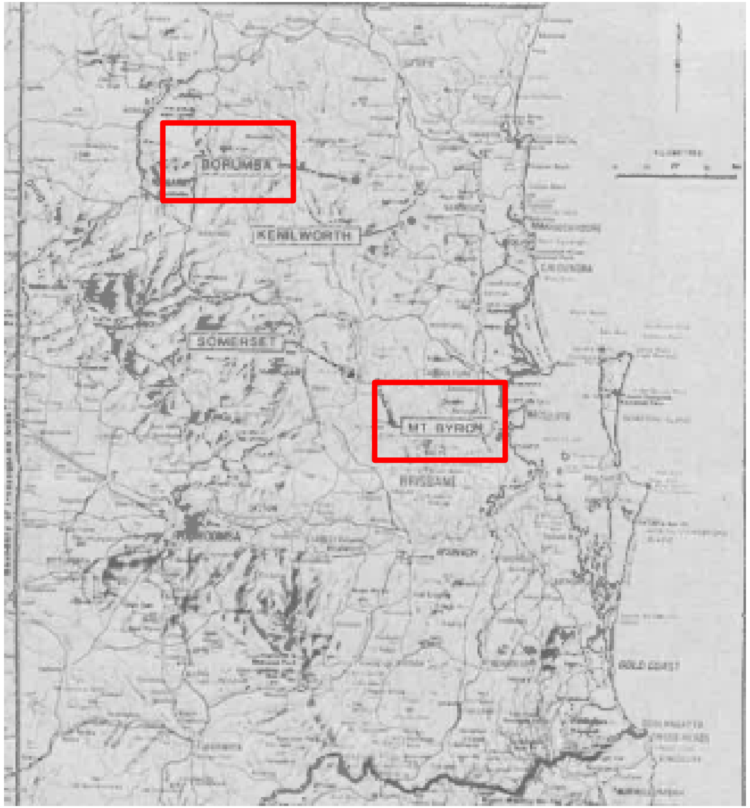
Burdekin Falls Options and Costs

Option	Capacity (MW)	Energy (Gwh pa)	$million
Burdekin Falls hydro	500MW hydro	830 Gwh pa	$800m
Burdekin Falls p/s	500MW p/s	1,200 Gwh pa	$1,100m
Burdekin Falls p/s	1,000MW p/s	1,200 Gwh pa	$1,400m
Burdekin Falls p/s	1,500MW p/s	1,200 Gwh pa	$1,700m

South east Queensland pumped storage investigation 1983-85



South-east Qld Pumped Storage Investigation



Those studies concluded that only four sites had sufficient potential to justify more detailed investigations. Those sites (shown in Figure 1) were:

- Mt Byron - east of Somerset Dam
- Somerset - Somerset Dam
- Borumba - Borumba Dam
- Kenilworth - south west of Kenilworth

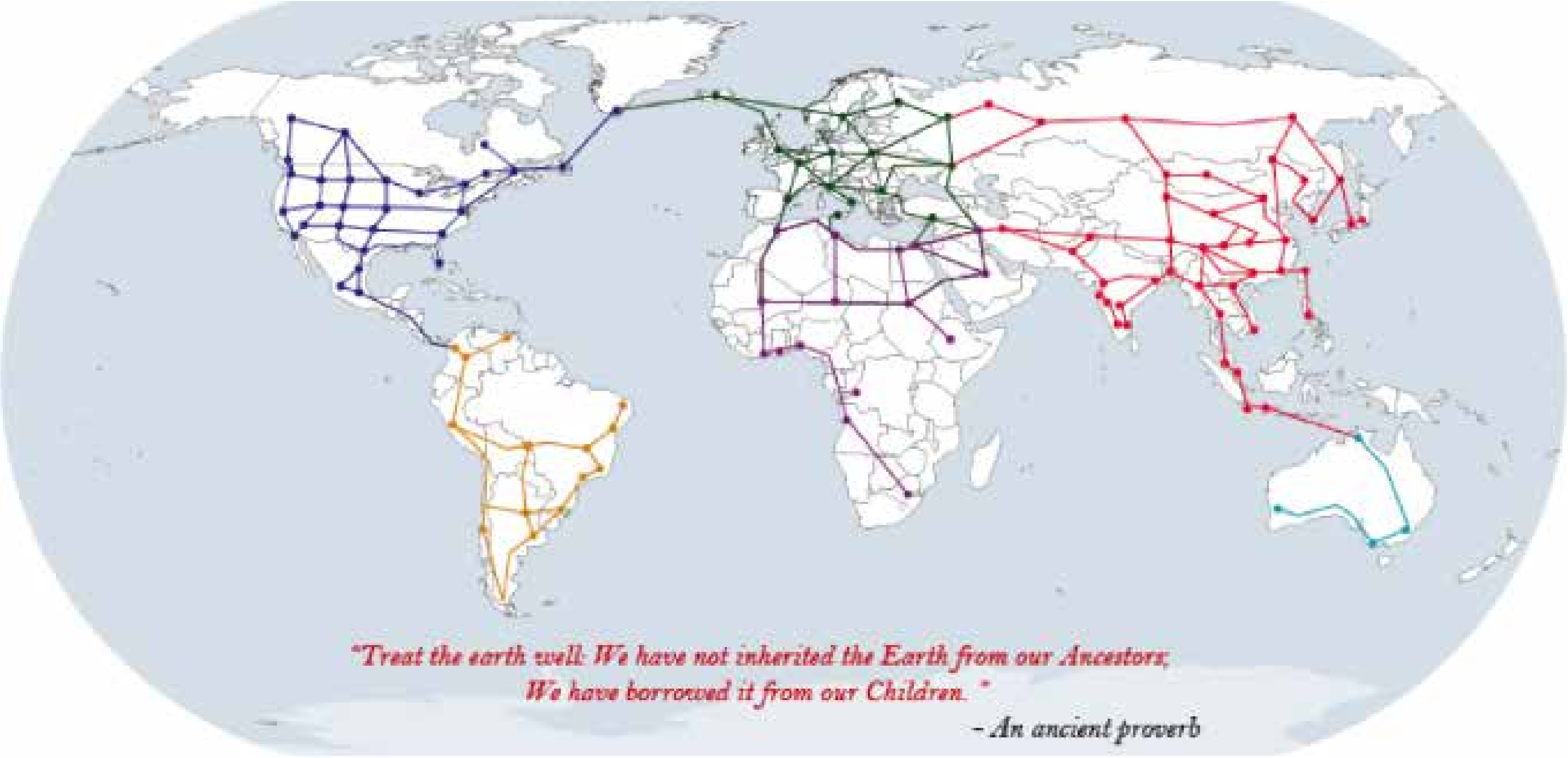
As a result of the programme of investigations, the number of sites which it is considered necessary to reserve at this time is two. These are Mt Byron and Borumba.

These two sites are preferred because of:

- More suitable geology
- Adequate water supply is available for the schemes to be self sufficient in water
- Minimal regional environmental impacts
- Lower overall costs of development compared to other schemes
- Large energy storage potential

Sites reserved	Capacity	Energy
Borumba	1,000 MW	30,000 GWh
Mount Byron	2,000 MW	50,000 GWh

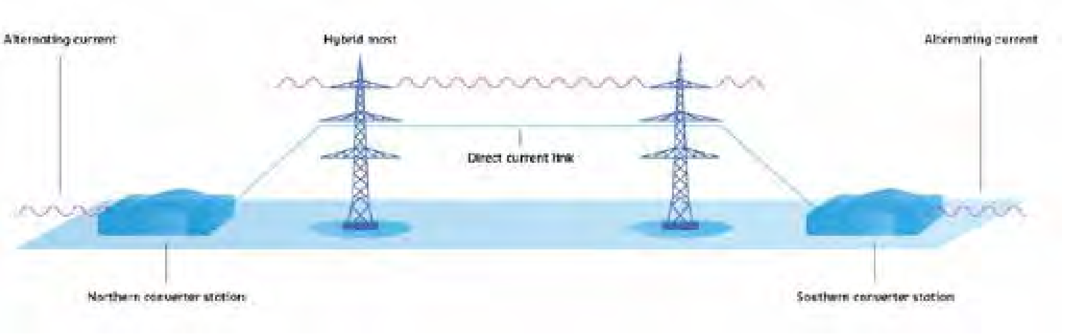
Global HVDC Interconnection

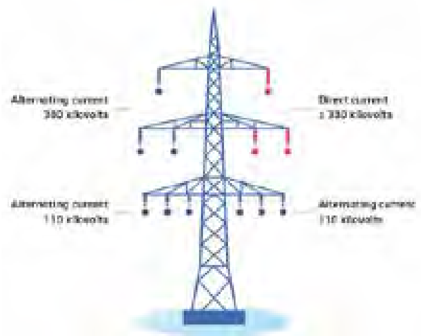


European HVDC VSC developments

- Europe most advanced with renewables integration and HVDC interconnectors
- EU grid code already mandates that new HVDC VSC performs as a virtual synchronous machine
- will become international standard
- CIGRE B4 Task Force investigating

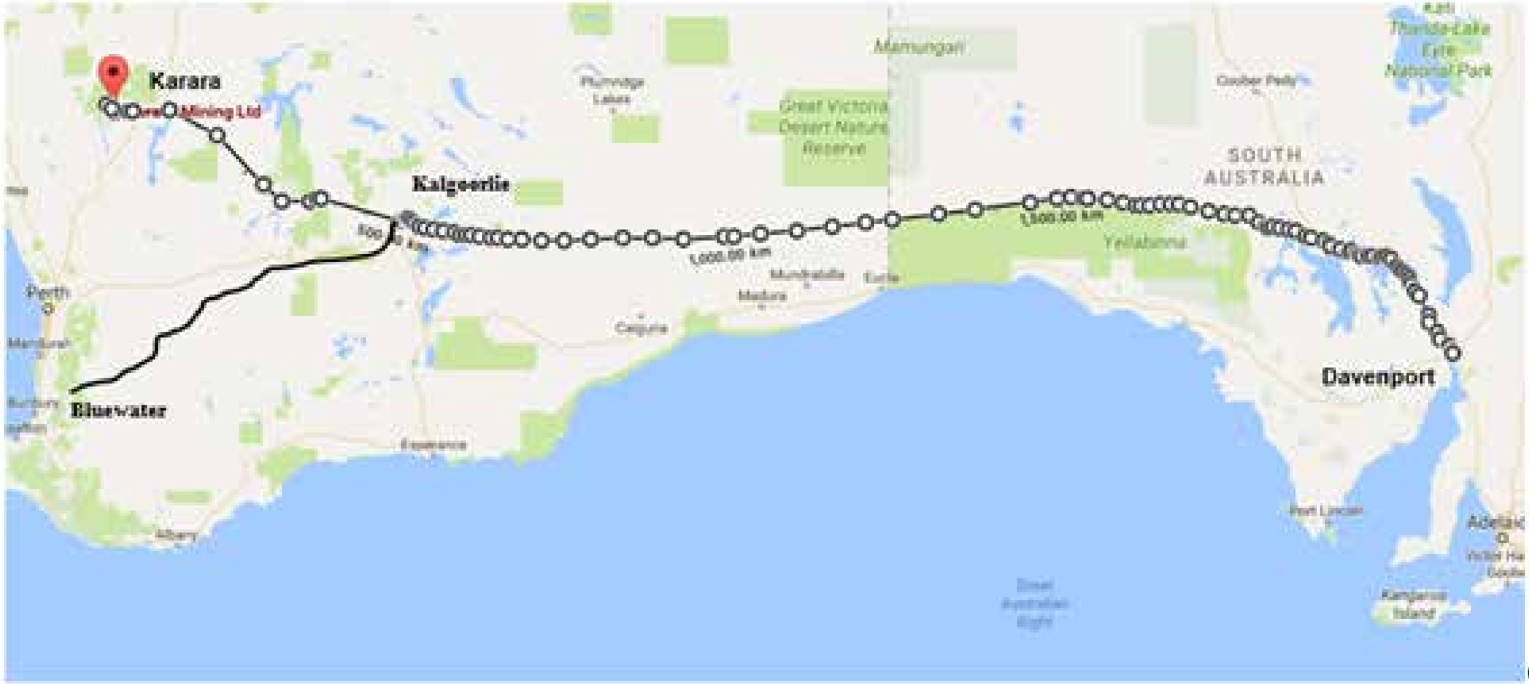
UltraNet, Germany





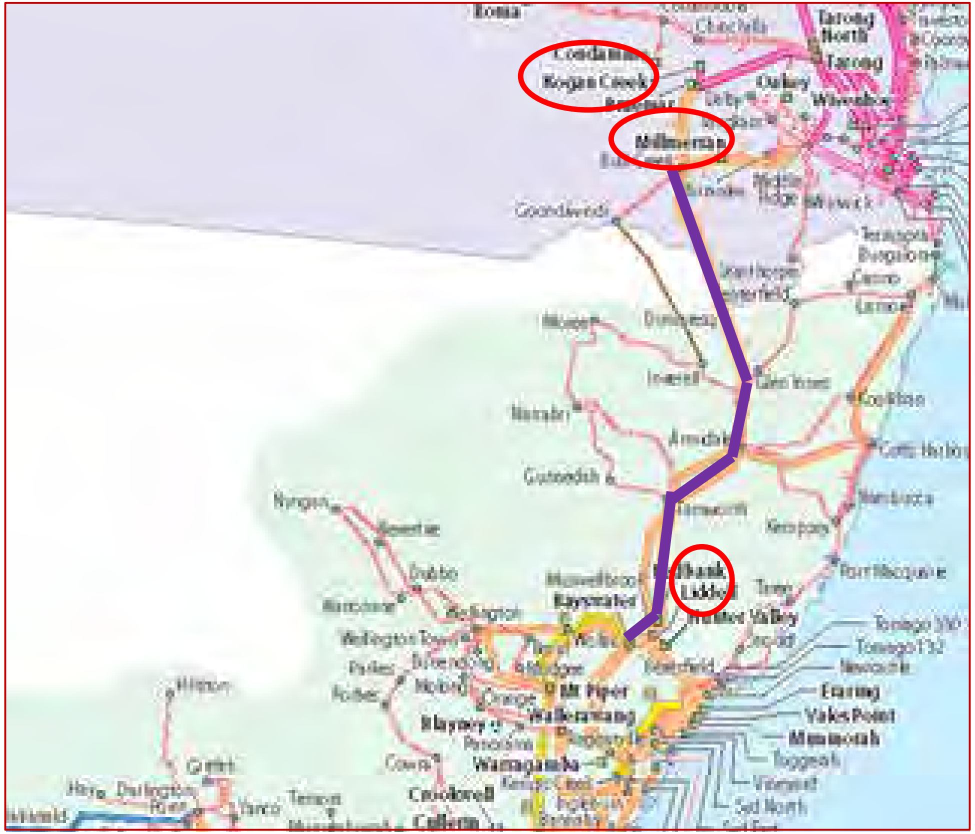
- HVDC VSC on existing line
- Stabilise power system
- Only replace insulators
- And install converters
- Similar HVDC voltage
- Increases limits of AC system

WA – SA Interconnector Concept



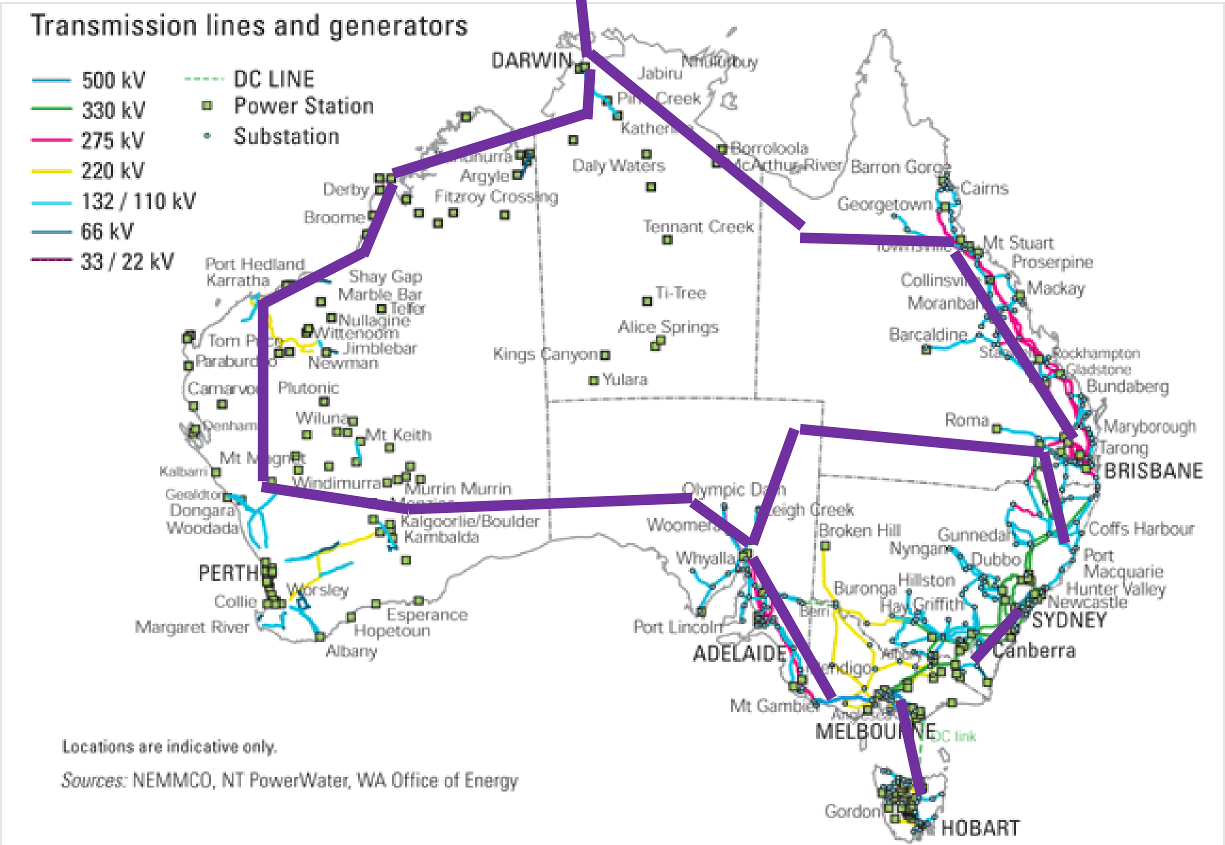
NQ – SQ HVDC VSC Overbuild

Qld – NSW HVDC VSC Overbuild



SA – Vic – Tas HVDC VSC Overlay

Trans- Australian Interconnections?



Conclusions

- Australia’s future power sytems will need:
  - stronger interconnection using HVDC VSC technology
  - with overbuilds of existing grid in developed areas
  - and Meshing the NEM – ARCMesh
  - need large scale energy storage , being hydroelectric pumped storage
- Queensland has already set aside best 4, high quality pumped storage sites for ~5,000MW and will need to develop several sites by 2030
- Progressively develop trans-Australian HVDC grid using low cost HVDC
- Eventually supplying Indonesia and global interconnection

Hydro Tasmania

CIGRE ANC Seminar

The impact of power electronics on network performance and capability

Comparison of FFR and Inertial Energy

Marian Piekutowski
Hydro Tasmania
Brisbane 9-10 November 2017

Outline

- Challenges of transition to renewable energy generation
- Principles of frequency control
- Synchronous generation and inertial response
- Properties of non-synchronous generation and inverters
- What is Fast Frequency Response (FFR)
- Comparison of inertial response and FFR
- Frequency control in the future

NEM Outlook

Key Issues:

- Increasing intermittency of supply
- Reduced synchronous generation
  - Lower fault levels
  - Lower inertia
- High RoCoF
- Shortage of FCAS
- Non-dispatchable sources, forecasting challenges
- Changes to daily demand curve

- **Operational demand is flat (retail growth supplied by PV and efficiency increases).**
- Total generating capacity of 52.5GW coal 47.7%, Gas 20.7%, Hydro 15%, Wind 7%; Solar 8.2%.
- 2016/17 max demand is 34.4 GW.
- **Rooftop PV capacity to increase from 4.4 GW to 20.2 GW in 2035.**
- AEMO has applications for 22 GW of wind and solar today.
- **75% of coal fired power plant are operating beyond design life.**
- In 2016/17 85% of generation capacity is synchronous. **In 2035/36, this will reduce to 55% (retirement of 11GW)**

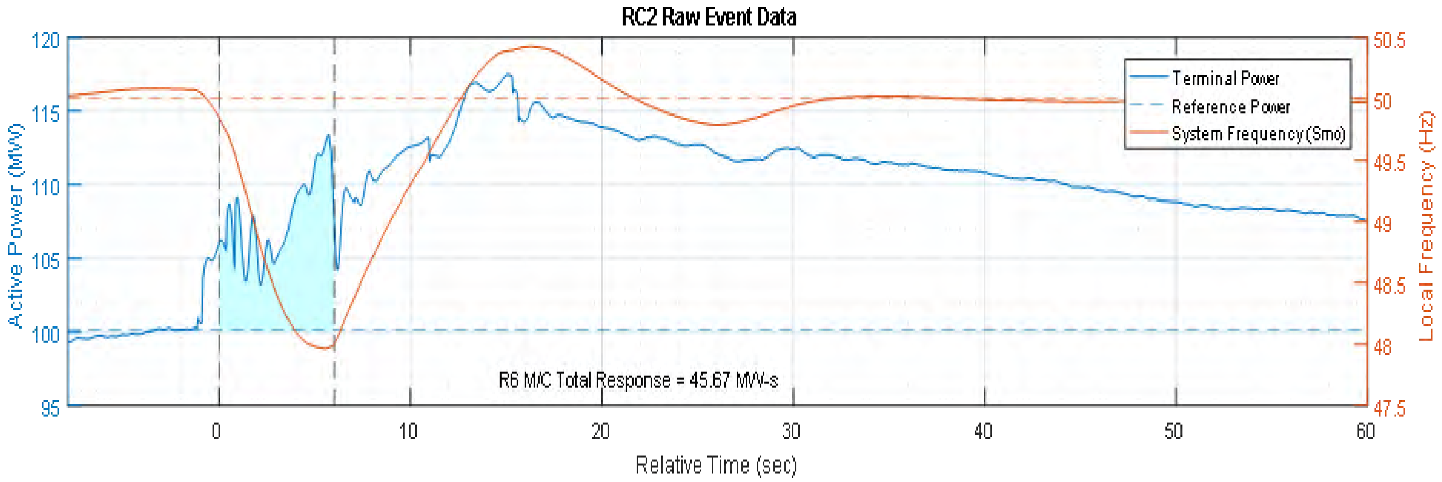
Impact of distributed generation

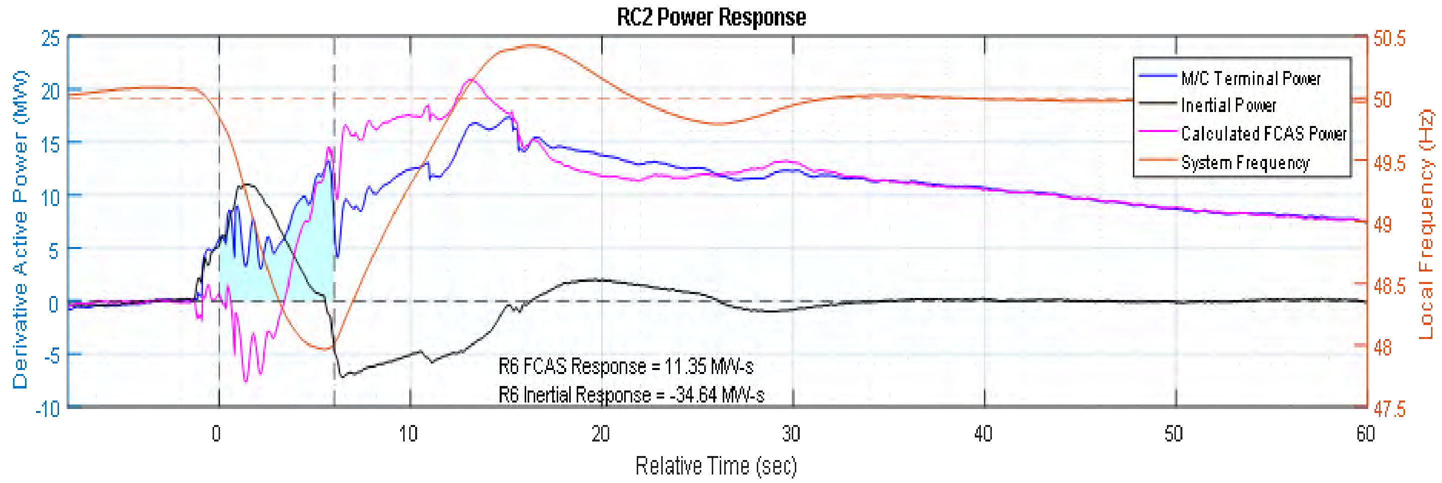
System Operability Framework, UK 2016

- With the growth of uncontrolled distributed generation, **conventional generators and interconnectors will have to provide greater system flexibility**.
- This system flexibility should also be complemented by **improved response of inverter connected technologies as well as flexible demand**.
- **Growing non-synchronous generation** contributes to delayed and reduced dynamic response and temporary withdrawal of energy affecting frequency and voltage performance.
- **A new approach to better utilise characteristics offered by power electronics is required.**
- **Provision of FFR to complement inertia.**

System Inertia

- **System inertia is a measure of the kinetic energy stored in the rotating components of machines.**
- The inherent behavior of rotating machines is to oppose changes in frequency through the transfer of power between their rotors and the power system.
- **System inertia is an inherent characteristic** which naturally and immediately damps the systems frequency response to a disturbance.
- **This differentiates inertia from fast active power injection that is available after a measurement delay.**





Inertial response

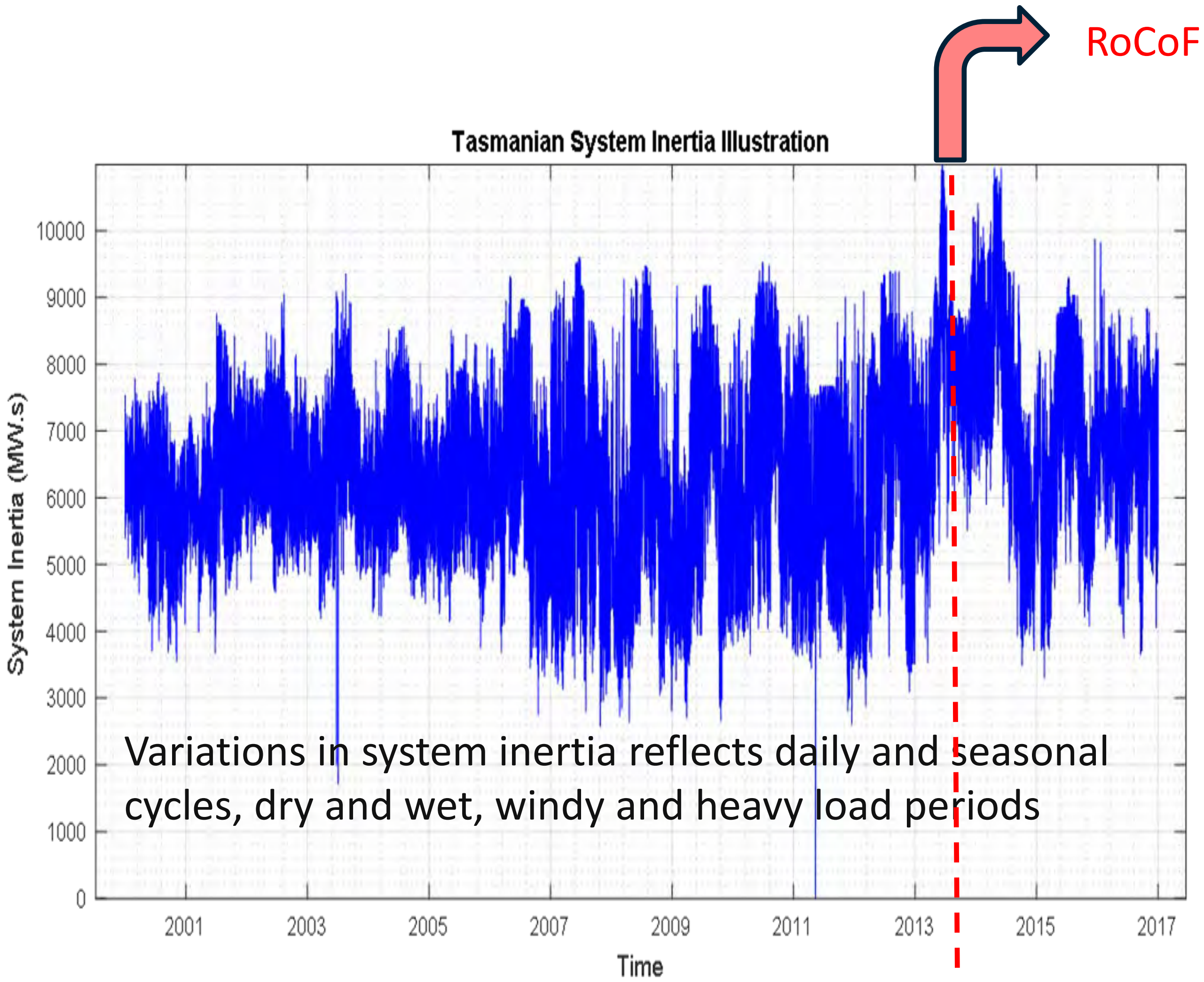
- **The kinetic energy stored in rotors varies with their speed of rotation**. When speed decreases the energy transfers from rotors to the power system. When speed increases, the energy is transferred from the power system back into the rotors.
- **Only a small portion of the kinetic energy is usable** (due to max allowable change in frequency) **however this is the dominant force opposing the frequency change during the first ≈250 ms after a disturbance.**

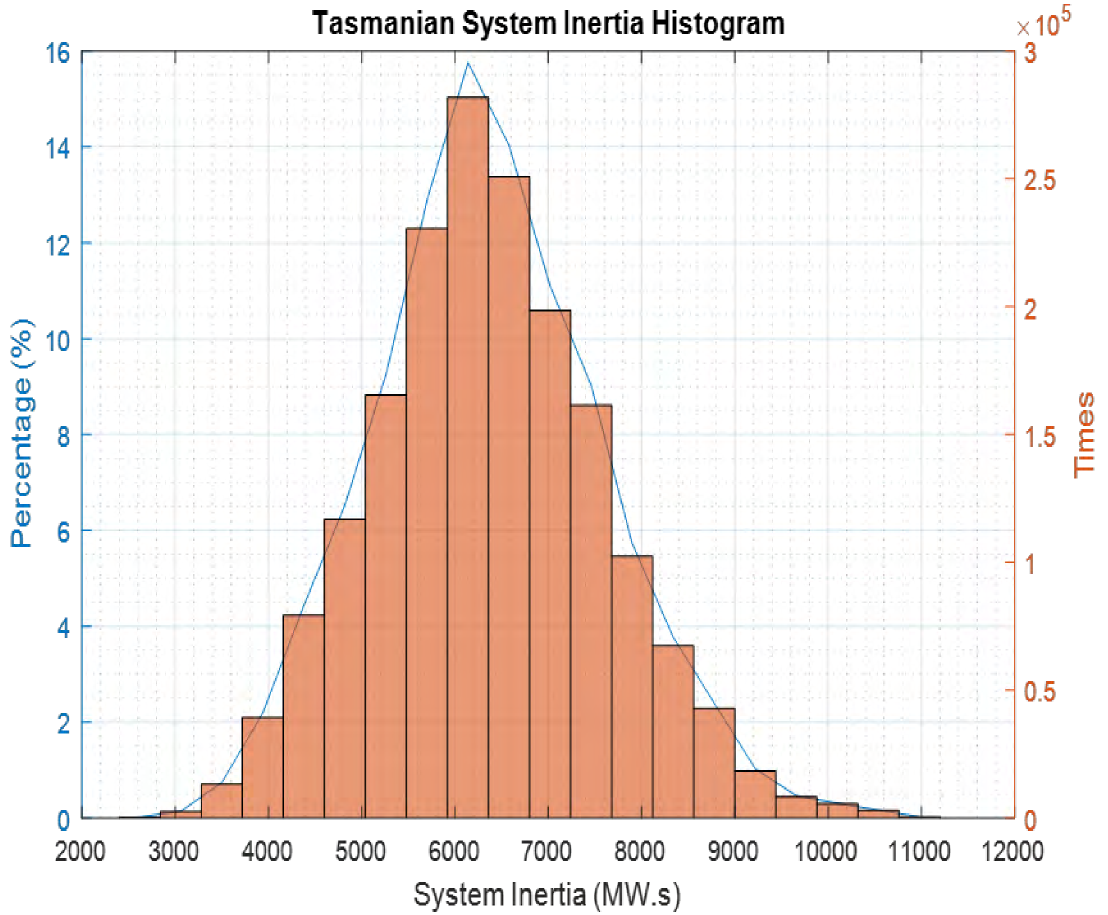
$$Energy\ released = S_{MVA} \times H \times \frac{f_{nom}{}^2 - f_{min}{}^2}{f_{nom}{}^2} = \text{MJ or MW.s}$$

Gordon 3 (160 MVA) = 49.1 MW.s , Poatina (per unit, 62.5 MVA) = 23.1 MW.s

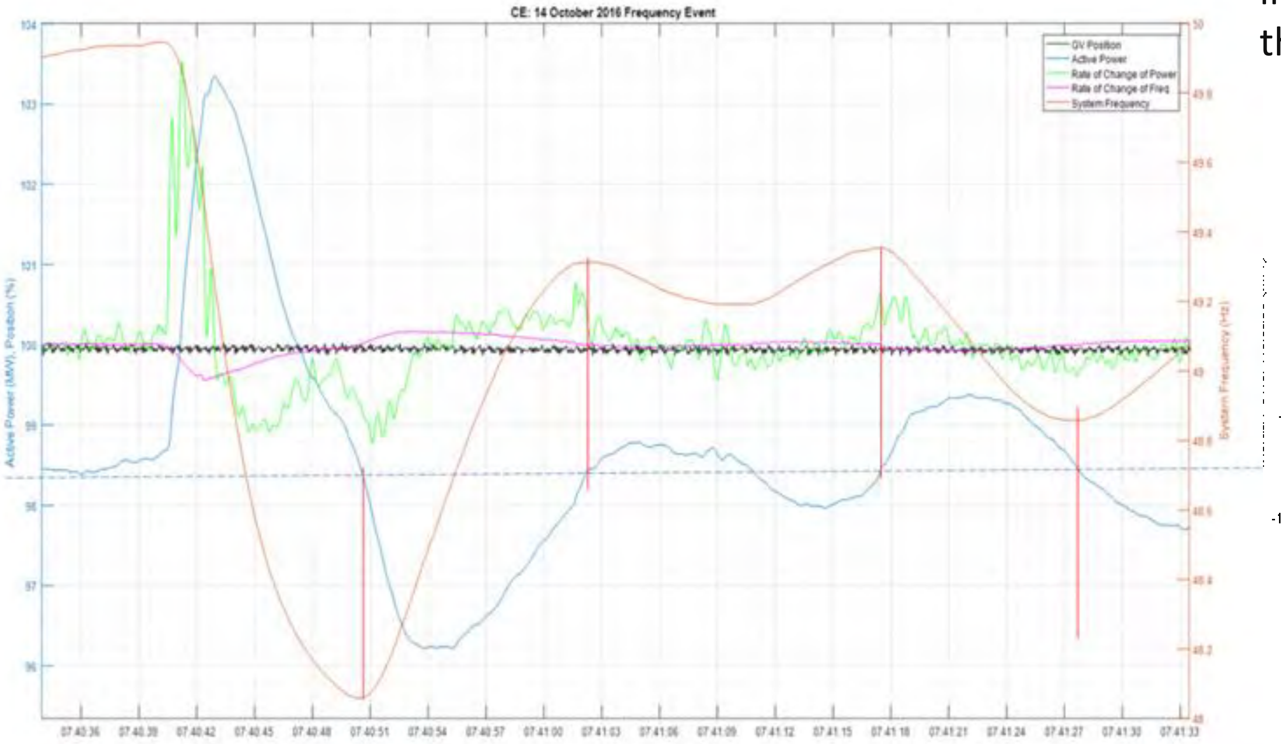
- **Retirement of synchronous generators** and their replacement by nonsynchronous sources **reduces system inertia**. Power electronic interfaces rapidly control electrical power output even for machines like Type 3 wind turbines.
- The power transferred out of 'energy storage' is equal to the imbalance between generation and demand → **the less contributors, the more energy that is extracted from those sources, the faster the Δf.**

Tasmanian System Inertia



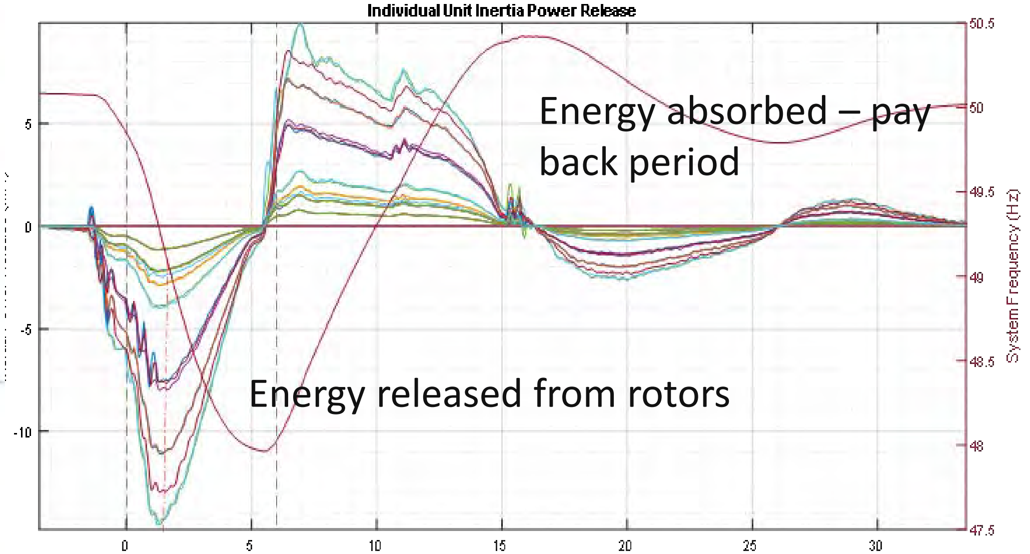


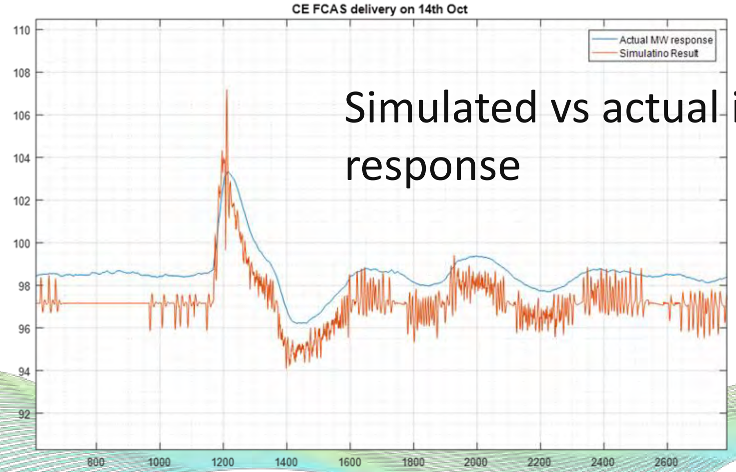
Inertial response examples



When machine is operated at full output, change in electrical output is purely due to exchange of inertial energy. When df/dt = 0, inertial energy contribution = 0.

For the same change in speed, a machine with greater inertia will transfer more energy in or out of the system than a lower inertia machine.





Simulated vs actual inertial response

Principles of Frequency Control (as they exist now)

Primary Frequency Response (PFR):
Actions from uncontrolled (inherent) sources in response to changes in frequency:

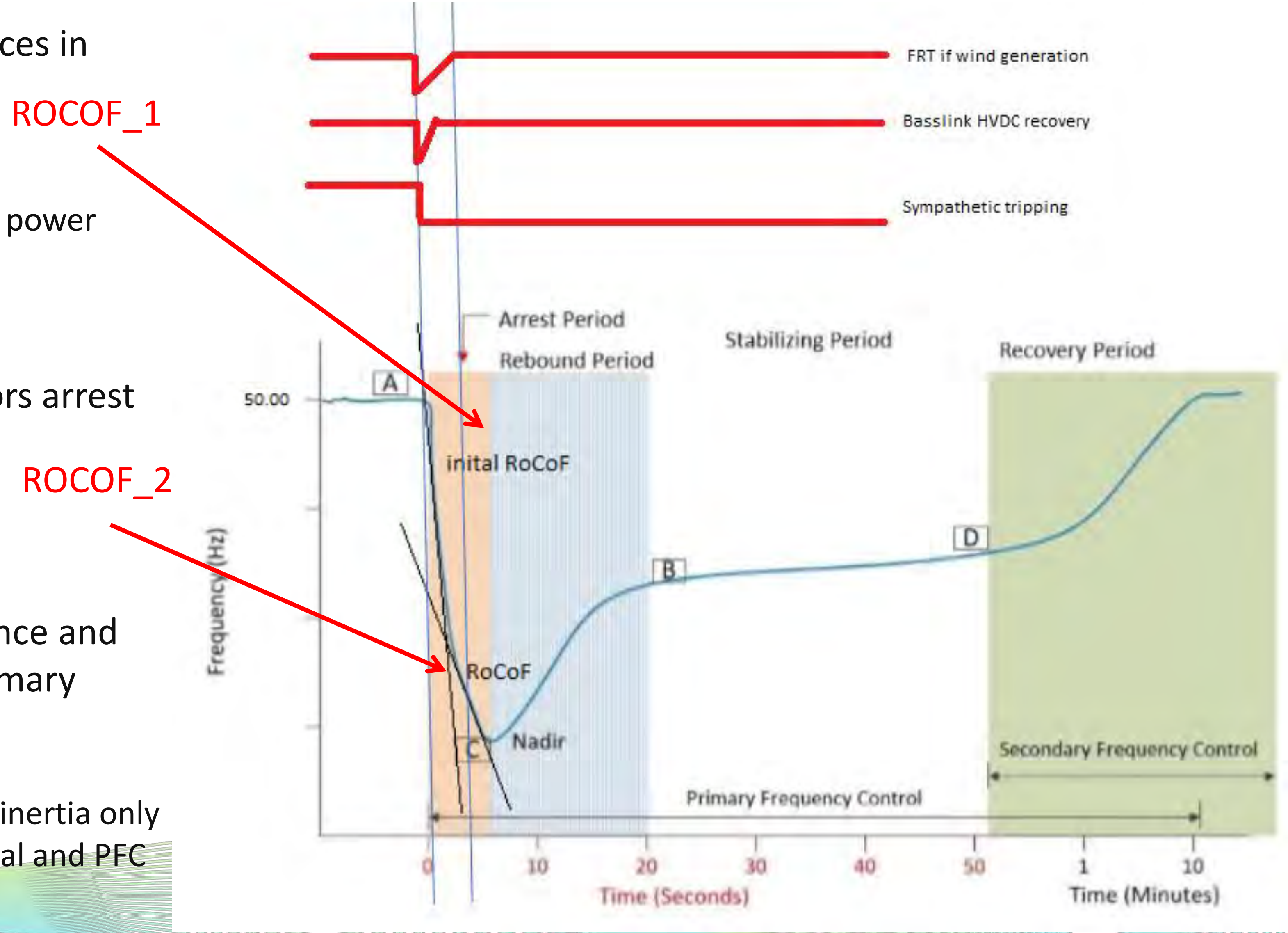
- Rotational inertia (H)
- Frequency dependent loads

PFR may need to counteract energy loss due to power electronics entering FRT or tripping.

Primary Frequency Control (PFC)
Actions provided by prime mover governors arrest and stabilise frequency after change in supply/demand balance results in Δf.

Secondary Frequency Control (SFC)
Actions to correct demand/supply imbalance and restore both scheduled frequency and Primary Frequency Control.

There are two RoCoF periods, initial shaped by inertia only while average affected by combination of inertial and PFC



Fast Frequency Response (FFR)

- FFR is the exchange of power between non-synchronous source and the power system via **modulation of inverter output** that opposes the frequency change.
- The control systems **respond to a measurement of system frequency**, which introduces a time delay (a reliable measurement needs to be made and then a control action initiated).
- Main characteristics that define value of of FFR are **speed and sustainability of the response**.
- Existing response times of inverters are in the 250 to 500 ms range. Faster responses are possible (20 ms) but need to be carefully implemented:
  - Robust measurement and clear identification of the system response is needed to minimise inadvertent triggering that may negatively impact on energy storage device → signal filtering and the need for dead bands introduces longer time delays.
  - Improved coordination between different frequency control providers is better when responses are a ‘little’ slower → FFR sources don’t need to fully correct frequency on their own for ‘normal’ contingency events.
  - However a very fast response during non-credible events can be highly beneficial.

Principles of Frequency Control (as they exist now)

Primary Frequency Response (PFR):
Actions from uncontrolled (inherent) sources in response to changes in frequency:

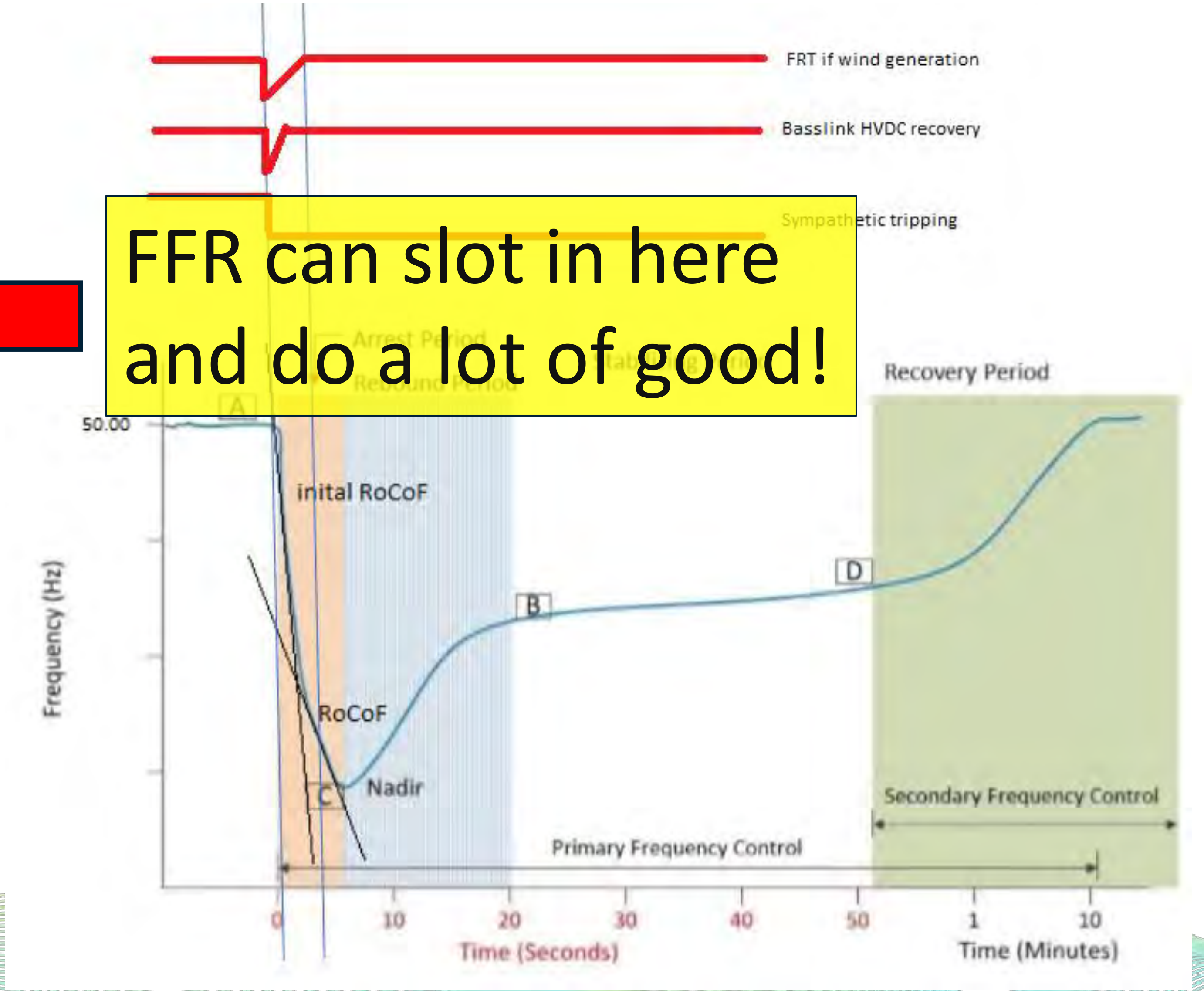
- Rotational inertia (H)
- Frequency dependent loads

PFR may need to counteract energy loss due to power electronics entering FRT or tripping.

Primary Frequency Control (PFC)
Actions provided by prime mover governors arrest and stabilise frequency after change in supply/demand balance results in Δf.

Secondary Frequency Control (SFC)
Actions to correct demand/supply imbalance and restore both scheduled frequency and Primary Frequency Control.

There are two RoCoF periods, initial shaped by inertia only while average affected by combination of inertial and PFC



FFR Technologies

A. Inverter connected technologies that facilitate FFR include batteries, VS flywheels, PVs, HVDC and supercapacitors

- Can respond very rapidly (milliseconds) to a trigger signal
- Are easy to modulate to match specific system requirements

B. Inertia-Based FFR (IBFFR) includes wind turbines capable of extracting kinetic energy from the rotor via the drivetrain

- "Synthetic inertia" more typically delivers FFR in one to two seconds
- Fixed speed flywheels

C. Load based FFR (load response)

- Rectifier supplied loads as found in metal smelting processes are a good example.

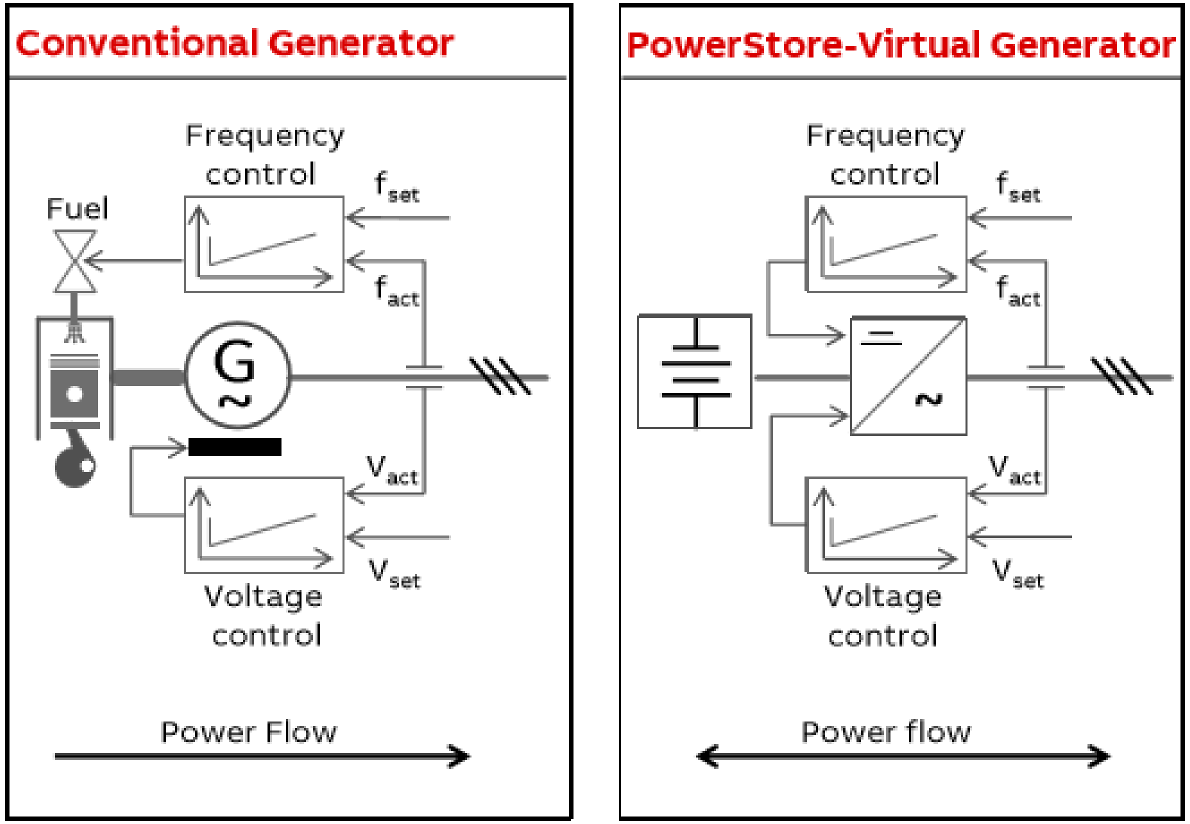


ABB Show Case 2017

Where can/should we be looking for FFR services?

- The 2016 NTNDP projected **10 GW of new wind generation capacity in NEM by 2033**
- If new generation is specified with IBFFR, it could provide response of up to 10% of the capacity.
- This suggests about **1 GW of IBFFR** could be available during high wind periods **by 2033** if we begin to **actively pursue its inclusion in connection requirements**.
- Locational diversity of wind developments could deliver required FFR over long periods. Actual IBFFR available would depend on wind speeds.
- High wind speed periods and high availability of IBFFR correlates well with lower inertia periods, when larger quantities of FFR are required.
- Co-optimisation of FFR with inertia and fast FCAS requirements could provide cost effective improvements for maintaining frequency control in the future.

Role of FFR Services in NEM

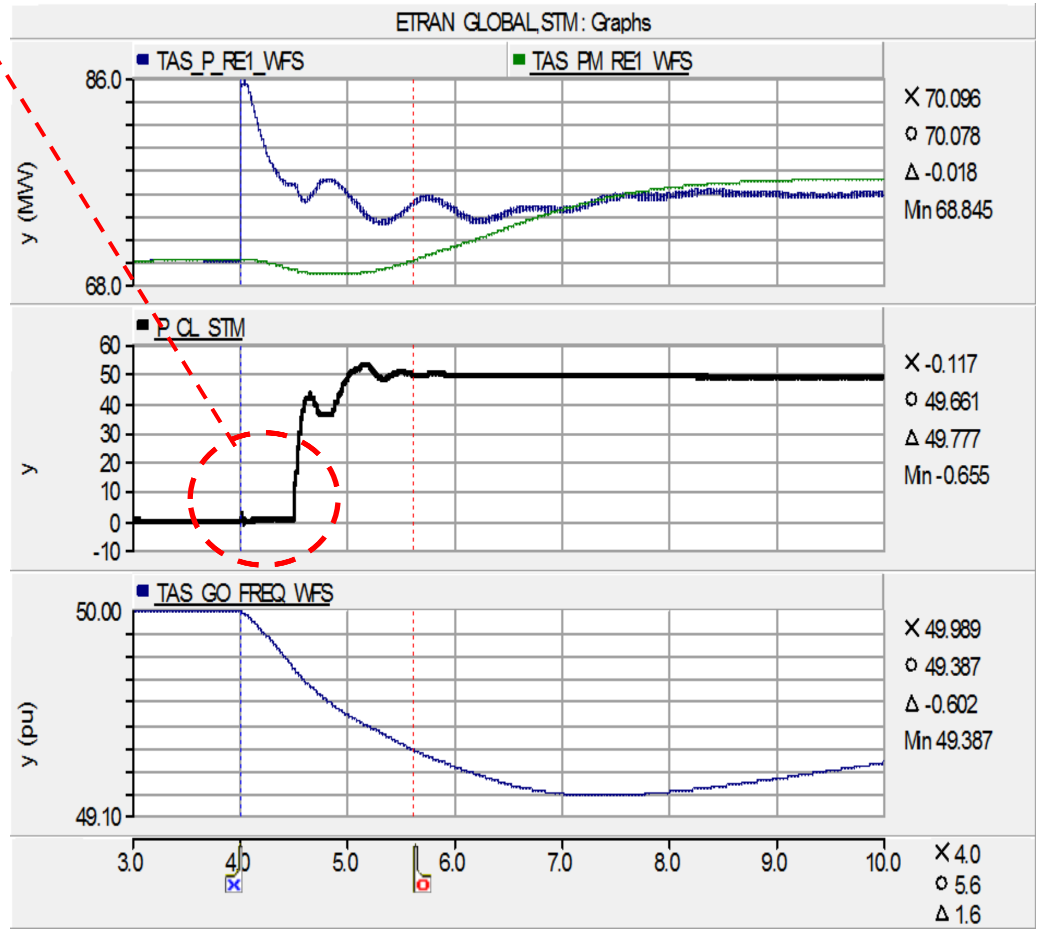
Delay predominantly due to dead band settings

Possible applications of FFR in NEM include:

- **A new type of Frequency Control Ancillary Service (FCAS), improving containment of credible contingency events**
- **Provision of emergency response for non-credible events eg separation of a region**

FFR specification should consider:

- **Suitable measurement methods (robust triggering)**
- **Proportional vs switched delivery**
- **Speed of response**
- **Sustainability of response (seconds or longer)**
- **Asymmetry of response (raise and lower)**
- **Potential for aggregation of multiple sources (distributed model)**
- **Tunable response to complement prevailing inertia levels**



Comparison Inertia vs FFR

- **They are different services** delivered via different physical mechanisms in partially overlapping timeframes.
- **FFR is not a substitute for inertia**, although it can improve the frequency response at lower levels of system inertia.
- **Rotating inertia provides an inherent response** by releasing the energy when the speed falls below rated and re-charges when the frequency starts to recover (and vice versa)
- The release of inertial energy reduces RoCoF, but cannot restore power system frequency.
- FFR injects active power to correct the imbalance and restore system frequency, but does not inherently slow ROCOF at least not in the initial time period after a disturbance.
- FFR can be controlled but is different from inertia due to some delay in its response.
- New generation/network technologies can supply new types of FCAS services and play an increasingly important role in managing system security.
- Access to such capabilities will require ongoing evolution of Rules based performance requirements and most likely markets that value the resulting services.

SVC PLUS FS
Frequency Stabilizer

Volker Hild

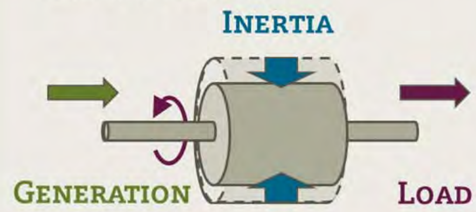
Siemens Transmission Solutions

CIGRE ANC Seminar, 9th -10th November 2017, Brisbane

Frequency Stability and Inertia challenge

Today's Trends

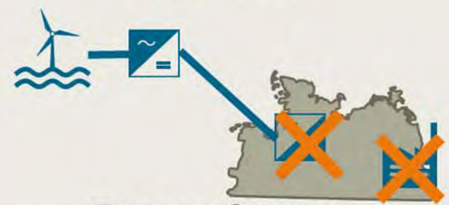
- Disconnection of large synchronous generation
- Renewable generation do not contribute to system inertia and frequency control today
- Reactive power reserve for voltage control is reducing



Frequency Stability

- Large frequency deviations can cause severe supply interruptions
- Over- and underfrequency situations can be critical
- Low inertia systems are sensitive to power unbalances due to high rate-of-rise of frequency (ROCOF)

Examples



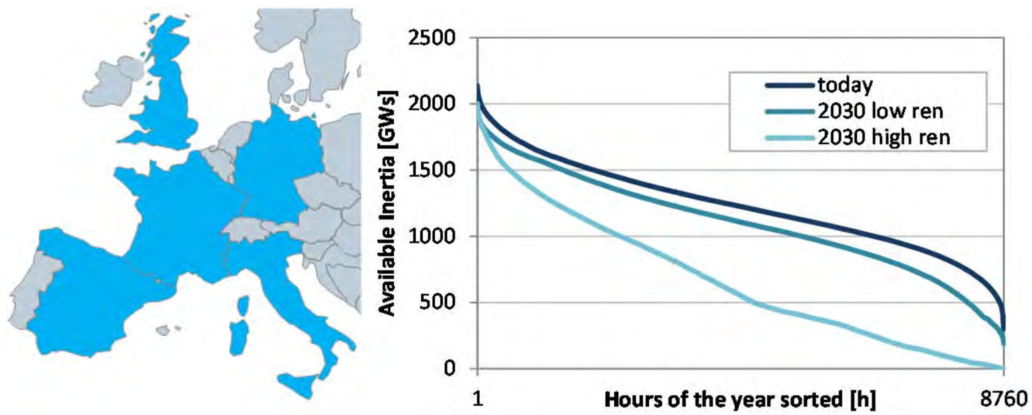
Example: Germany
Generation trip

Example: Ireland
Trip of interconnecting lines

Future development of inertia is critical

Example: Selected European countries

Strong increase of renewables and phase out of classical power generators:

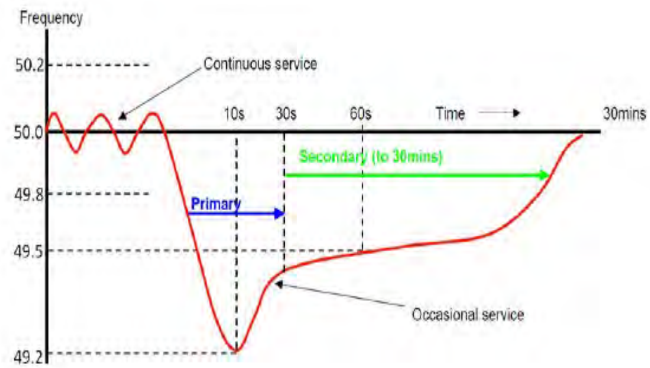


Data and scenarios derived from ENTSO-E “Ten year network development plan”, 2014

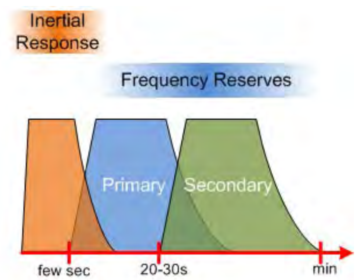
- Significant decrease of system inertia, especially in times with high renewable penetration
- Similar results for short circuit current and voltage conditions

Transmission System strength

- The key indicators for transmission system strength:
  - System inertia
  - Short circuit level
- Frequency behavior defined on operational and statutory limits
- Synchronous generators participate in frequency control
- Two types of mandatory frequency response services
  - Primary (tens of seconds)
  - Secondary (up to minutes)



Continuous frequency regulation, Primary and secondary response



Exemplary critical frequency trajectory

Ireland and South Australia, 2016

Frequency stability limitations

- Large unbalances cause positive and negative frequency deviations
- Under- and overfrequency f_{nadir} leads to
  - load shedding
  - generator trip
  - black out
- High rate of change of frequency **ROCOF** leads to
  - tripping of ROCOF relays of generators to avoid pole transient instability and subsequent black out

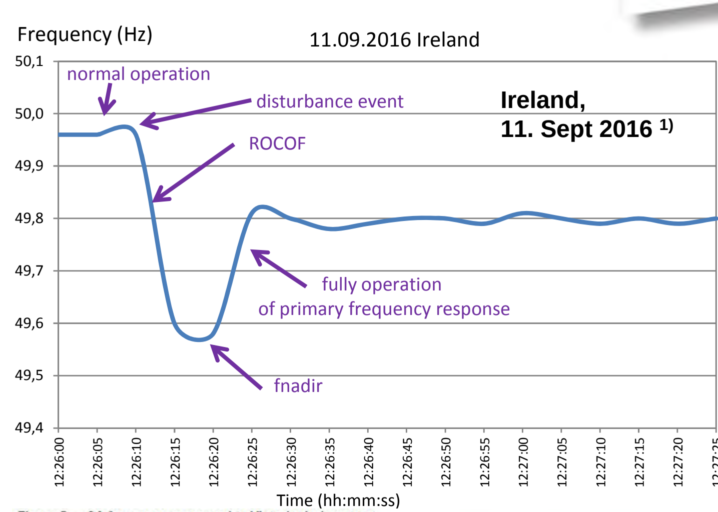


Figure 5 SA frequency compared to Victoria during event

1) Website of EirGrid
2) AEMO: Black System South Australia 28 September 2016 – Final Report

How do we solve the challenges today?

Challenges

- Reduced system inertia
- Reduced spinning reserve and primary reserve
- Increasing absolute positive and negative frequency deviations
- Higher ROCOF values

Today's solutions

- Increase number of must-run units
- Increase primary reserve power
- Curtailment of renewable generation
- Increasing costs for frequency response measures

Disadvantages

- Costs for power plants
  - Start-up
  - Maintenance
  - Fuel costs
  - Efficiency & losses
- Environmental impact
  - CO2
  - Use of fossil fuels

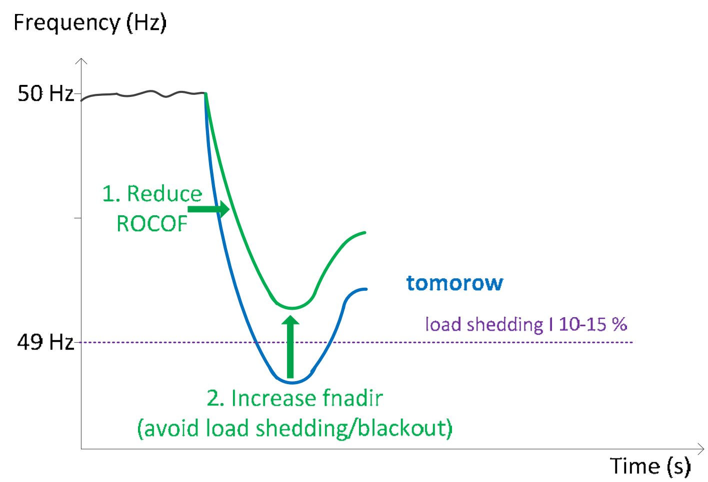
A new alternative solution:

SVC PLUS Frequency Stabilizer (FS)

A device focusing on short-term frequency support to

- ✓ reduce ROCOF and
- ✓ increase f_{nadir}

by **providing Synthetic/Virtual Inertia** in addition to its Statcom functionality



SVC PLUS Frequency Stabilizer

Fast response and short time grid stabilization

Technology	Proven Technology SVC PLUS (Modular multilevel STATCOM)	Add-On: Supercapacitors +/- 50 for rated power output up to several seconds
Principle	 Platform: SVC PLUS (STATCOM) based on VSC*-technology	+  Supercapacitor tower
Features	• +/-50… 250MVA scalable multi-level converter design • Storage based on “Supercapacitors” • Rated power output: several seconds discharge, longer time possible at lower power • Programmable control algorithms, independent from frequency deviation	

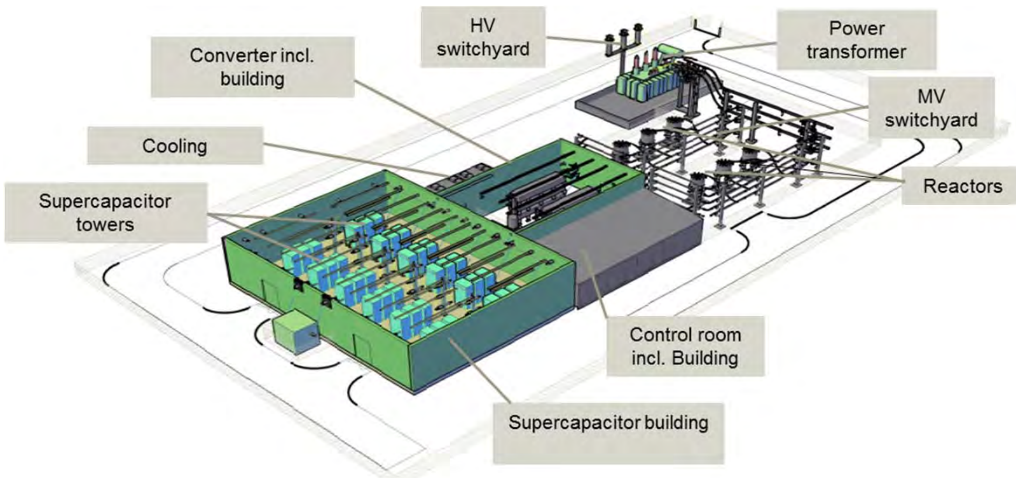
Use Cases @ Transmission Grid
≥ 52 kV, ≥ 25 MVA
	• Fast Dynamic Voltage Control and Frequency Control:
	  ◦ Reducing frequency response at transient events
	  ◦ Providing „synthetic inertia“ at grids with high renewable share
	• Support HVDC LCC @ weak AC grids
	• Grid code compliance for grid access of non-synchronous power generation (e.g. wind, PV)
	• Contribution to primary reserve	

* VSC = Voltage Sourced Converter

SVC PLUS Frequency Stabilizer

Concept & Layout

STATCOM with power intensive storage for short time



- Operations in 4 PQ-quadrants +/-50 Mvar and +/-50 MW for 6-8 seconds
- Significantly smaller footprint (app. 3000 m² for 50 MVA) compared to batteries (app. 20000m²)
- Significantly lower costs comparing with other technologies

Frequency Stabilizer vs. Battery Storage

	Supercapacitors	Batteries
Power Density	+	-
Energy Density	-	+
Applications	Seconds	hours

	SVC PLUS FS	Battery Storage
Voltage Support	+	0
Peak Shifting	-	+
Target Users	TSOs	DSOs, utilities

SVC PLUS Frequency Stabilizer

Highlights

Proven Technology SVC PLUS

- Improvement in dynamic stability of transmission systems
- Fast voltage control
- Increase in Power Quality
- Static Frequency Converter in traction supplies
- Low electric Losses
- No filtering of harmonics required

Frequency Stabilizer – using storage (supercapacitors)

- Extended frequency support and control
- Fault ride through capability
- Allows flexible control-algorithms that enables efficient active power injection or absorption
- Improves the performance of HVDC Classic connected to weak AC systems
- Power Oscillation Damping (POD)

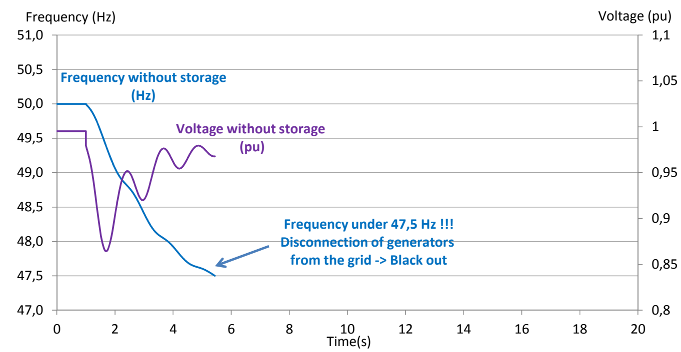
SVC PLUS Frequency Stabilizer

Simulation Results

In second 1 an outage of one generator is simulated

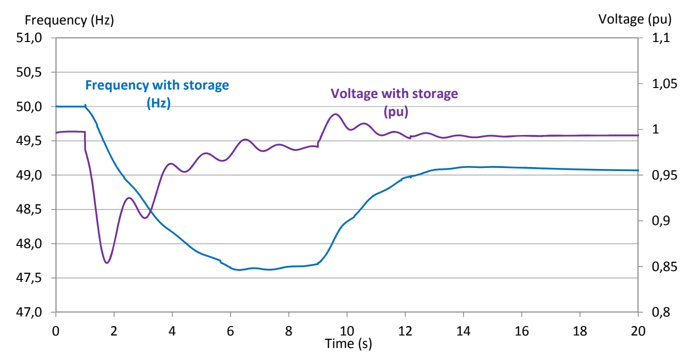
The SVC PLUS <u>without</u> storage (Supercapacitors):

- Reaches the frequency below 47,5 Hz
- Power plant disconnection i.e. Blackout according to UCTE grid code @47.5 Hz



The SVC PLUS <u>with</u> storage (Supercapacitors):

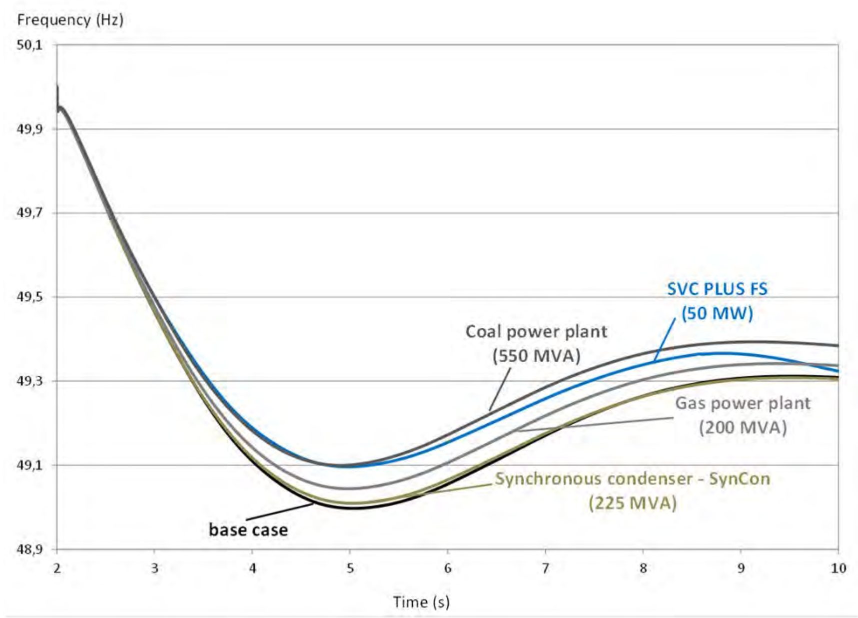
- Provides active frequency control
- Decreases the rate of change of frequency
- Provides voltage control
- Lowers the risk of black-outs



Performance Simulation

Impact on primary reserve and possible benefits

- Example on the detailed All-Island grid of Ireland for summer 2022. Load at ~2500 MW. Renewables 65%. Trip of 500 MW (HVDC connection)
- SVC PLUS FS of 50 MW has the same impact on the first swing frequency as a coal power plant of 550 MVA!
- f_{nadir} improvement of >0,1 Hz!
- ROCOF reduction
- SVC PLUS Frequency Stabilizer can reduce level of "must run" units (required for secure operation of the system) and reduce primary reserve
- Fast response time. Time needed for "synthetic/virtual" inertia:
  - For 4 Hz/s – full power at 49,6 Hz means activation time of 100 ms.



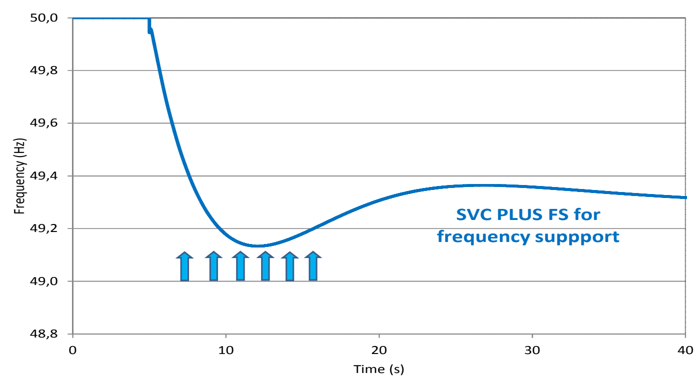
Comparison of technologies

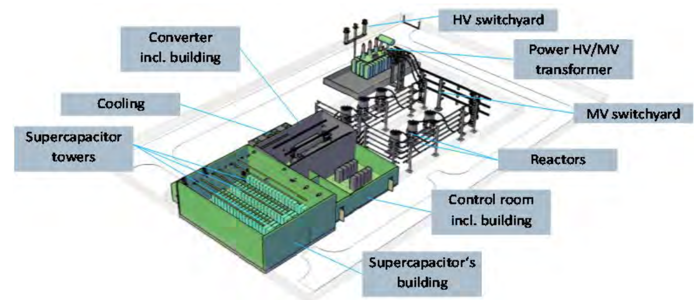
	Synchronous Condenser	SVC PLUS Frequency Stabilizer
Voltage Support	Yes, continuously. But slow response time (seconds)	Yes, continuously. Very fast (<40ms)
Short-circuit power / current	Yes (> 5 times)	Only rated power
Inertia	Comparably small	Yes (virtual inertia, H=6…8)

- The technologies do NOT substitute each other.
- Especially short-circuit power is essential as inverter-based generation hardly provides any.
- Also operational costs have to be considered (e.g. Electric Losses significantly higher with SynCon)
- Individual analysis of network requirements has to be performed.

Conclusion

- Inertia becomes one of the biggest issue in the power system stability - already today
- SVC PLUS Frequency Stabilizer is an option to overcome those issues
- Full active and reactive power support – four quadrant operation
- One SVC PLUS Frequency Stabilizer of 50 MW has the same impact on the first swing frequency stability as one typical coal power plant of 550 MVA or as two typical gas power plants of 200 MVA
- Significant savings in costs for running must run units





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CIGRE ANC Seminar

The impact of power electronics on Network performance and Capability

Impact of a STATCOM with the frequency stabiliser on the frequency control in Tasmanian power system

Marian Piekutowski
Hydro Tasmania
Brisbane 9-10 November 2017

Outline

- TasNetworks interest in Statcom
- Availability of FCAS in Tasmania
- Siemens SVC Plus FS & Tasmanian opportunities
- PSCAD/ETRAN/PSSE modelling
- Overview of results

Network Performance Improvements

TasNetworks has recently investigated market benefits of STATCOM:

- Temporary Over Voltage (TOV) & reactive margin constraints on Basslink HVDC flow to VIC
- Voltage unbalance
- Rate of change of frequency

Increase transmission supply capacity to GT to support higher demand – shortage of dynamic reactive power

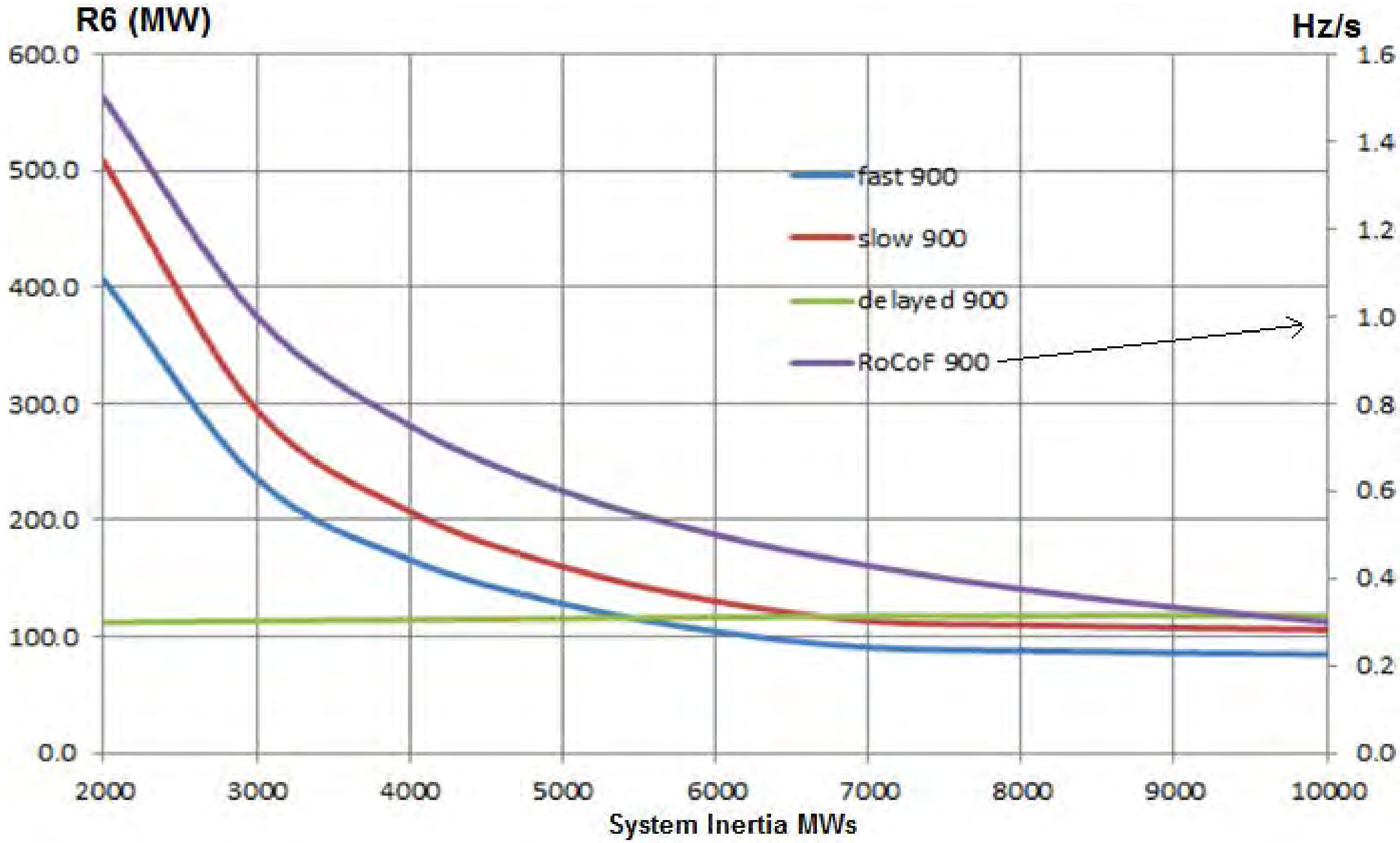
Support growth of RE generation - better wind turbine fault ride through (FRT)

Improve “steady-state” voltage to reduce # of tap changer operations per day

Dispatch Limitations

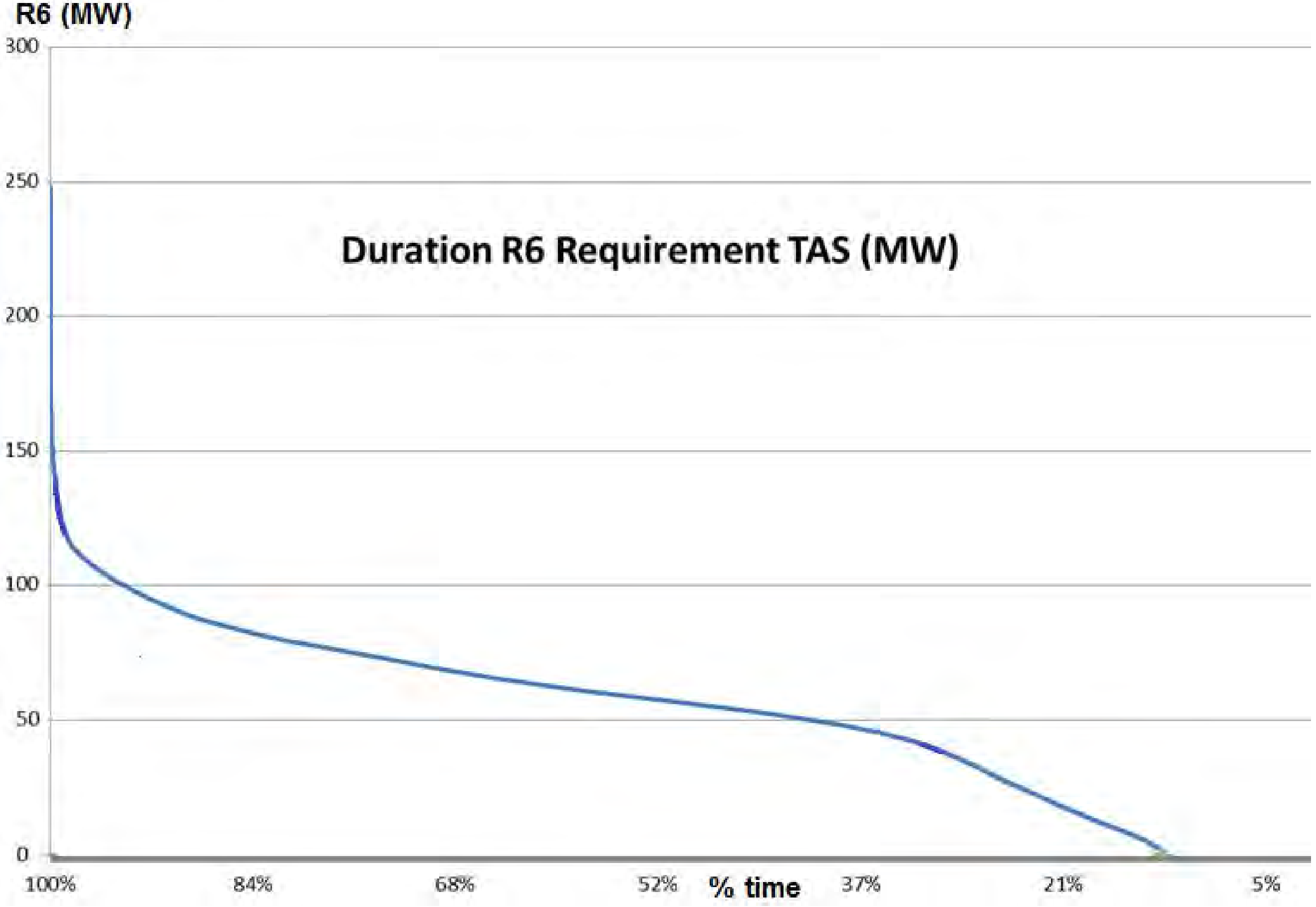
- Hydro generation has limited fast FCAS capability (for contingencies) but provides excellent slow and regulation FCAS services
- HVDC does provide fast response but needs available headroom
- There are constraints (e.g. minimum fault level, min inertia, TOV, etc) affecting operation of Tasmanian system
- Installed capacity of wind generation is expected to double – required solutions supporting increased RE penetration
- RoCoF with two main limits in Tasmania:
  - 3 Hz/s (result of design requirements, anti-islanding protection)
  - and average 1.176 Hz/s when f is below 49Hz (affecting UFLS) affecting minimum inertia

Tasmanian Demand for Raise 6 s FCAS



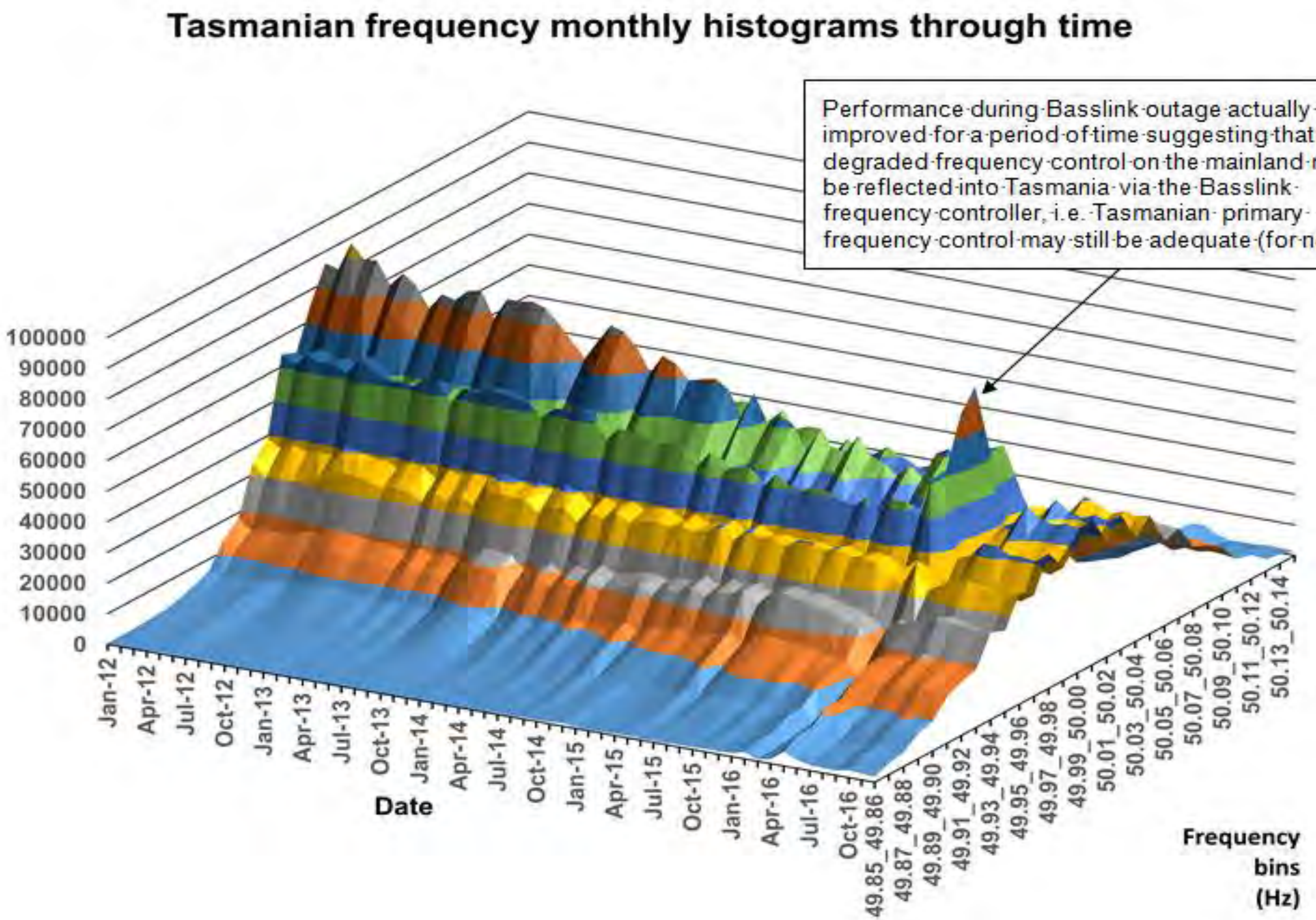
- For past 3 years average Tasmanian R6 costs approx. $ M 5.0 pa
- For largest contingency RoCoF varies between 0.3 to 1.0 Hz/s
- FCAS demand increases exponentially when the system inertia is < 6 GWs
- Typical availability of R60 is 536 MW, R60 Dispatch = 165.1 MW & R60 Requirement = 131MW

Annual R6 duration curve



Typical R6 demand over past few years is 30 to 120 MW with occasions up to 250 MW

Worsened frequency performance within NOFB



Big deterioration in NOFB excursions observed since 2016

On mainland 150 excursions per month while in Tasmania approx. 800

Fast FCAS Delivery Improvements

- Low output operation
- Improved hydro governor transfer function
- Tail water depression mode
- AUFLS2 scheme (switching controllers)

21-26 August 2016 CIGRE Siemens paper: 'Power Intensive Energy Storage and Multilevel Statcom for Frequency and Voltage Grid Support (SVC PLUS Frequency Stabiliser)', 50 MW/400 MJ

A Statcom with energy storage offers good fit to Tasmanian conditions and opens new market benefits that may allow project justification

SVC Plus FS benefits for Tasmania

Hydro Tasmania

New project combines TasNetworks STATCOM functionality and addresses low availability of R6 FCAS in Tasmania reducing

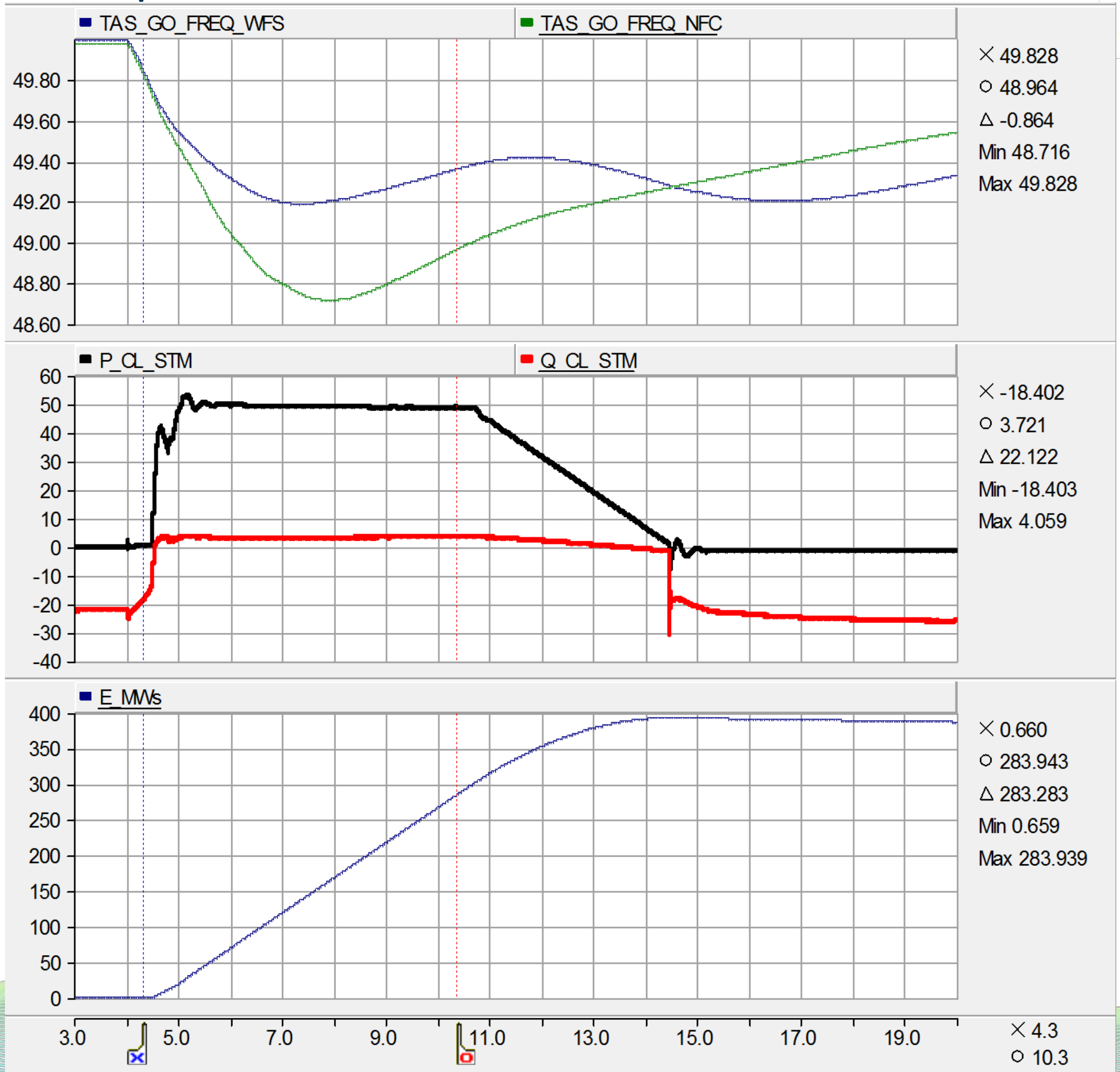
- Requirements to supply frequency control and inertia by SG (or SC) to support more asynchronous RE sources
- Rate of Change of Frequency (RoCoF)

Improve energy security in Tasmania

- Increased HVDC transfer limits
- More efficient use of water/gas resource, particularly important during energy shortage

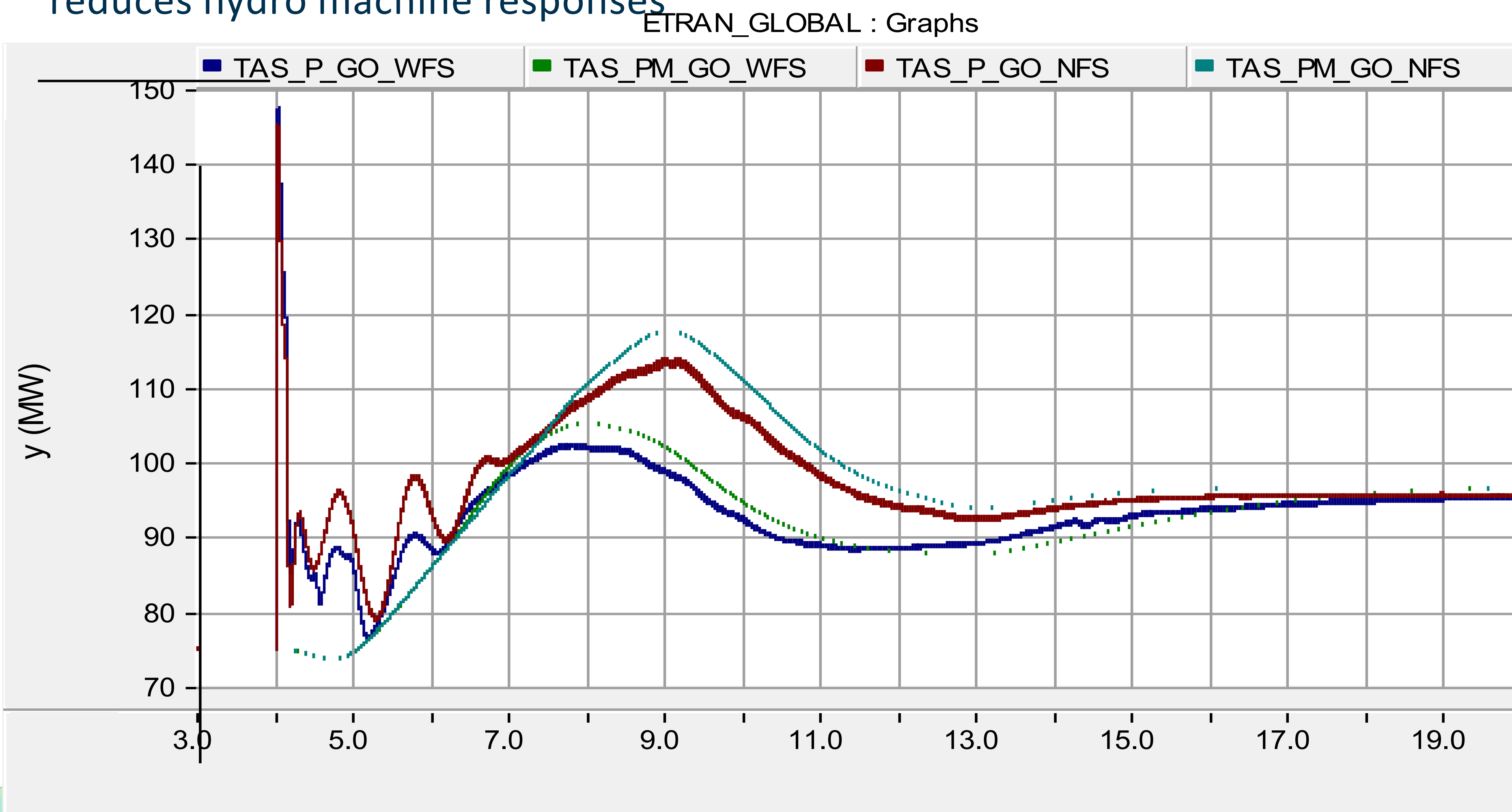
The project creates a test bed for Fast Frequency Response (FFR) plant based on super capacitor energy storage

Isolated system, gen contingency = 140 MW ($R6_{req} = R6_{avail}$ = 100 MW), inertia = 5600 MWs



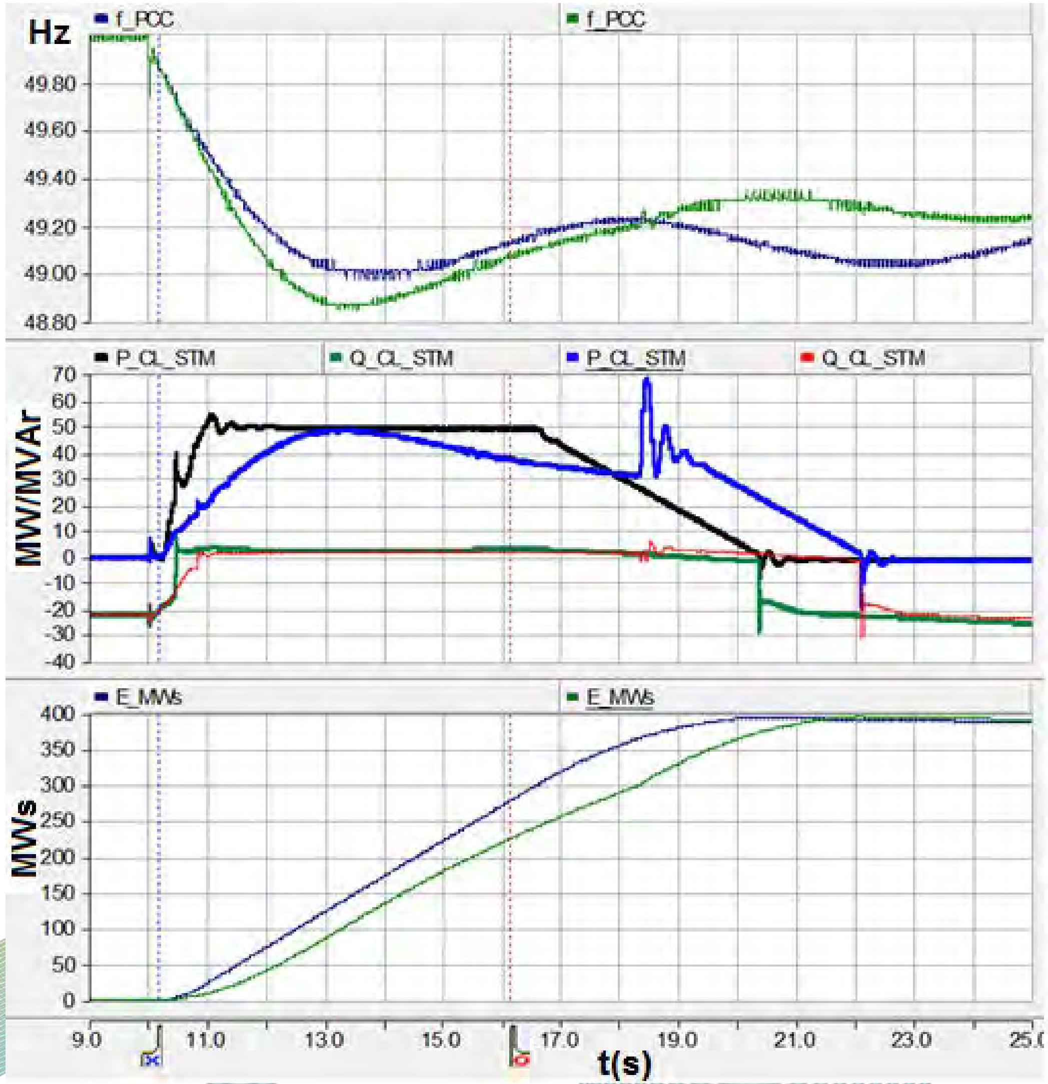
Impact of FS on hydro machines

Electrical and mechanical power outputs of Gordon 1 unit is shown for a case with (WFS) and without (NFS) the frequency stabiliser. The stabiliser reduces hydro machine responses



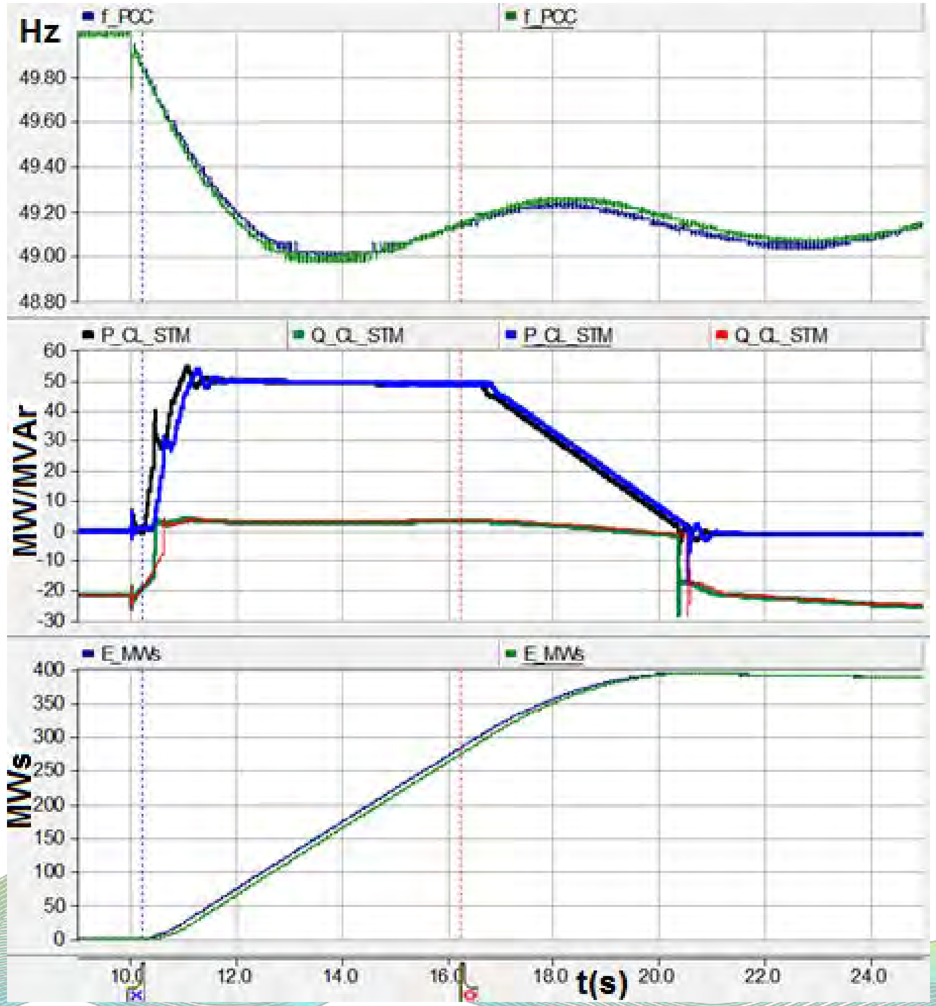
Impact of two FS gains (16.7 vs 47.6)

Frequency trigger Hz	gain	Time to start response(sec)	Time to 50 MW (sec)	R6 released (MWs)	R6 delivered (MW)
49.85	47.62	0.241	0.934	278.0	92.6
49.85	16.67	0.241	2.966	225.1	75.0



Impact of Frequency Trigger 49.85 Hz vs 49.75 Hz

Frequency trigger (Hz)	Time to start response (sec)	Time to 50 MW (sec)	R6 energy released (MWs)	R6 delivered (MW)
49.85	0.255	0.954	278.0	92.6
49.75	0.416	1.157	268.8	89.6



Very low inertia 3900/3300 MWs

R6 requirements = 150 MW
Gordon 1 (72.5 MW) and Reece 2 (70 MW) substituted by Musselroe wind farm 142.5 MW
Trip of 120 MW unit

R6 available 32.8 MW

All governors enabled

FS energy release after 6 seconds 286 MWs (R6 = 95.36 MW)

Minimum frequency 48.6 Hz

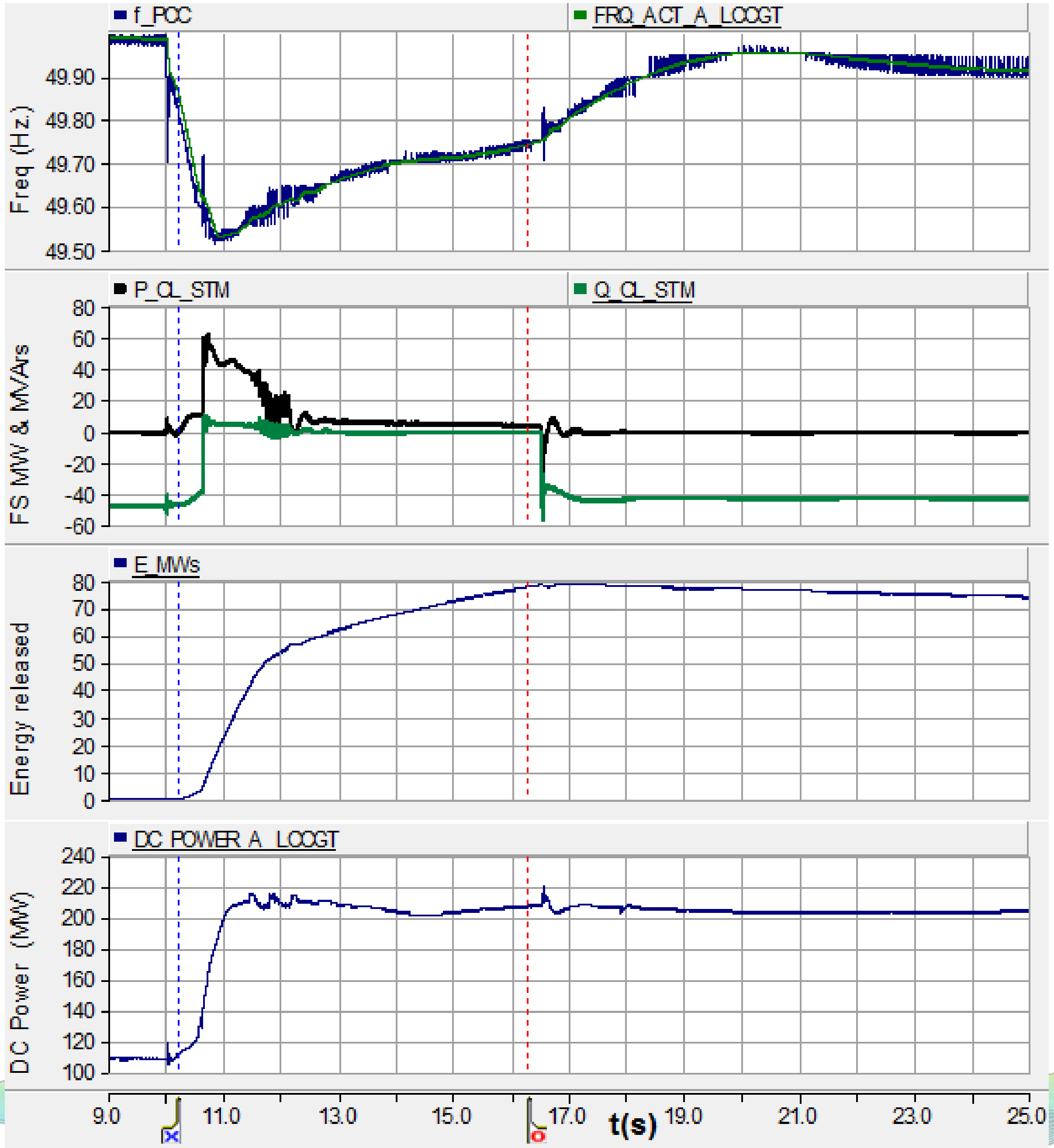
R6 available 6.7 MW

Additionally disabled governors at Cethana (R6=8.3MW), Reece 1 (9.3), Tribute (3.4) and Meadowbank (5.0)

FS energy release after 6 seconds 286 MWs (R6 = 96 MW)

Minimum frequency 48.2 Hz

Response of FS and HVDC



Loss of 140 MW unit with HVDC in service importing 110 MW

Initial FS response faster than HVDC (400 ms delay)

HVDC increases power transfer and unloads FS

FS releases only 80 MWs

FS fast FCAS contribution

FS can contribute R6 service in two ways:

1. **Compliant with MASS R6 service definition where 50% of energy (200 MWs) is discharge during the first 6 seconds while the rest is discharged between 6 and 60 seconds. This option provides up to 66.7 MW of R6**
2. **Maximum discharge over the first 6 seconds, with reduced energy delivery in the following 54 sec maximises R6 delivery however undelivered energy during the second period needs to be compensated by increased requirements for R60 service**

(2) is more efficient in hydro system, but regulatory changes to service definition may be required

Delaying FS trigger to outside NOFB to preserve discharge:

- **With 0.5 s time delay FS discharges 275 MWs in the first 6 seconds which is equivalent to 91.7 MW of R6**
- **Deficit of R6 is supplemented by additional 150 MWs of R60 (275 – 125 MWs left in storage), which is equivalent to increase in R60 requirements by 6 MW**

Alternatively, FS can avoid Tasmanian R6 FCAS requirement supplied by hydro units

Preliminary comments on FS FCAS contribution

50 MW / 400 MWs FS can deliver approx. 66 MW of R6 service

The approach maximising provision of R6 (up to 90 MW, 275 MWs) within the first 6 s and calculating the energy deficit between 6 and 60 s. The deficit can be covered with increased R60 requirements

With 0.5 seconds time delay in FS response the energy discharged is about 275 MWs $\therefore$ at least 150 MWs must be additionally delivered by R60 between 6 and 60 s

Future issues:

- **Explore capability of asynchronous sources to provide FCAS**
- **Use demand management to provide R6 back up**
- **Aggregated unshaped R6 services (distributed sources)**
- **Reliability of FCAS delivery - impact of supplying R6 from a single source**

2017-10-11

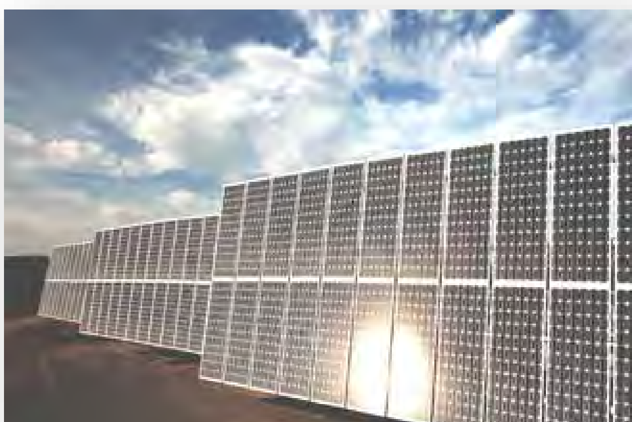
Wind and Solar Power Integration

SVC, STATCOM and HYBRID STATCOM

Peter Andersson, System Lead Engineer, ABB FACTS

Challenges

Wind and Solar Power Integration



- Varying Sources of Energy
  - Solar and wind are neither constant nor predictable sources of energy.
  - This can lead to voltage fluctuations and instabilities.
- Reactive Power Balance
  - Increasing requirements, grid code, for maintaining reactive power balance.
- In Case of a Fault in the Grid
  - Voltage ride-through capability required.
- Use of Converters
  - Converters generate harmonics.

Dynamic Shunt Compensation

SVC, STATCOM and HYBRID STATCOM

SVC – Static Var Compensator

- Thyristor controlled shunt regulator of reactive power.
- Line commutated converter.

STATCOM – Static Synchronous Compensator

- IGBT or IGCT controlled shunt regulator of reactive power.
- VSC – Voltage Source Converter.

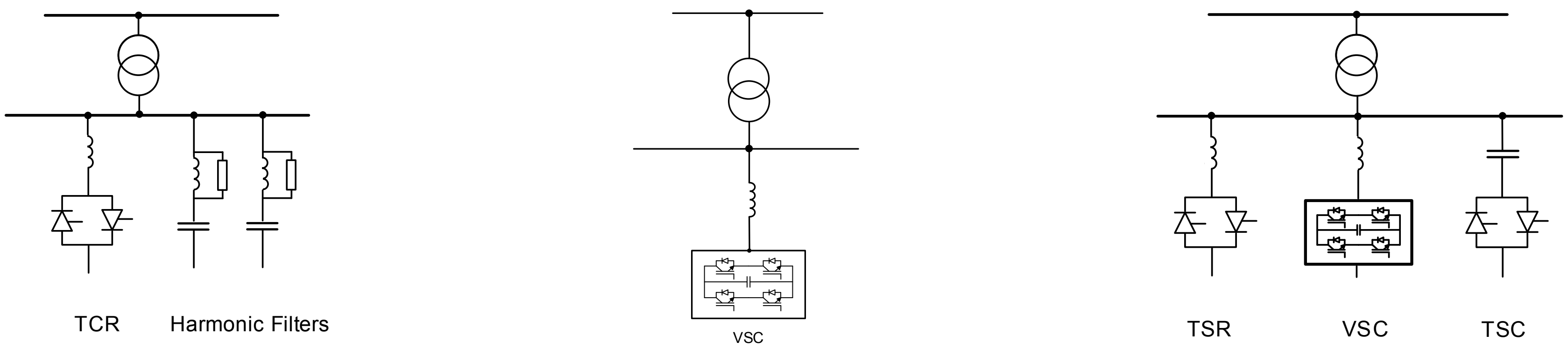
HYBRID STATCOM

- Combination of STATCOM and SVC.
- VSC used for continuous control.
- Thyristor Switched Capacitor (TSC) and Thyristor Switched Reactor (TSR) used for offset.

Dynamic Shunt Compensation

What Technology to Use?

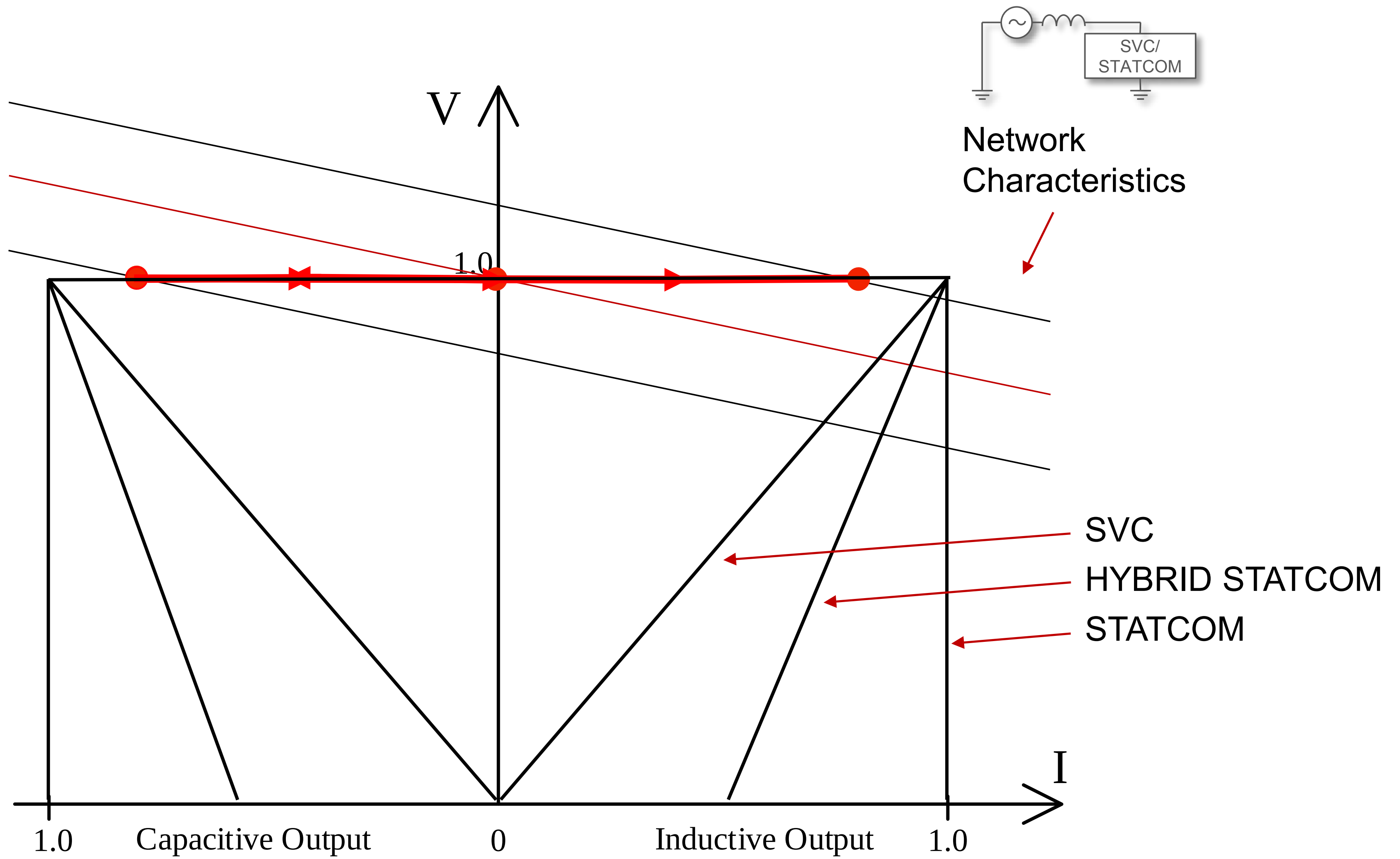
SVC **OR** STATCOM **OR** HYBRID STATCOM



- From a grid perspective, the technologies are doing the same job.
- The network requirements determines what technology to use.
- Studies are <u>required</u> by supplier to determine the most optimal technology!

Dynamic Shunt Compensation

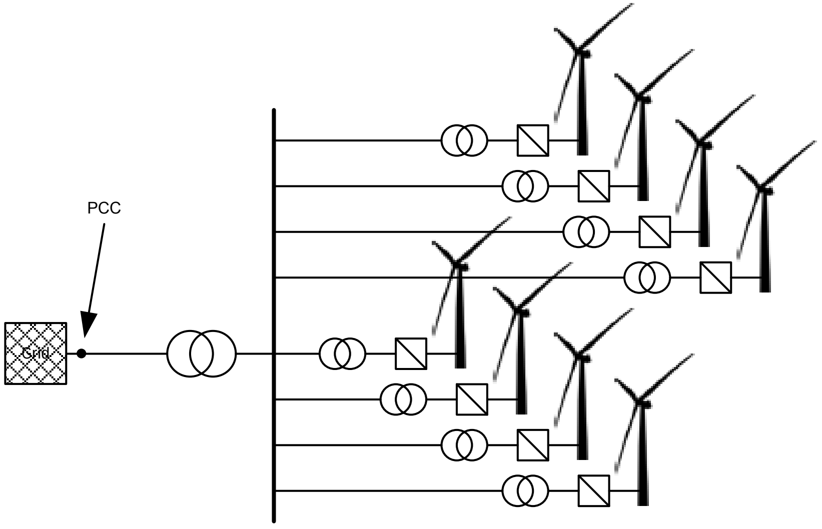
VI-Characteristics and Functionality



Grid Code – Wind and Solar Power Integration

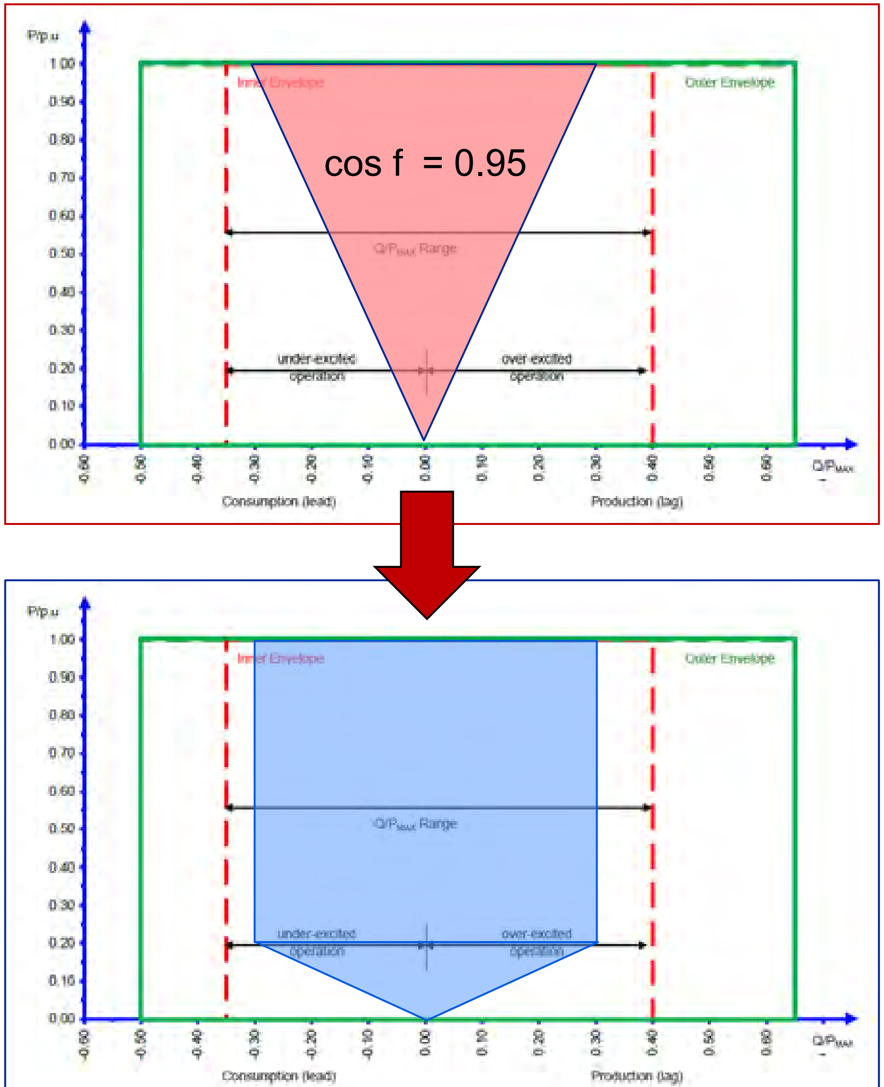
General

- The wind farm and solar plant need to fulfill the grid code at the point of PCC
- This includes not only the wind turbines and solar plant, but also includes reactive power losses in the wind park i.e. transformers, cables, capacitor banks etc.



Grid Code – Wind and Solar Power Integration

Reactive Power Balance – Example

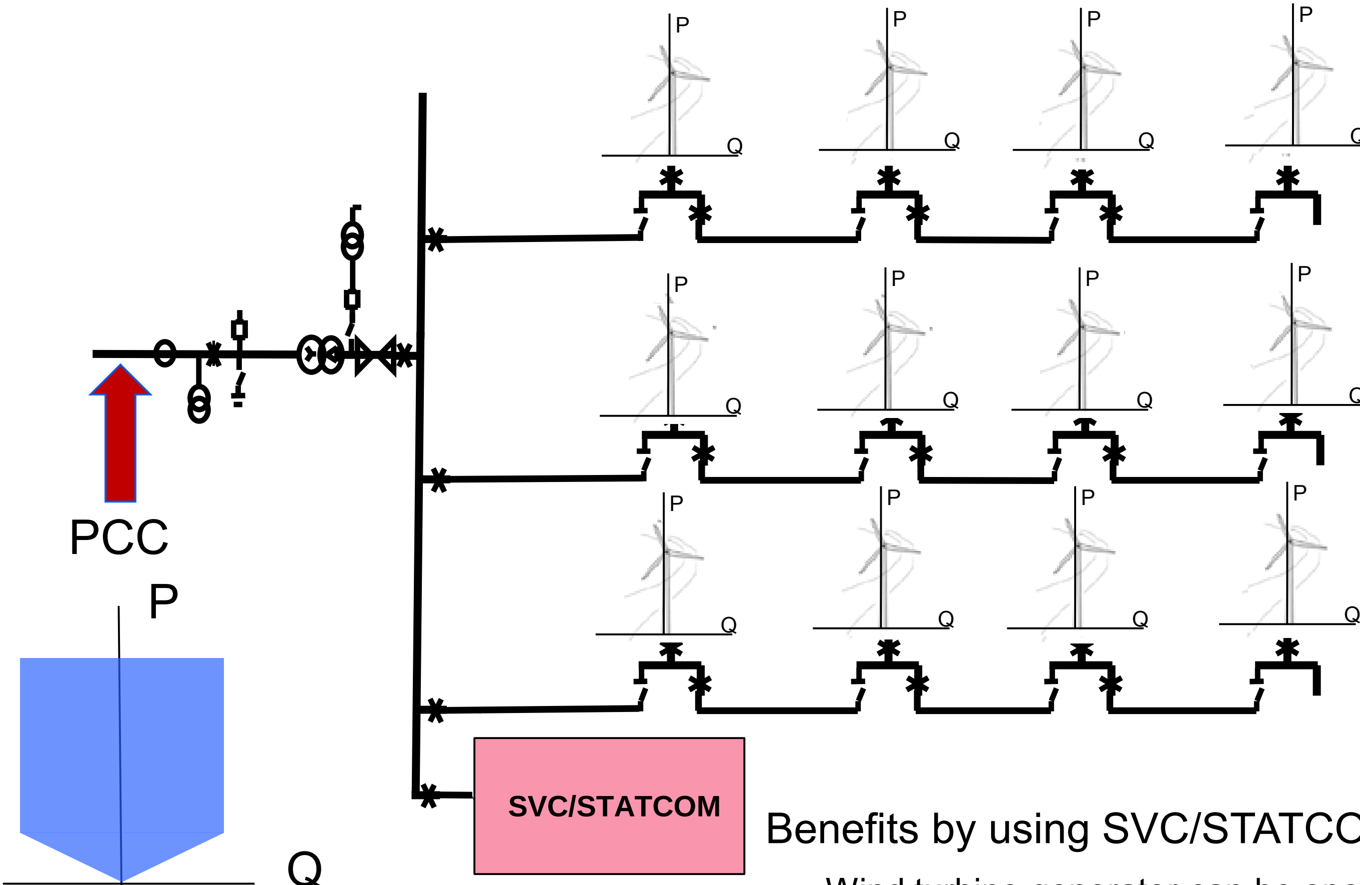


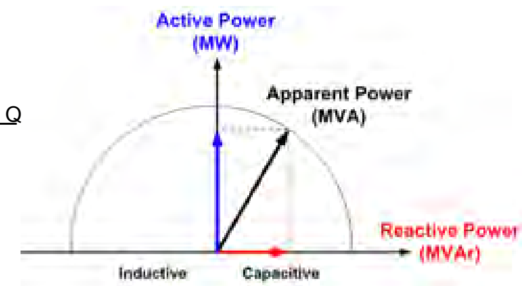
- Traditionally world wide, there has been a very small amount of wind and solar generated power in power systems.
  - The requirement on providing reactive power has been modest.
  - Typically, requirements corresponding to active factor at network connecting point of cosf =0.95$_{\text{underexcitited}}$ to cosf =0.95$_{\text{overexcitited}}$

- What now can be seen globally!
  - A larger amount of wind and solar power is installed.
  - Stricter requirements on providing reactive power.
    - Example: Some grid code states the need of producing up to 30-40% reactive power of the rated apparent power.

Grid Code – Wind and Solar Power Integration

Reactive Power Balance – Benefits using SVC/STATCOM/HYBRID STATCOM





Benefits by using SVC/STATCOM connected to PCC

- Wind turbine generator can be operated at a cosf =1 and the apparent power will be used for active power generation only.
- The SVC/STATCOM will compensate for turbines, capacitors and cable system, assuring a grid compliant PCC point.
- Less complexity and better dynamic performance.

Grid Code – Wind and Solar Power Integration
High Voltage Fault Ride Through (HVRT)

- Wind and solar power plants are subjected to high voltages that can occur in the transmission system
  - Fault clearance
  - Loss of large loads or other system transients.
- In many countries, the grid code requires the wind power plant not to trip for high voltages.
- Typical HVRT (High Voltage Ride Through) requirements can be;
  - Upto 110% of nominal voltage at PCC and even higher for shorter time periods.

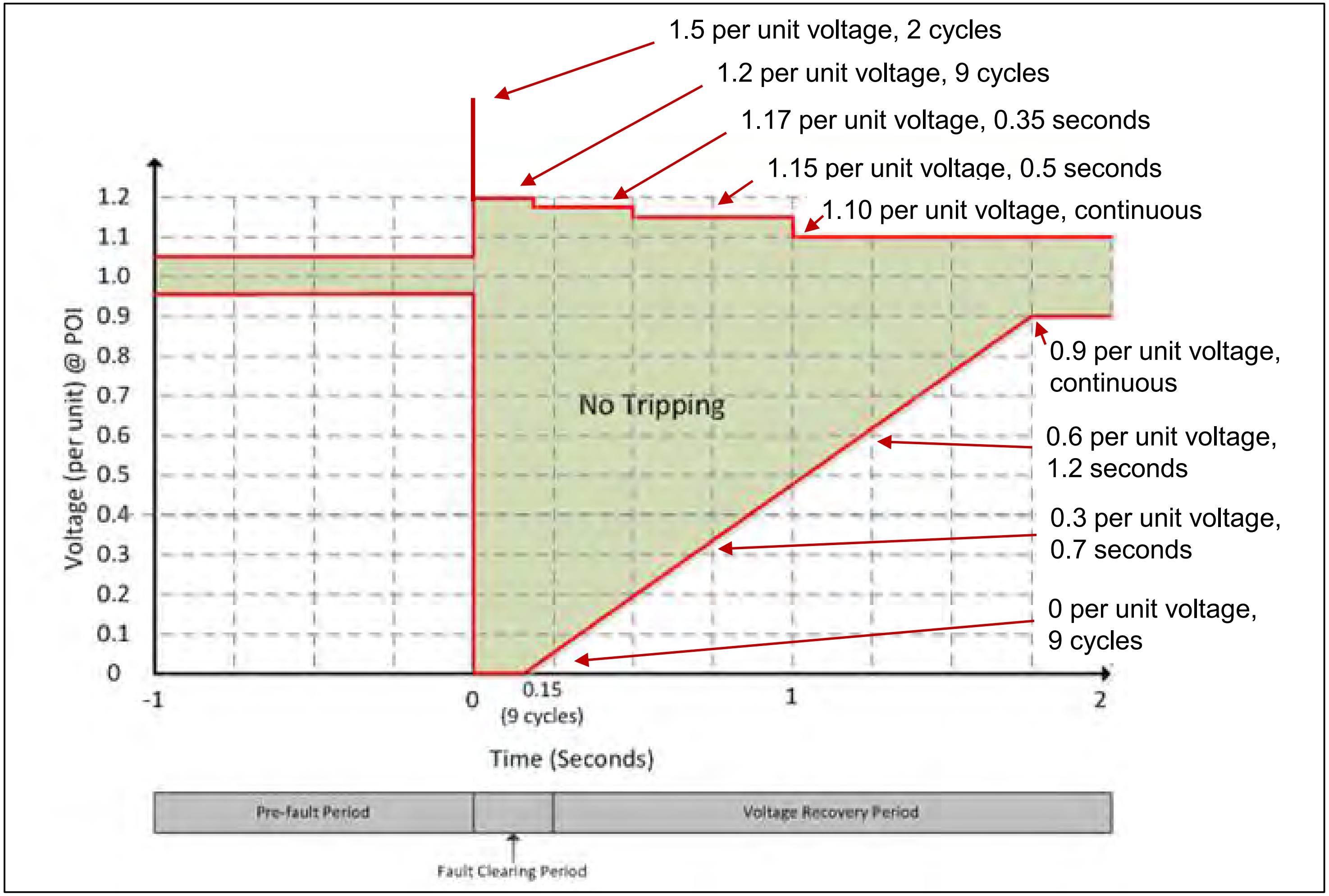
Grid Code – Wind and Solar Power Integration

Low Voltage Fault Ride Through (LVRT)

- The solar and wind plant and any constituent wind turbine unit shall remain transiently stable and connected to the system without tripping during low voltage.
- If a wind turbine trips during such a voltage dip and becomes disconnected;
  - The overall stability of the grid will be weakened.
  - Potentially causing more turbines to trip in a self-amplifying ripple effect.
  - Even small voltage dips in weaker electricity grids can cause a lot of wind turbines to trip and lose production.

Grid Code – Wind and Solar Power Integration

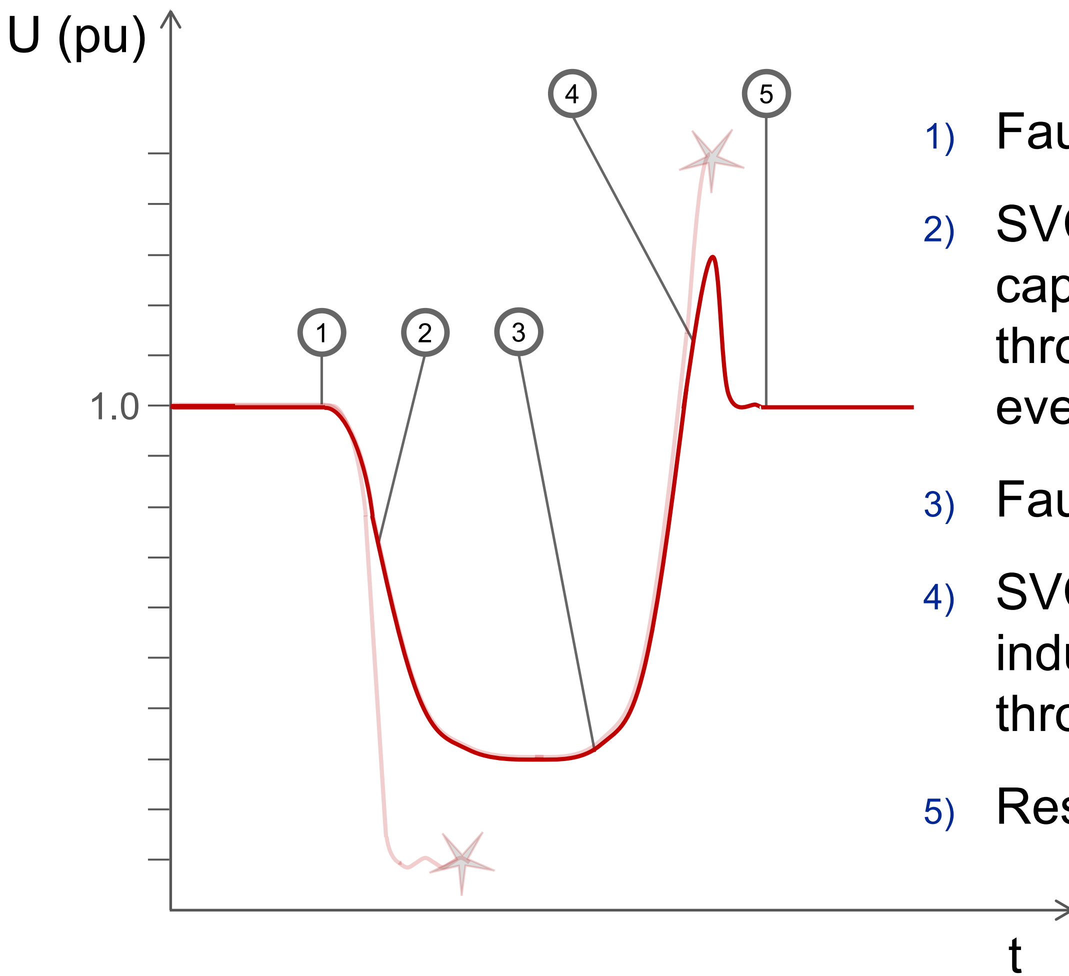
Voltage Ride Through – Example



- **Wind Power and Solar Power** installations shall not trip for voltage conditions described in the voltage ride through cycle (green area above).
- **SVC, STATCOM and HYBRID STATCOM** installations must be designed for more severe voltage conditions and longer durations.

Requirements on SVC, STATCOM and HYBRID STATCOM
Voltage Ride Through

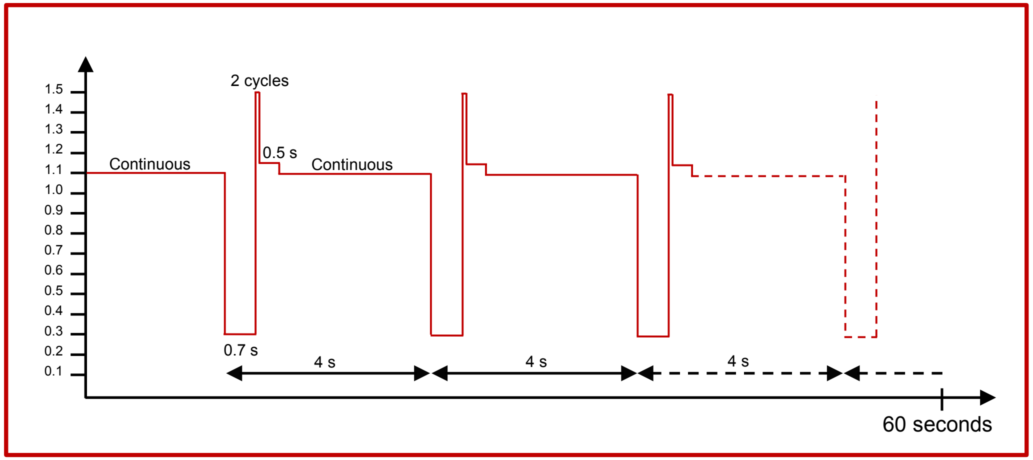
Operation with undervoltage ride through capability, and with overvoltage ride through capability



1) Fault
2) SVC/STATCOM/HYBRID at capacitive operation to ride through the undervoltage event
3) Fault is cleared
4) SVC/STATCOM/HYBRID at inductive operation to ride through the overvoltage event
5) Resume normal operation

Requirements on SVC, STATCOM and HYBRID STATCOM
Voltage Ride Through Cycle – Example

- **SVC, STATCOM and HYBRID STATCOM** installations must be designed for multiple ride through cycles without blocking the converter or tripping.
- Example: The installation must be able to provide the following without blocking or tripping:
  - Continuously provide max current at 1.1 p.u
  - Then provide full capacitive current at undervoltage down to 0.3 p.u during 0.7 seconds
  - Then provide full inductive current at overvoltage up to 1.5 p.u during 2 cycles
  - Then provide full inductive current at overvoltage up to 1.15 p.u during 0.5 seconds
  - Then continuously provide max current at 1.1 p.u
  - This shall occur cyclically every 4th second for up to 60 seconds



Grid Code – Wind and Solar Power Integration

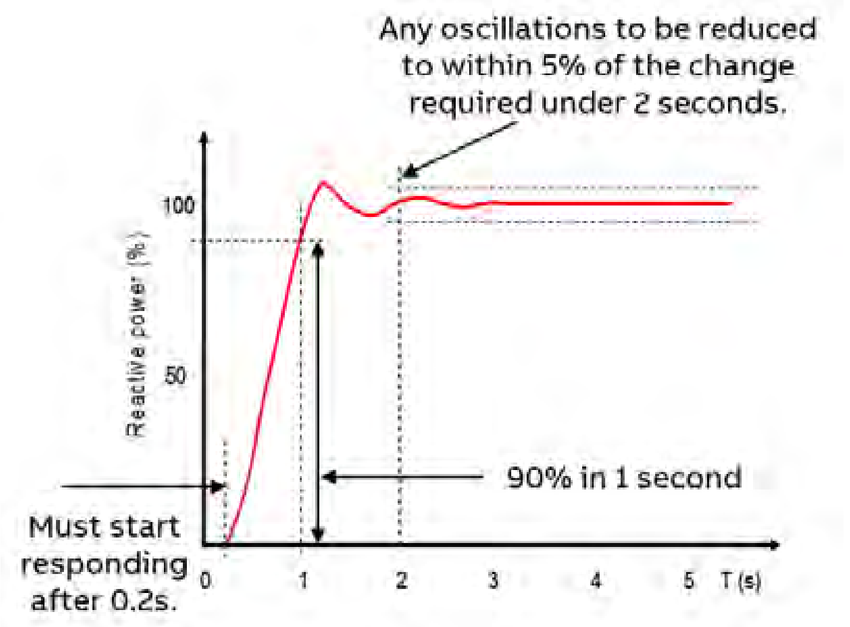
Dynamic Response of Reactive Power Control Scheme - Example

For a step change in voltage at the connection point:

- Wind farm to be capable of achieving 90% of the required change in steady state reactive power output within a certain time.
- Any oscillations in reactive power shall be damped out within a certain time.
- The wind farm must be able to respond within a certain time.
- A step from zero output to maximum required continuous reactive power output is required.

Example

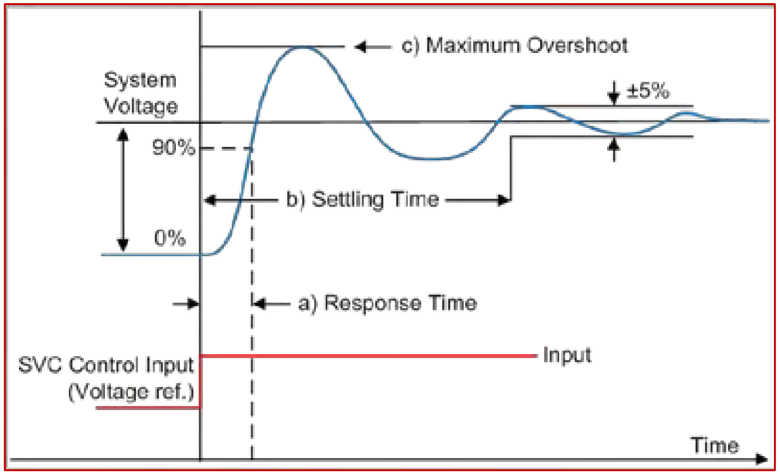
- Achieve 90% of the required change in 1 second.
- Oscillations in reactive power shall be damped out in less than 5% within 2 seconds.
- Respond within 0.2 seconds.



Requirements on SVC, STATCOM and HYBRID STATCOM

Dynamic Response for SVC, STATCOM and HYBRID STATCOM

- **SVC, STATCOM and HYBRID STATCOM** installations must be designed for more severe dynamic response conditions than Wind Power and Solar Power installations.



- **Requirements to be determined by studies!**
  - Typical response time 2-2.5 cycles (40-50 ms).
  - Typical overshoot <10%
  - Typical settling time <5 cycles (<100 ms).

Source: IEEE 1031-2011

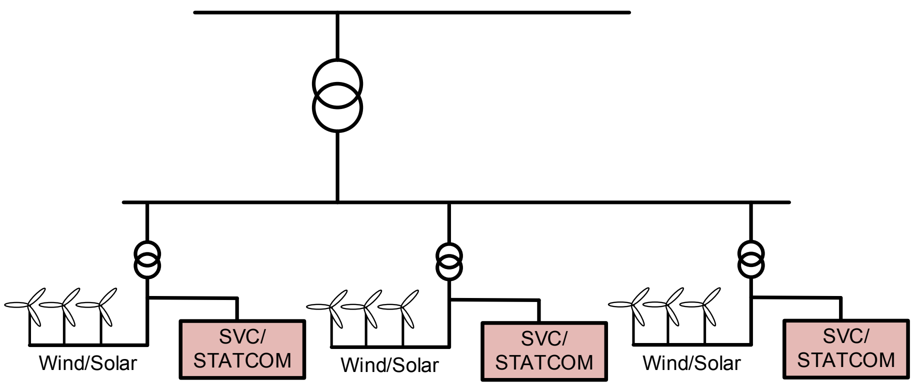
Specifying SVC, STATCOM and HYBRID STATCOM

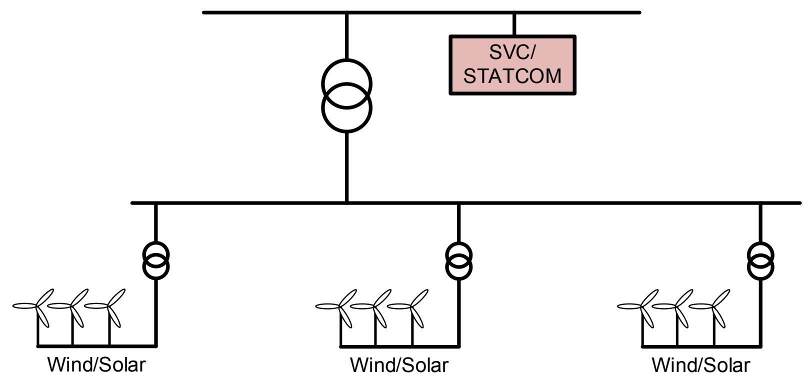
Location, Rating and Dynamic Performance

Several small distributed SVC/STATCOM installations?

OR

A large SVC/STATCOM installation upstream?





- Location, rating and dynamic performance of SVC, STATCOM and HYBRID STATCOM installations depends on the grid code and system requirements, e.g:
  - Power factor correction
  - Voltage stability requirements
  - etc.
- Location, rating and dynamic performance requirements to be determined by studies!

Specifying SVC, STATCOM and HYBRID STATCOM
How to Define the Location, Rating and Dynamic Performance of the Installation?

- What is the purpose of the SVC, STATCOM or HYBRID STATCOM installation?
  - Regulation and control of a defined voltage to the required set point under normal and contingency conditions.
  - Provide fast response reactive power following contingencies.
  - Prevent and reduce risk for voltage collapses in the grid.
  - Prevent overvoltages at loss of load.
  - Boost voltage during undervoltage disturbances such as faults.
  - Increase power transfer capability, by stabilizing voltage in weak points (heavy loads) in the grid.
  - Power factor control.
  - Detecting and damping of active power oscillations.
- To be determined by studies performed by customer!
  - Dynamic performance requirements
  - Mvar for different voltages
  - Location
- Supplier to select technology and design based on the outcome of the studies!

Specifying SVC, STATCOM and HYBRID STATCOM

Type of studies to be performed in order to specify optimal rating and performance!

Studies to be performed by Customer before request for tender is submitted!

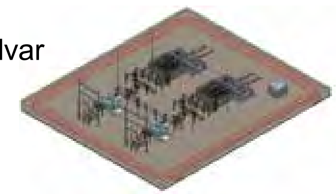
- Steady State Studies
  - Load Flow Studies
  - QV and PV analysis
- Dynamic Studies
  - Undervoltage conditions (angular stability, voltage stability)
  - Overvoltage conditions

Specifying SVC, STATCOM and HYBRID STATCOM
Studies and Modeling

- Data needed for studies and modeling
  - Grid code and power system requirements to meet.
  - Network contingencies and future scenarious.
  - Location of PCC
  - Minimum and maximum short-circuit levels with associated X/R ratios at the PCC.
  - Make, model, MW rating and number of wind turbine generators (WTGs).
  - Control mode(s) at the PCC; (i.e. voltage control, power factor control, constant susceptance control) along with the acceptable tolerances, dead bands, slopes, or other measures of dynamic response for these items.
  - Location of turbines relative to the PCC.
  - Dynamic models of SVC, STATCOM or HYBRID STATCOM.
  - Dynamic models of PV plant or Wind Turbines.
  - Power factor capability, control modes available (i.e., power factor, voltage, or reactive power).
  - SCADA dynamic response times, Wind Turbine Generator VRT (Voltage Ride Through) capability.
  - Step-up transformer details (MVA, percent impedance, X/R ratio, and available taps).
  - Collector cable schedules, including cable types, sizes, and lengths.
  - Details of collector substation transformer(s) (MVA, percent impedance, X/R ratio, and available taps)
  - Transmission line data (R, L, C) and distance from the collector substation transformer to the PCC

References
SVC, STATCOM and STATCOM HYBRID for Wind Power Integration

East Anglia STATCOM, UK



Rating:
- Two STATCOM, each rated ±215 Mvar
- Connected to 400 kV

Purpose:
- Grid integration of East Anglia One 714 MW wind farm.
  - Voltage control of 400 kV
  - Power factor control at 400 kV

McCamey Area SVC, Texas USA

Rating:
- 3 SVC, each rated -40Mvar to +50Mvar
- Directly connected to 69 kV (no transf.)

Purpose:
- Grid integration of a wind farm cluster in McCamey area in Texas, 1000 MW and growing
  - Voltage control of 69 kV under steady-state and transient conditions
  - Support the wind farms with reactive power to avoid losing synchronism at low voltage

La Ventosa SVC, Mexico

Rating:
- SVC rated ±300 Mvar
- Connected to 400 kV

Purpose:
- Grid integration of a windfarm cluster of 2000 MW and in the future totally 3900 MW
  - Control of 400 kV voltage under steady-state and transient conditions.
  - Provide damping of active power oscillations between wind farms and between wind farms and the grid.

Borken HYBRID STATCOM, Germany

Rating:
- HYBRID STATCOM rated -250 Mvar to +400 Mvar
- Connected to 400 kV

Purpose:
- Increased contribution of wind and solar plants in the system leads to stability and fluctuation issues that affect power supplies.
  - Need to reduce the risk of voltage collapse and power outages.
  - Control of 400 kV voltage under steady-state and transient conditions.

ABB

References
SVC, STATCOM and STATCOM HYBRID for Wind Power Integration

Westermost Rough STATCOM, UK

Rating:
- Two containerized STATCOM, each rated ±25 Mvar
- Connected to 35 kV

Purpose:
- Voltage control
- Power quality improvement
- Grid code compliance

Whitelee STATCOM, UK

Rating:
- Two containerized STATCOM, each rated ±15 Mvar
- Connected to 35 kV

Purpose:
- Voltage control during steady state and transient conditions
- Grid code compliance

Harestanes, UK

Rating:
- Two containerized STATCOM, each rated ±34 Mvar
- Connected to 35 kV

Purpose:
- Maximize power production of wind farm
- Fast response for full grid code compliance

Scout Moor STATCOM, UK

Rating:
- Two containerized STATCOM, each rated ±25 Mvar
- Connected to 35 kV

Purpose:
- Indoor solution installed in an existing building
- Grid code compliance
- High reliability and low losses
- “Ride through support” for grid failures

ABB

AMSC D-VAR® STATCOM Applications in Australia

November 2017

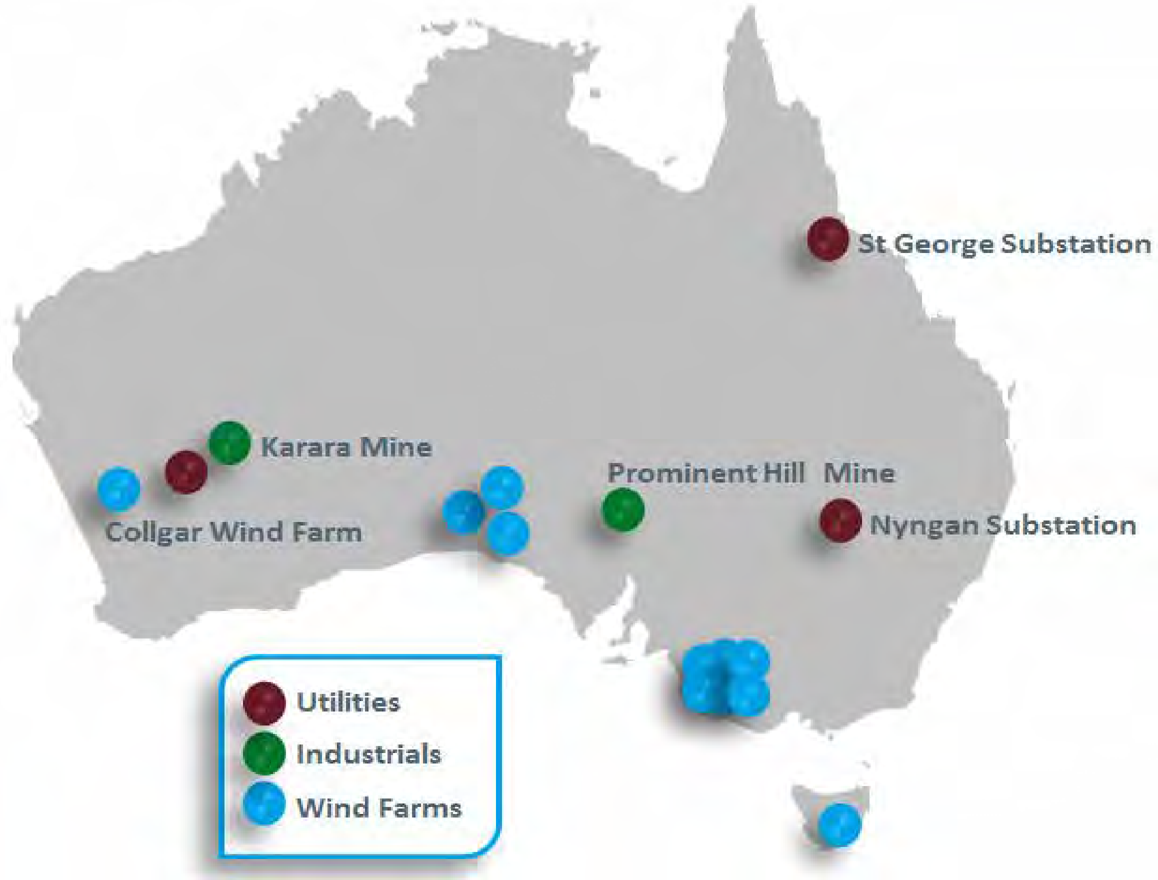
AMSC's D-VAR® STATCOM Solutions

- Proprietary 4 MVA building block technology exclusively available from AMSC
- Provides dynamic reactive capability – both leading and lagging
- D-VAR STATCOM has overload capability of 3.0 times its continuous rating
- It can seamlessly switch other devices and communicate with wind farms and PV solar plants to increase net reactive output

D-VAR® STATCOMs Installations in Australia

- Renewable Applications
- Industrial Applications
- Utility Application

148 Installations World Wide



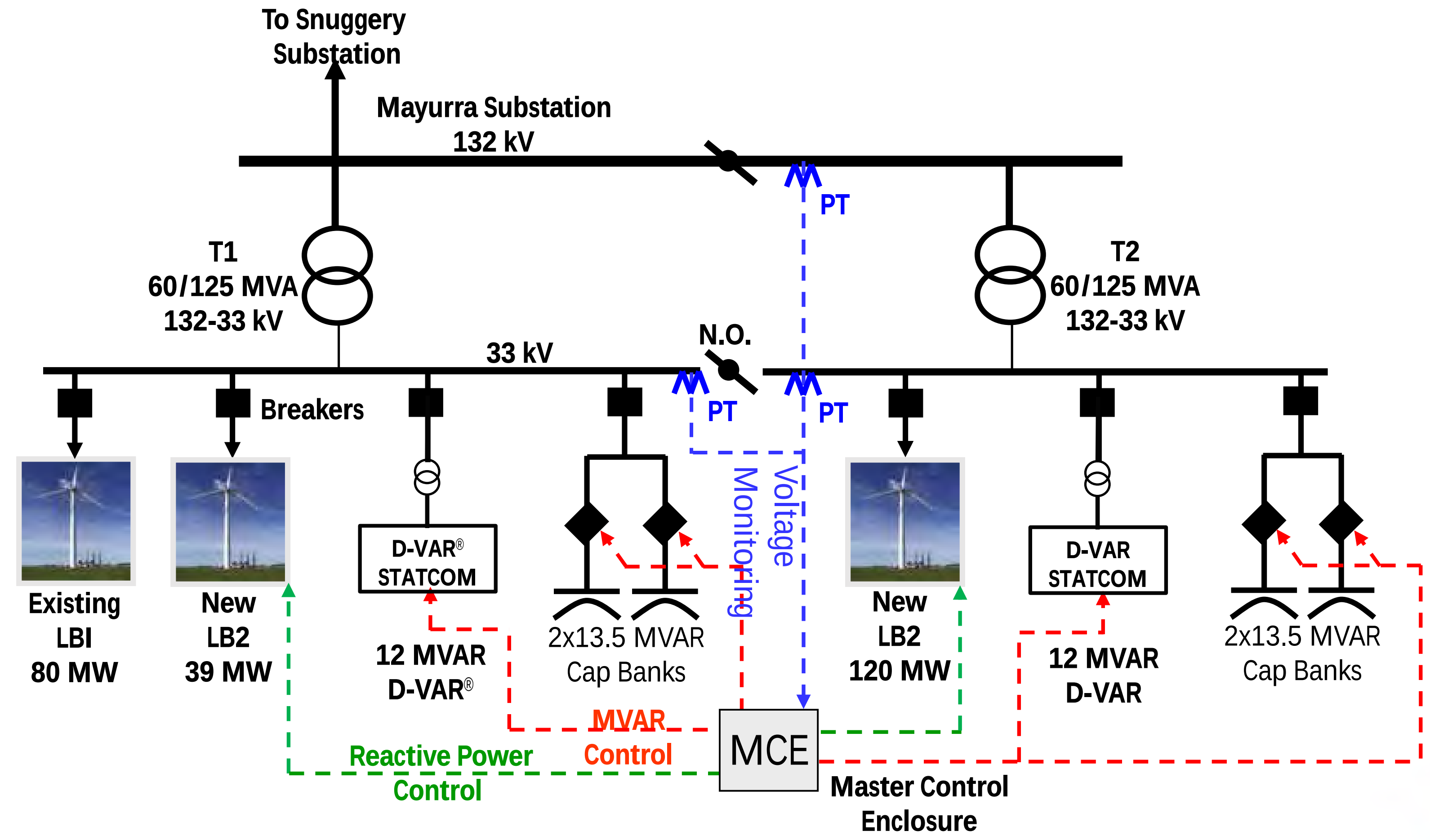
South Australia

Grid Code Requirements

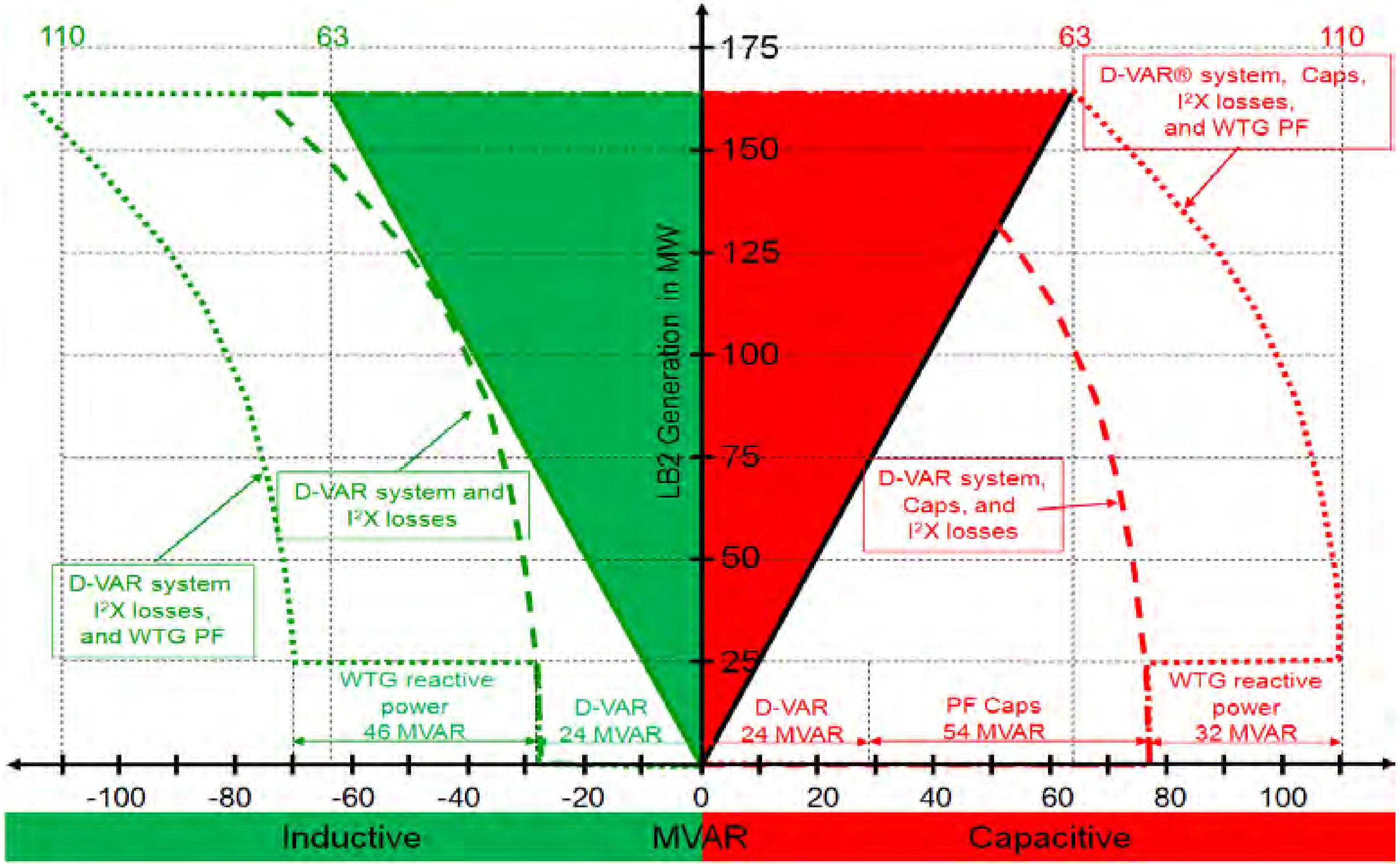
- Capable of supplying anywhere within +/-93% PF at the POI during full generation conditions
- Half of the reactive power capability shall be dynamic
- Reactive output proportional to generation level
- Regulate transmission system voltage
- Avoid tripping wind farm for nearby transmission grid faults and high voltage (LVRT, HVRT)
- Restore transmission system post fault voltage to a minimum of 90%

Lake Bonney I and II Wind Farms

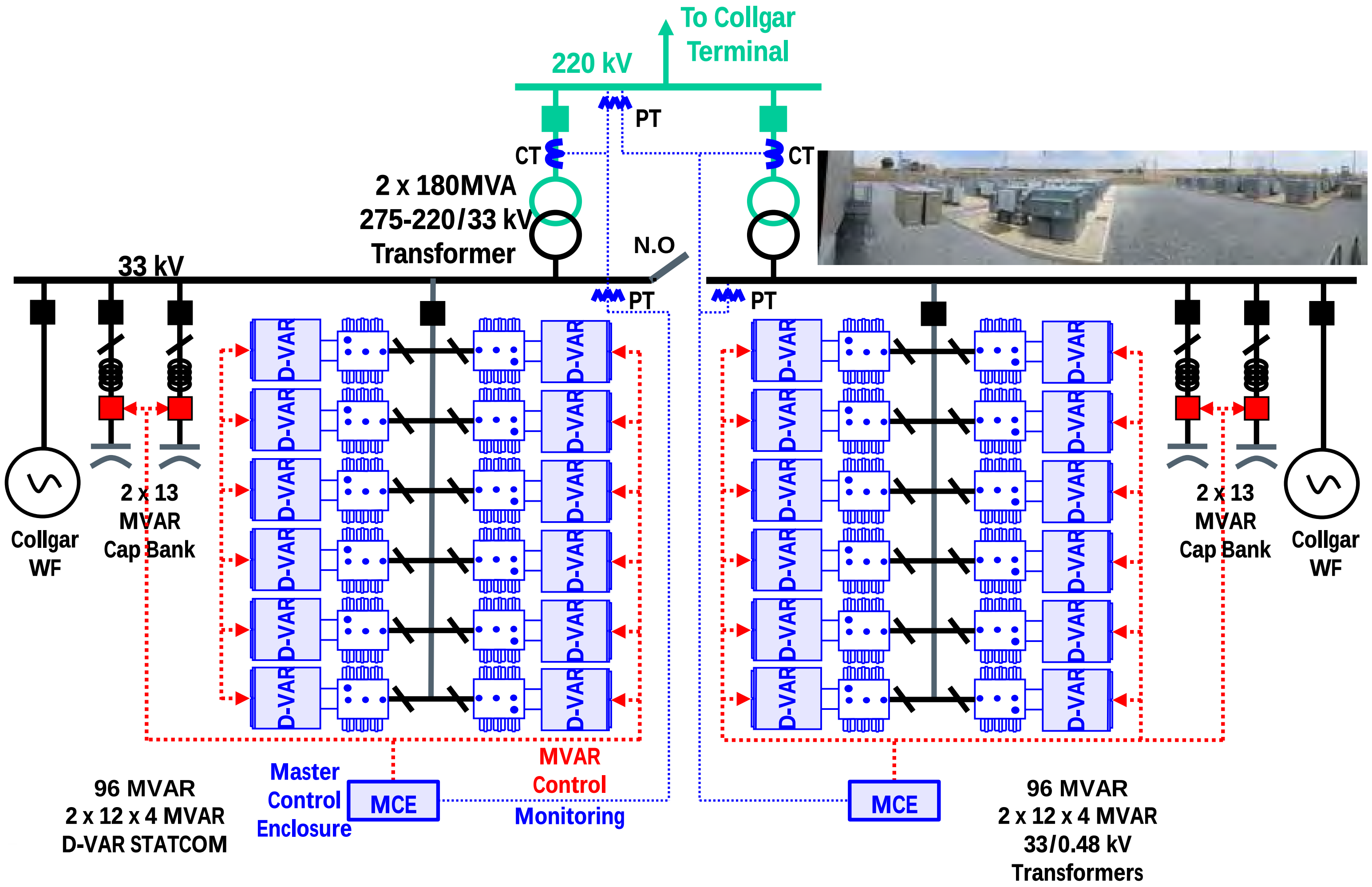
D-VAR® STATCOM Solution



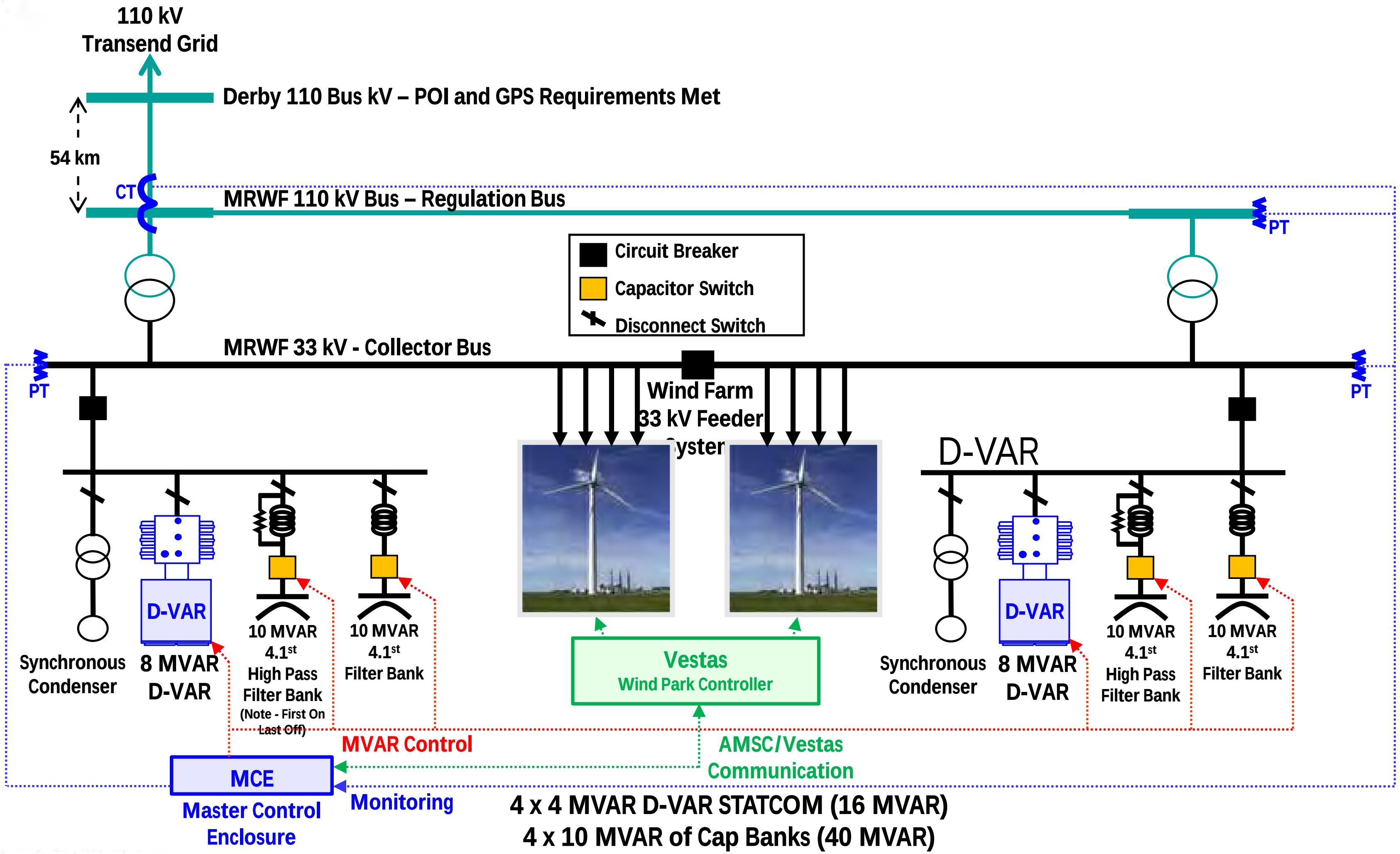
Lake Bonney II Reactive Requirements & Capability as a Function of Generation Level



Collgar Wind Farm D-VAR® Installation



Musselroe WF D-VAR® Installation



4 x 4 MVAR D-VAR STATCOM (16 MVAR)

4 x 10 MVAR of Cap Banks (40 MVAR)

South Australia Blackout – September 28, 2016
D-VAR® Performance

Black System Event in S. Australia on 28 SEP 2016

Event Summary from AEMO Report - 19 Oct 2016

Reference: https://www.aemo.com.au/Media-Centre/Update-to-report-into-SA-state-wide-power-outage

Transmission Line Faults

Event Summary from AEMO Report - 19 Oct 2016

Table 3 Transmission line faults

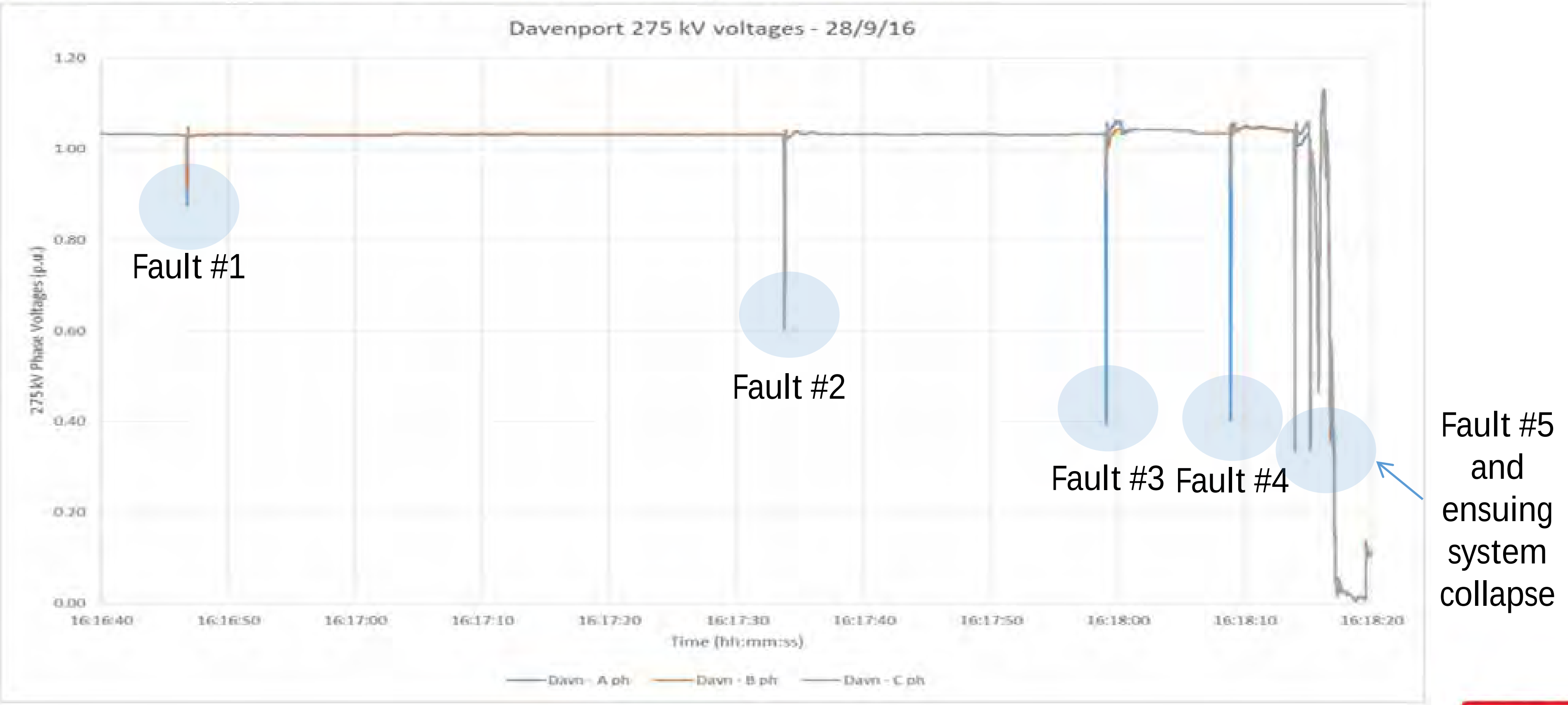
Fault number	Time	Details
1	16:16:46	Fault on Northfield-Harrow 66kV feeder in the Adelaide metropolitan area. Trip and successful auto-reclose. Voltage dipped to 85% at Davenport.
2	16:17:33	Two phase to ground fault on the Brinkworth – Templers West 275kV transmission line. No reclose attempt. Voltage dipped to 60% at Davenport.
3	16:17:59	Single phase to ground fault on the Davenport – Belalie 275kV transmission line. Faulted phase successfully auto-reclosed. Voltage dipped to 40% at Davenport.
4	16:18:08	Single phase to ground fault on the Davenport – Belalie 275kV transmission line. No auto-reclose attempted as fault is within 30 seconds of the previous fault Line opened on all three phases and remained out of service. Voltage dipped to 40% at Davenport.
5	16:18:13	Single phase to ground fault on the Davenport – Mt Lock 275kV transmission line. Voltage dipped to 40% at Davenport.
	16:18:14	Single phase to ground fault on the Davenport – Mt Lock 275kV transmission line due to unsuccessful auto-reclose. Fault still on line. Line opened on all three phases and remained out of service. Voltage dipped to 40% at Davenport.

Reference: https://www.aemo.com.au/Media-Centre/Update-to-report-into-SA-state-wide-power-outage

Davenport – Olympic Dam Line Voltage

Event Summary from AEMO Report - 19 Oct 2016

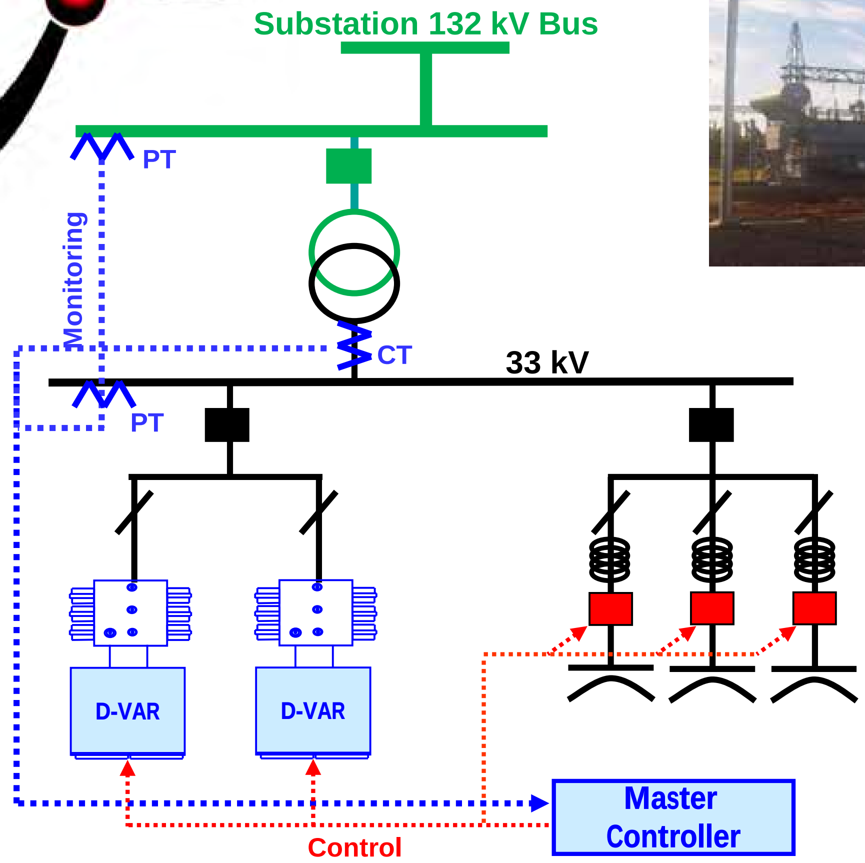
Figure 4 Voltages measured at Davenport – Olympic Dam 275 kV line



Reference: https://www.aemo.com.au/Media-Centre/Update-to-report-into-SA-state-wide-power-outage

D-VAR® Response During Faults on 28 Sept 2016

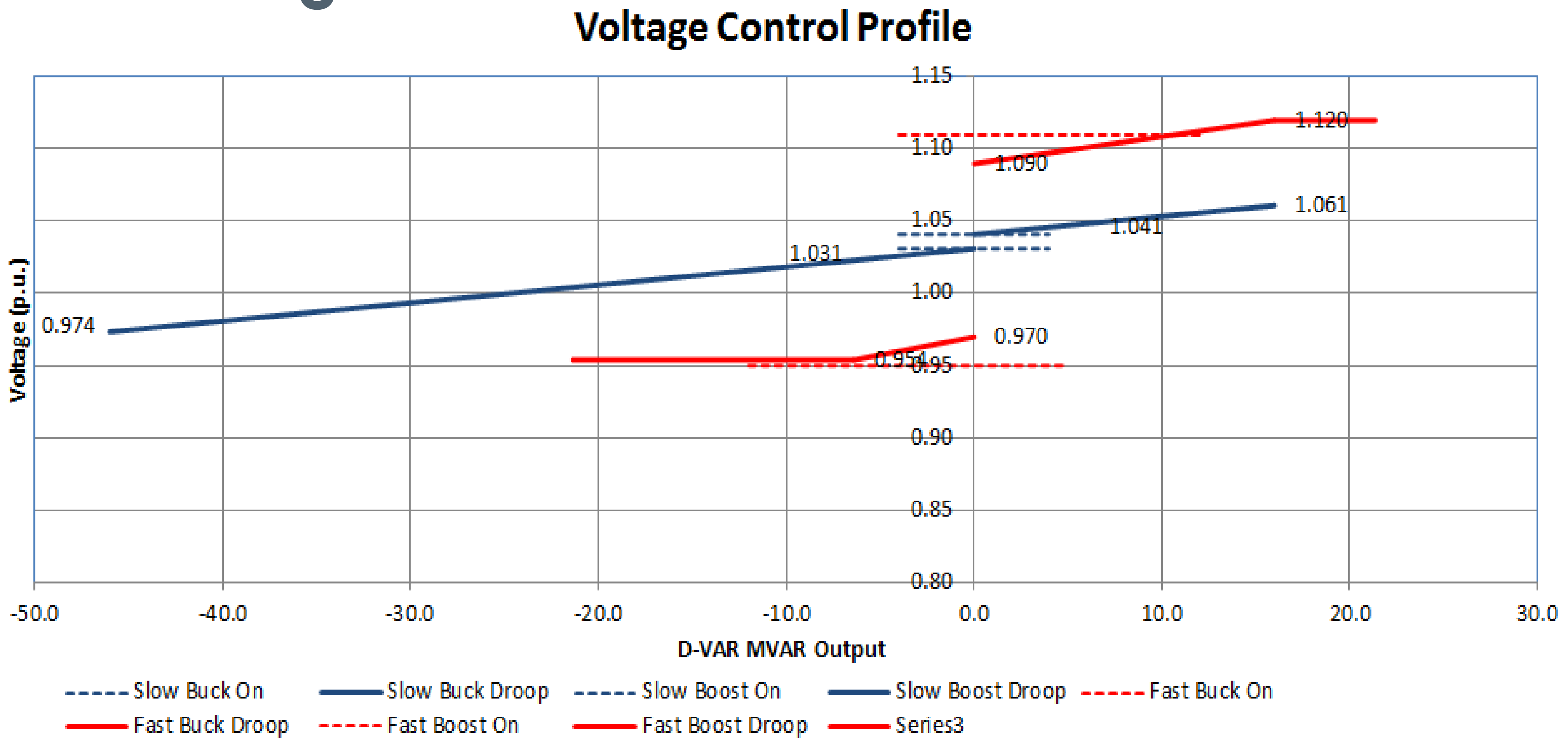
D-VAR® STATCOM System for a Wind Farm



AMSC D-VAR System

- During transient low voltage events, D-VAR® controls the low side voltage (33 kV) with a control target of 1.0 pu
- As long as the voltage is above 0.20 pu, D-VAR® will respond up to its full overload capability (2.67 pu current)
- Low side voltage and DVAR current response to the faults (#1 thru #5) are provided

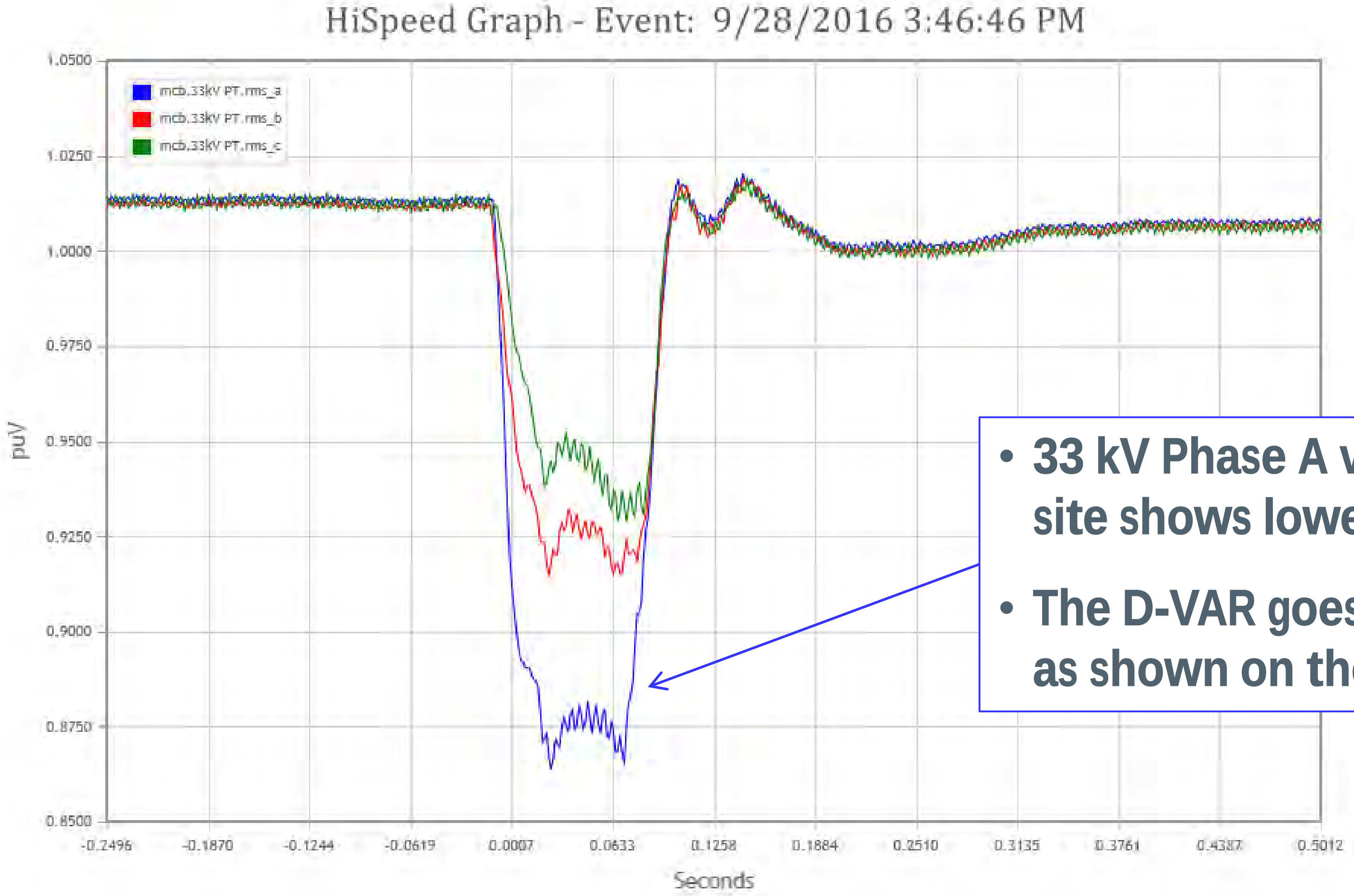
Voltage Control Profile of Wind Farm A



Fault #1 at 16:16:46 – Wind Farm A

33 kV RMS Voltage: Phase A-Blue, Phase B-Red, Phase C-Green

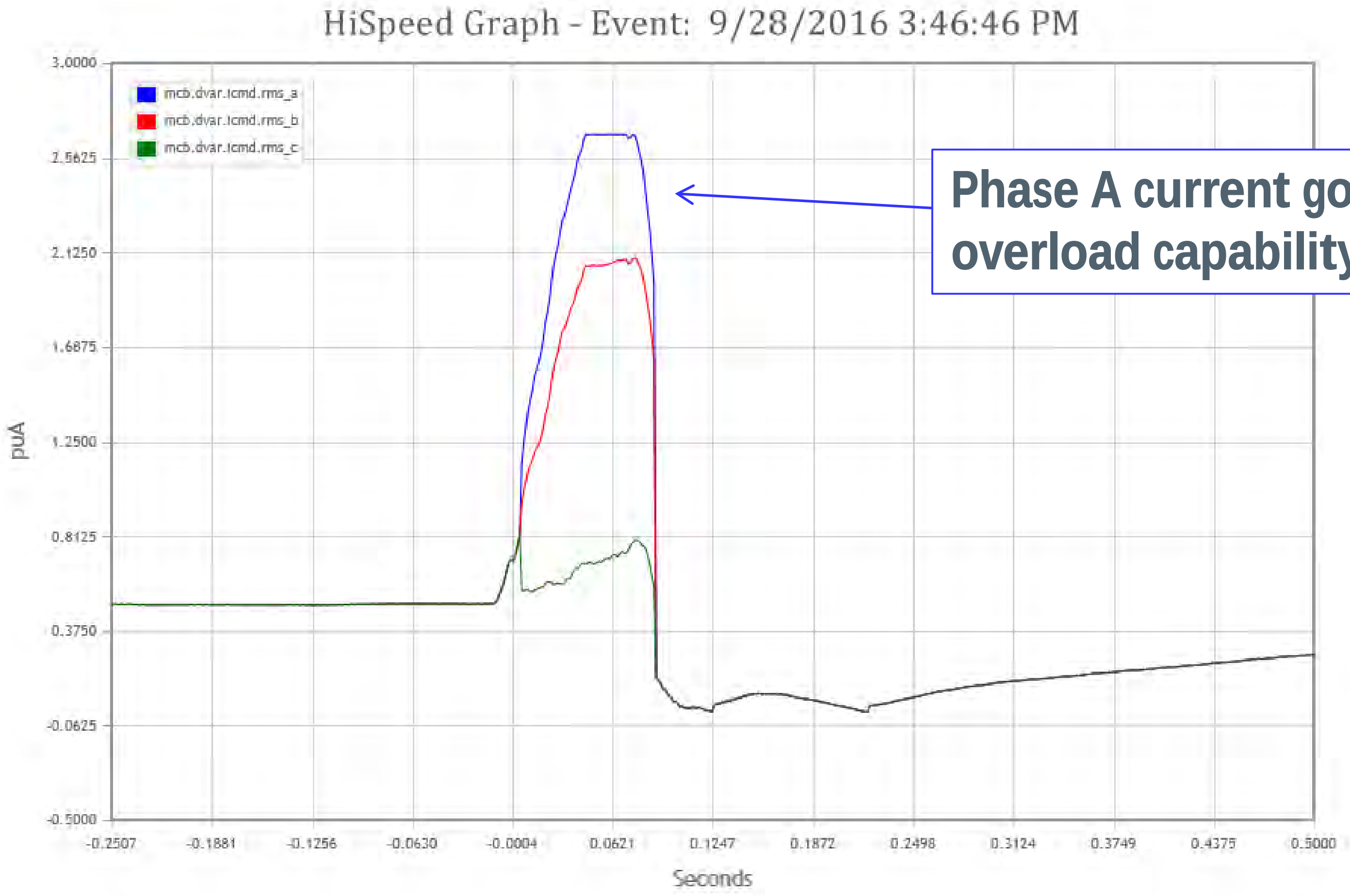
- **Fault on Northfield-Harrow 66 kV feeder in the Adelaide metropolitan area**
- **Trip and successful auto-reclose. Voltage dipped to 85% at Davenport**



- **33 kV Phase A voltage at the site shows lowest voltage dip**
- **The D-VAR goes to overload as shown on the next slide**

Fault #1 at 16:16:46 – Wind Farm A

D-VAR RMS Current: Phase A-Blue, Phase B-Red, Phase C-Green

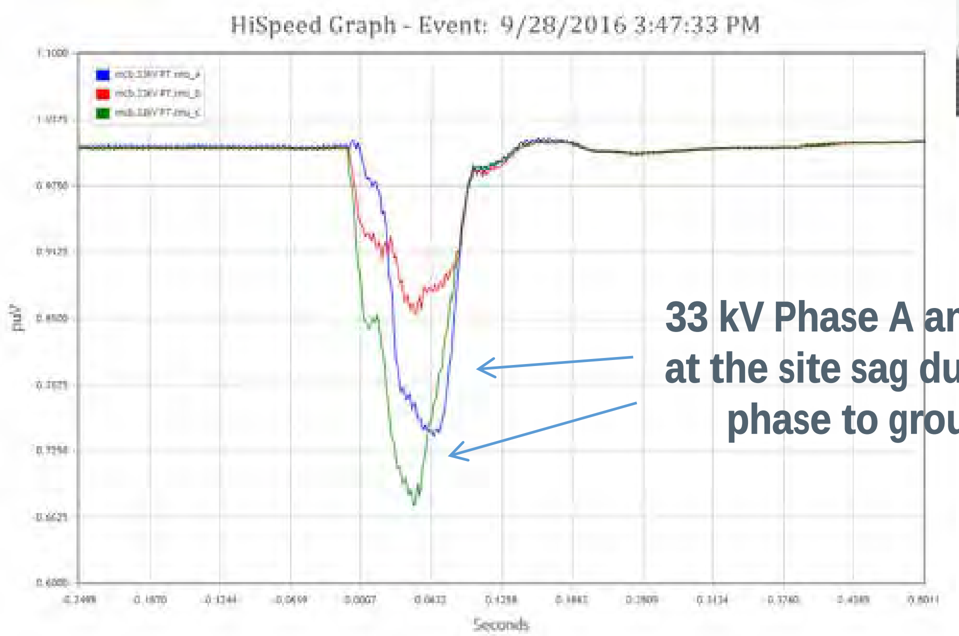


Phase A current goes to full overload capability (2.67 pu)

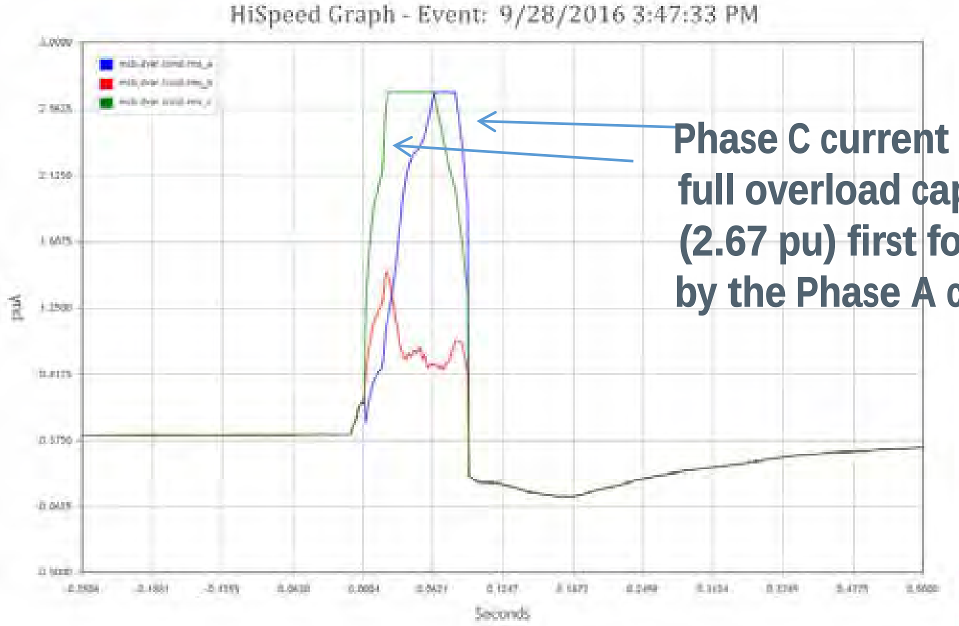
Fault #2 at 16:17:33 – Wind Farm A

- Two phase to ground fault on the Brinkworth – Templers West 275 kV transmission line
- No reclose attempt
- Voltage dipped to 60% at Davenport

33 kV RMS Voltage



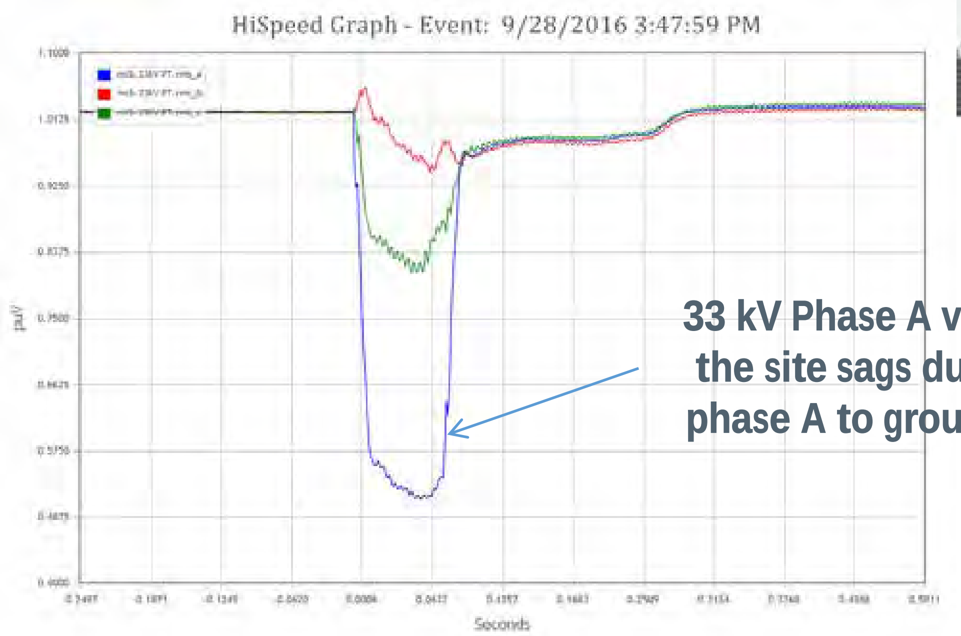
D-VAR RMS Current



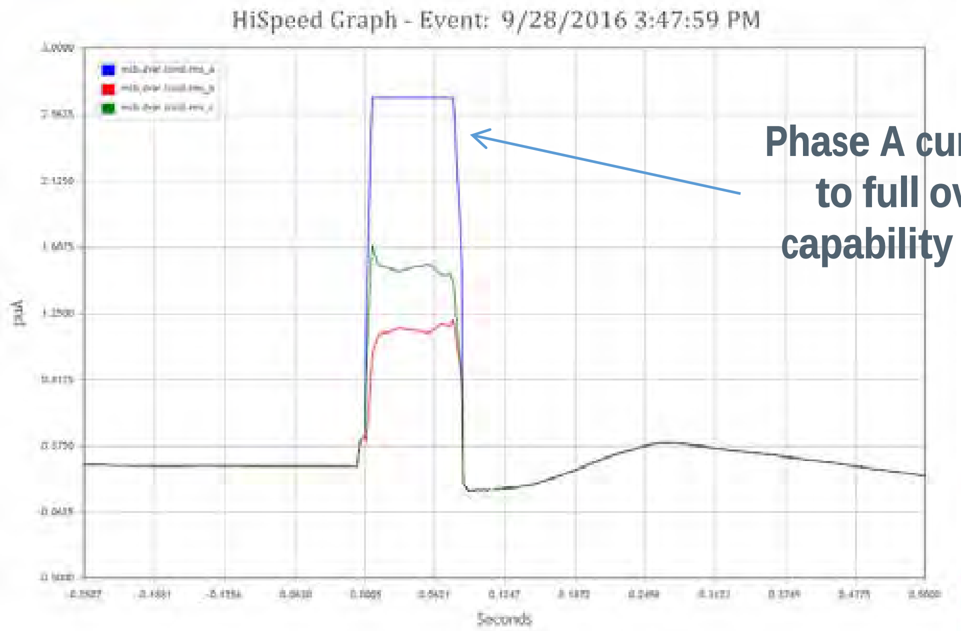
Fault #3 at 16:17:59 – Wind Farm A

- Single phase to ground fault on the Davenport – Belalie 275 kV transmission line.
- Faulted phase successfully auto-reclosed.
- Voltage dipped to 40% at Davenport.

- 33 kV RMS Voltage



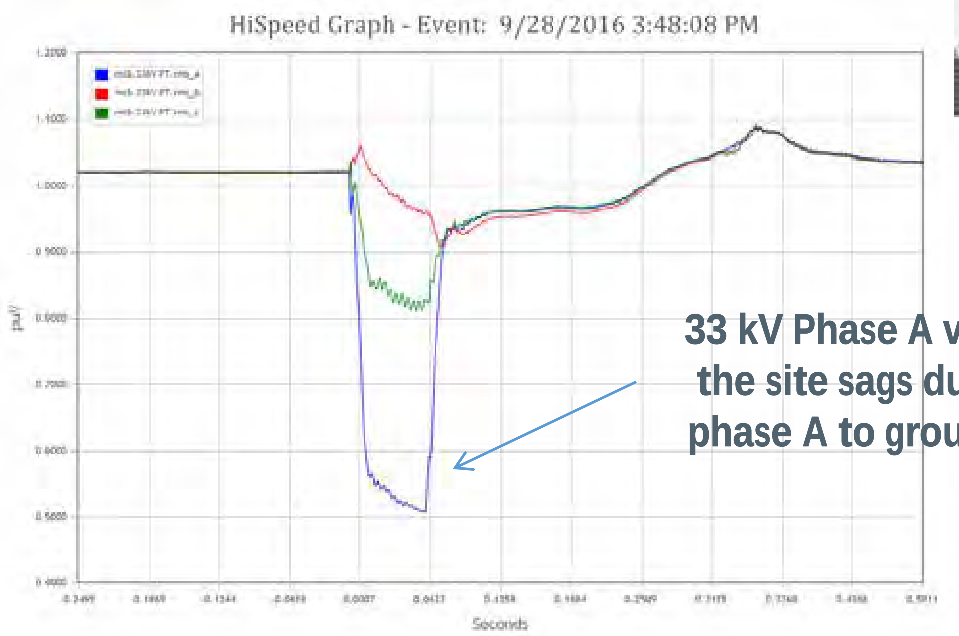
D-VAR RMS Current



Fault #4 at 16:18:08 – Wind Farm A

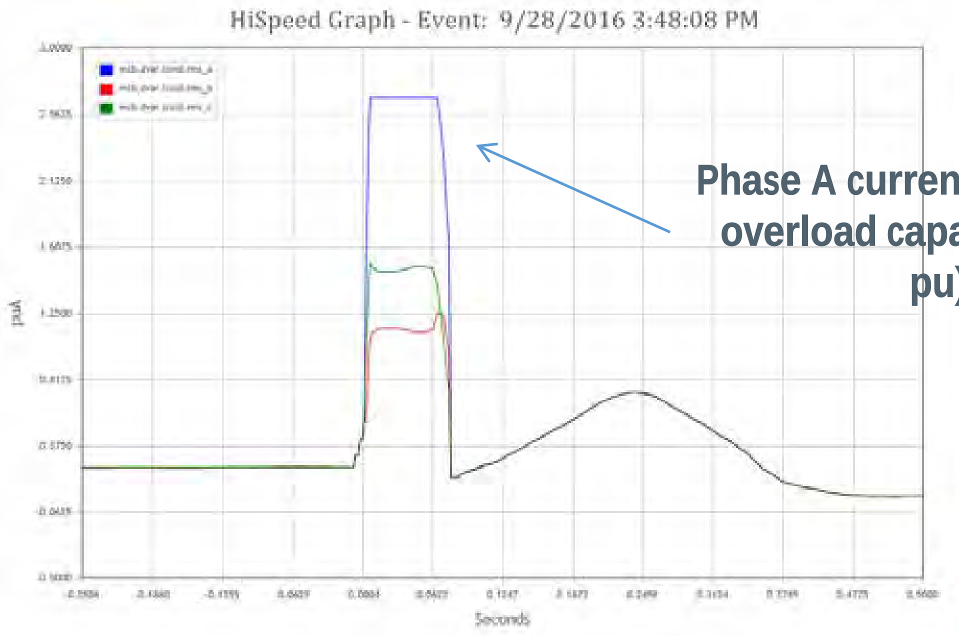
- 33 kV RMS Voltage

- Single phase to ground fault on the Davenport – Belalie 275 kV transmission line.
- No auto-reclose attempted as fault is within 30 seconds of the previous fault.
- Line opened on all three phases and remained out of service.
- Voltage dipped to 40% at Davenport.



33 kV Phase A voltage at the site sags due to the phase A to ground fault.

D-VAR RMS Current

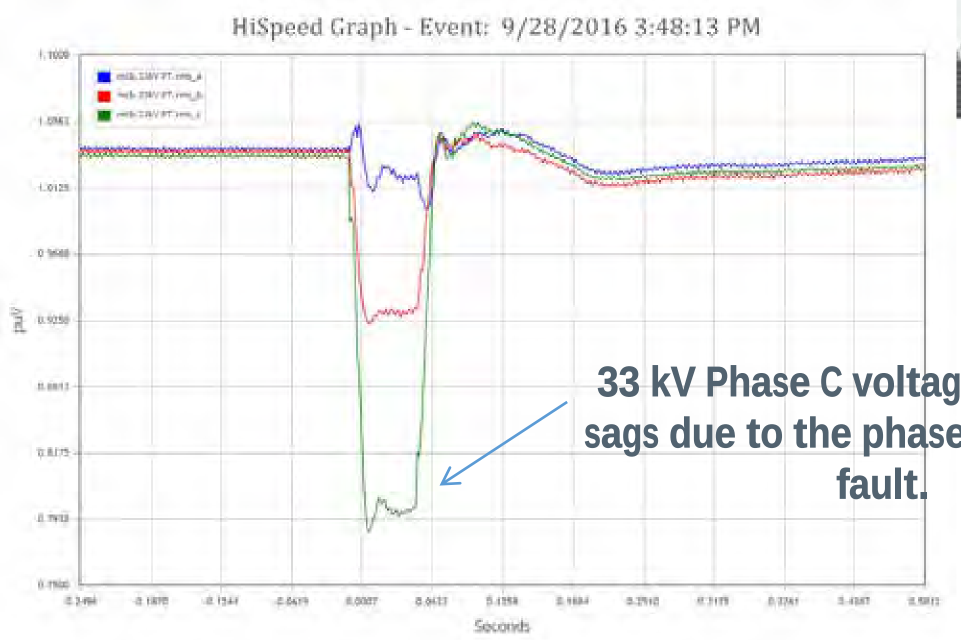


Phase A current goes to full overload capability (2.67 pu)

Fault #5 at 16:18:13 – Wind Farm A

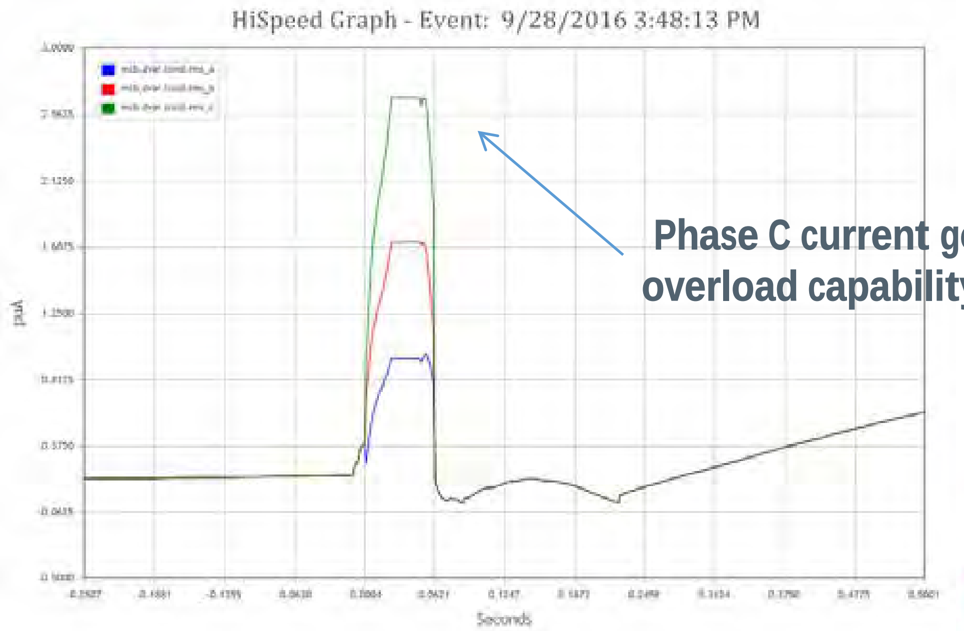
- Single phase to ground fault on the Davenport – Mt Lock 275 kV transmission line.
- Voltage dipped to 40% at Davenport.

33 kV RMS Voltage



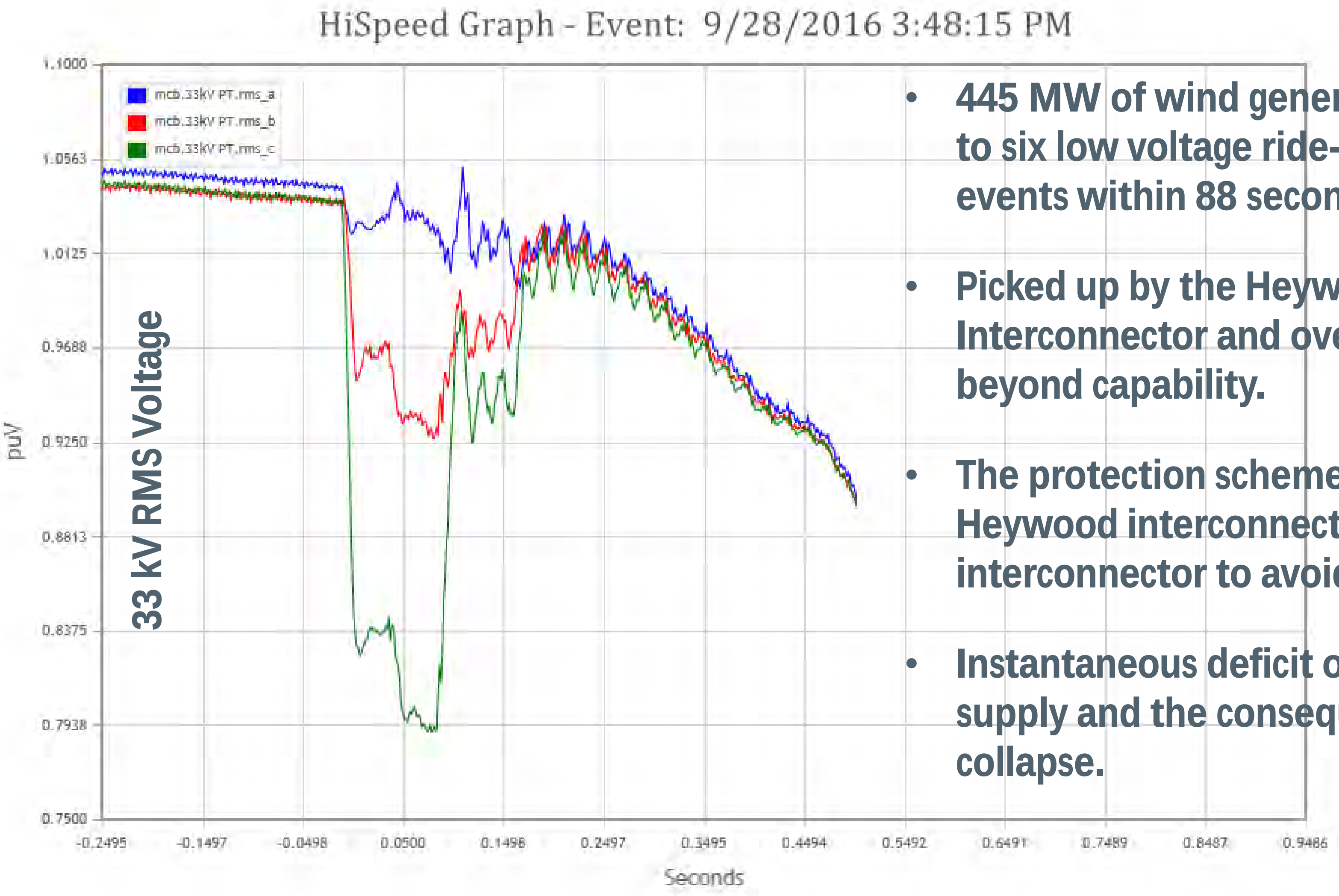
33 kV Phase C voltage at the site sags due to the phase C to ground fault.

D-VAR RMS Current



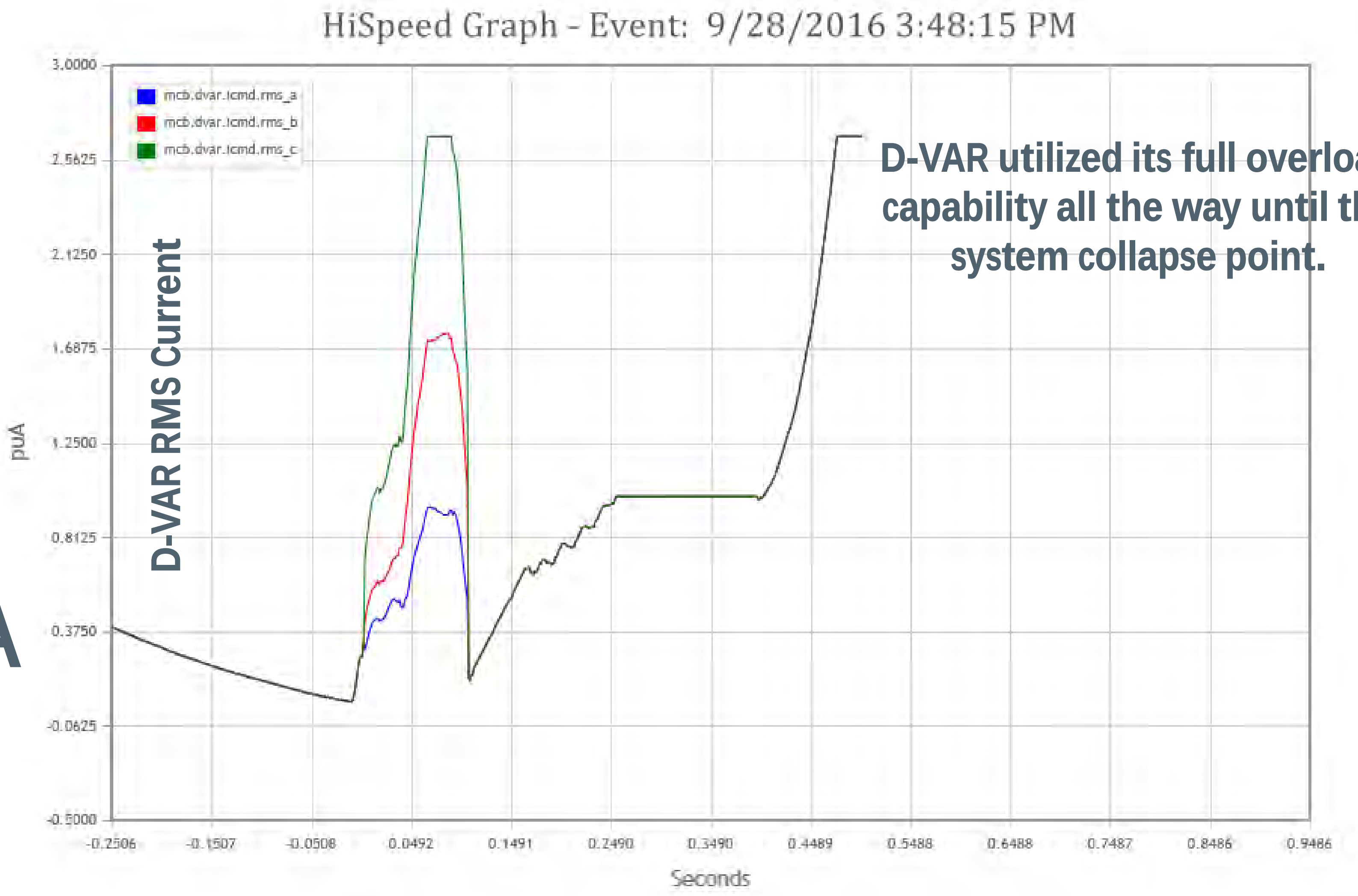
Phase C current goes to full overload capability (2.67 pu)

Voltage Collapse at 16:18:15 – Wind Farm A



- **445 MW of wind generation lost due to six low voltage ride-through events within 88 seconds.**
- **Picked up by the Heywood Interconnector and overloaded it beyond capability.**
- **The protection scheme of the Heywood interconnector tripped the interconnector to avoid damage.**
- **Instantaneous deficit of 900 MW of supply and the consequent system collapse.**

Voltage Collapse at 16:18:15 – Wind Farm A



D-VAR utilized its full overload capability all the way until the system collapse point.

Summary of D-VAR® Response during SA Blackout

- D-VAR STATCOM provides the dynamic power factor that the wind farm must fulfill as part of the Grid Code requirements.
- D-VAR® response for all the faults were as designed.
  - All units provided full overload capability during fault conditions.
- D-VAR provides voltage support during transient events.
- Wind turbine generators go into their low voltage ride-through modes during faults since the voltage sag depends on the location and severity of faults.
  - The fault ride-through settings of wind turbines are determined by the wind farm manufacturer.

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Utilizing dSTATCOMs for improving voltage profile of LV distribution networks with high levels of PV

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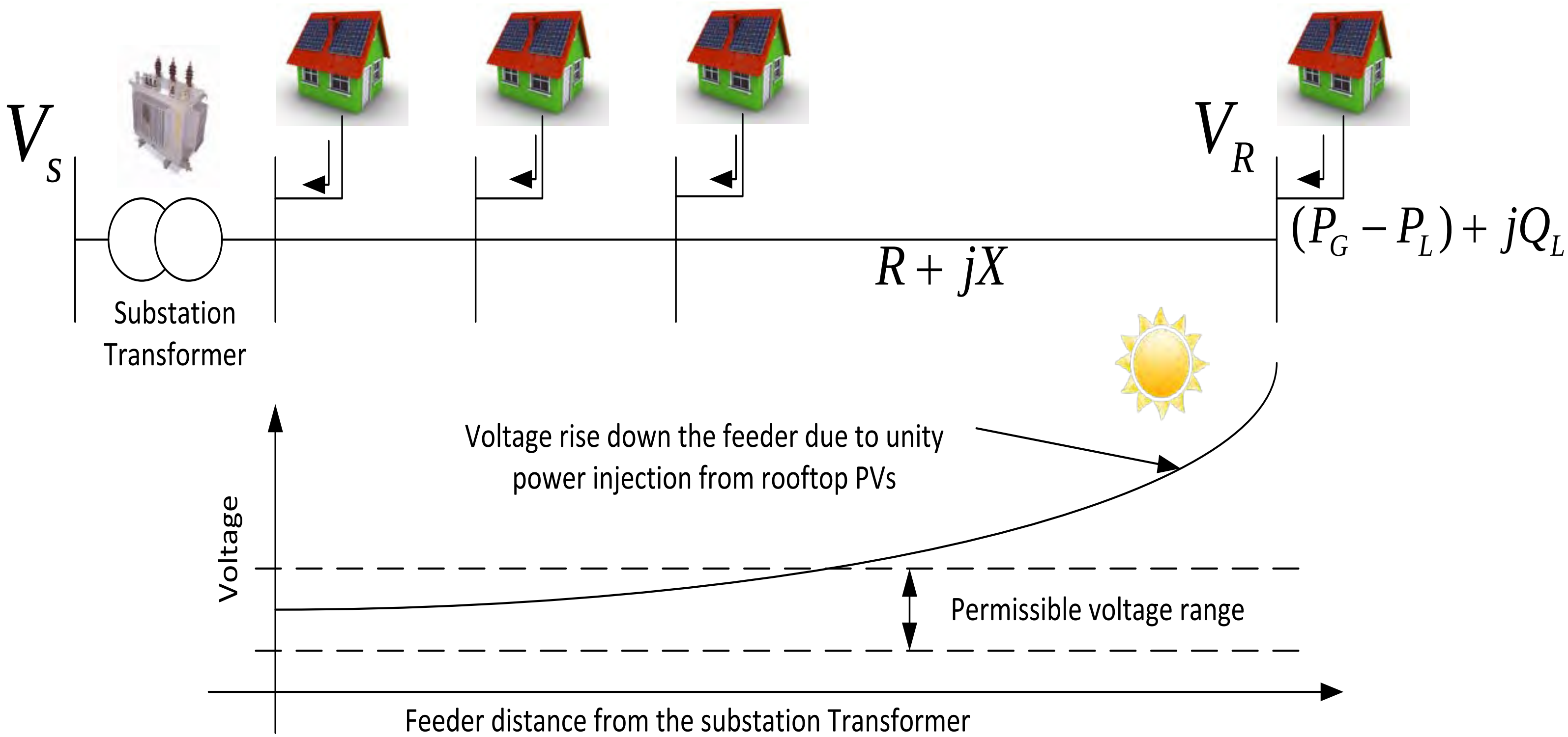
Increasing penetration of Rooftop PVs in LV network

- Unprecedented growth in the uptake of rooftop PVs in Australia, particularly in Queensland and its only going to go up
- State government aims at having one million rooftops or 3,000 megawatts of solar photovoltaics in Queensland by 2020
  - o Solar for public housing trial
  - o Advancing Clean Energy Schools
  - o Solar for small to medium business
- However, even at current penetration level, several utilities are finding it difficult to maintain voltage profile in LV feeders (240V ±6% i.e. 254-225V or 230V +10%/- 6% i.e. 253-216V)

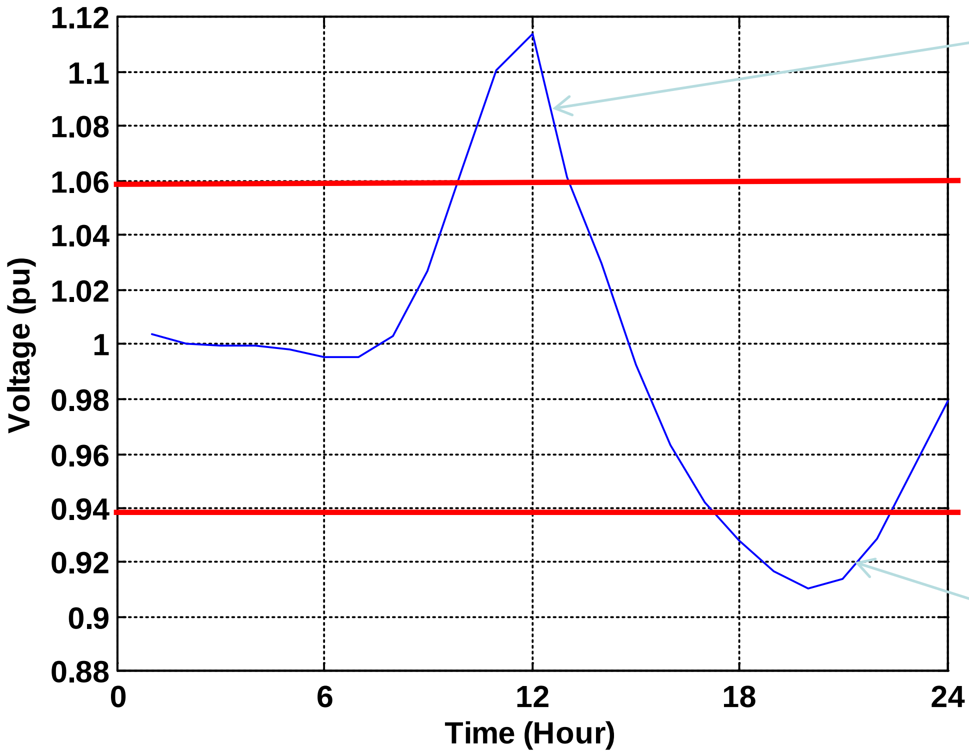
https://www.dews.qld.gov.au/electricity/solar

Voltage-rise problem in LV feeders due to PV injection



Receiving end voltage, $$V_R = V_s + \frac{R(P_G - P_L) - XQ_L}{V_R} + j\frac{X(P_G - P_L) + RQ_L}{V_R}$$

Voltage violations in LV feeders



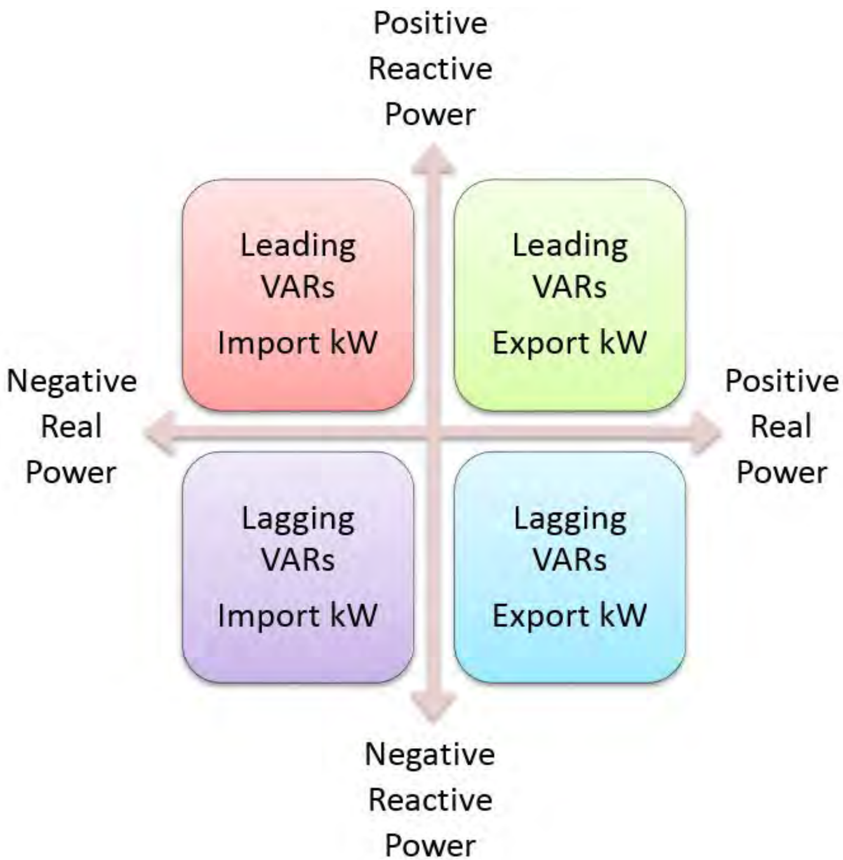
- Voltage rise problem during the day time, when PVs are injecting power;
- Voltage dip problem during evening peak

WHY dSTATCOMs ??

- Conventional approach to deal with voltage drop/rise problem are ineffective
  - o Tap-changer in distribution transformer
  - o Network Augmentation e.g. upgrading LV backbone or Customer service cable
- LV dSTATCOMs, whereas, suits best in these situations benefits
  - o Minimise short-term voltage fluctuations;
  - o Fast voltage response;
  - o Ability to correct phase imbalance;
  - o Set and forget functionality;
  - o Low-CAPEX and OPEX compared to network augmentation

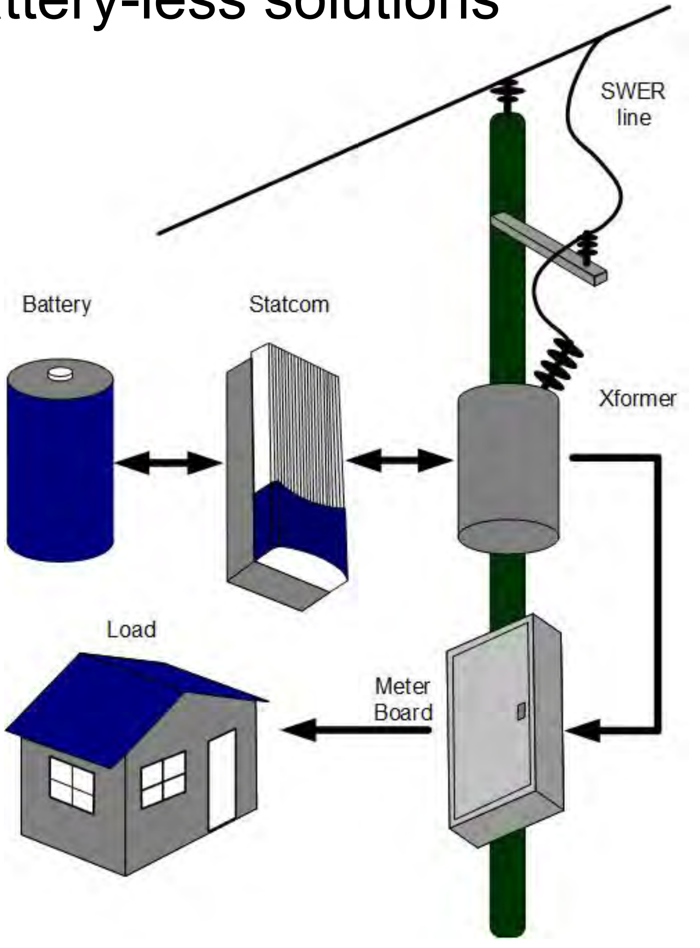
WHY dSTATCOMs ??

- dSTATCOMs are designed to be used in applications on the LV network and can produce reactive power (leading and lagging), with a surge rating capabilities
- It has sub-cycle response times to adjust the voltage to desired levels
- These units can be operated with/without integrated batteries for real power injection/absorption directly on the LV feeders



LV distributed dSTATCOMs

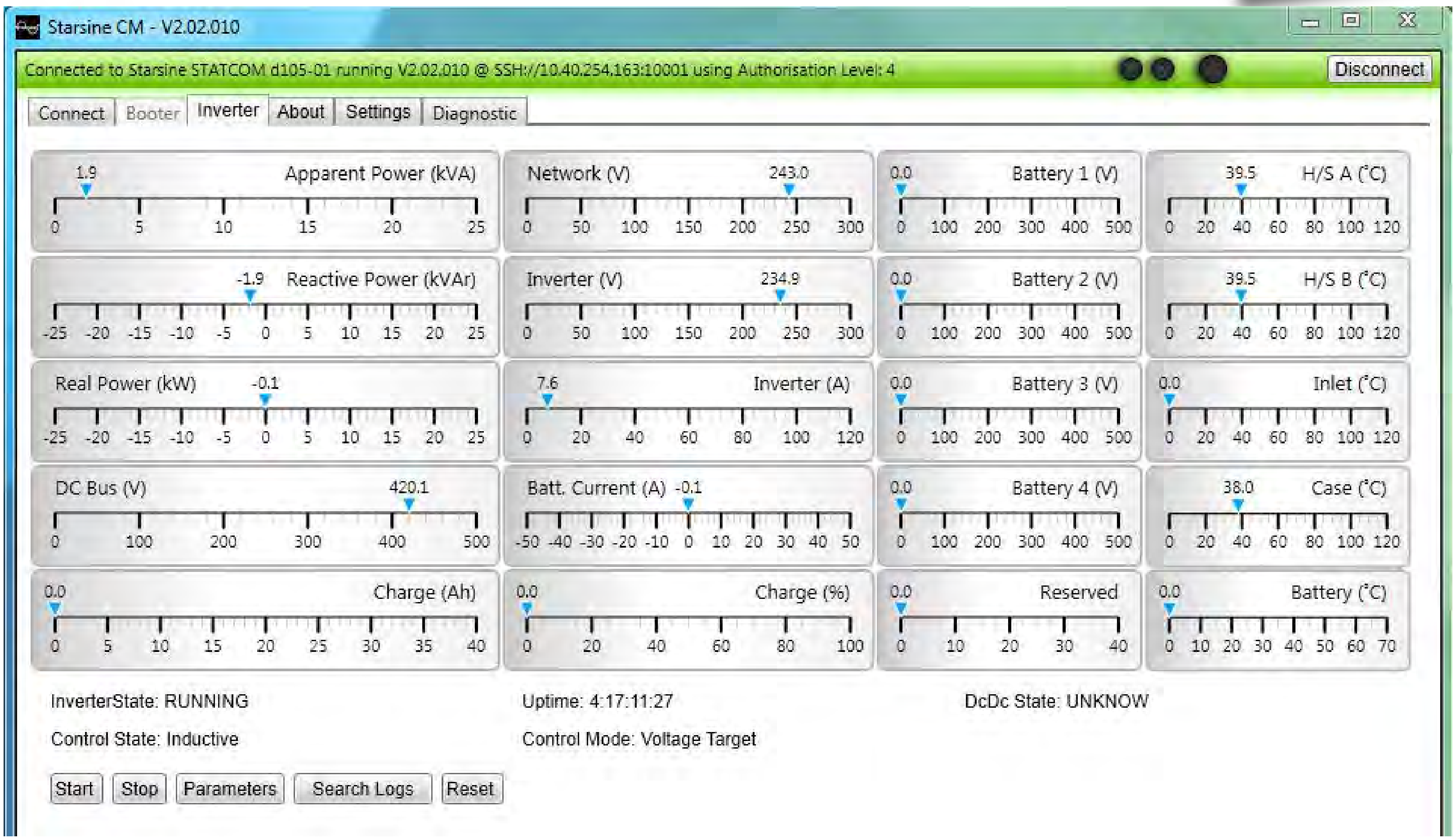
Urban & Rural, Battery and Battery-less solutions



dSTATCOMs operating Software

STATCOM Solutions

Queensland University of Technology

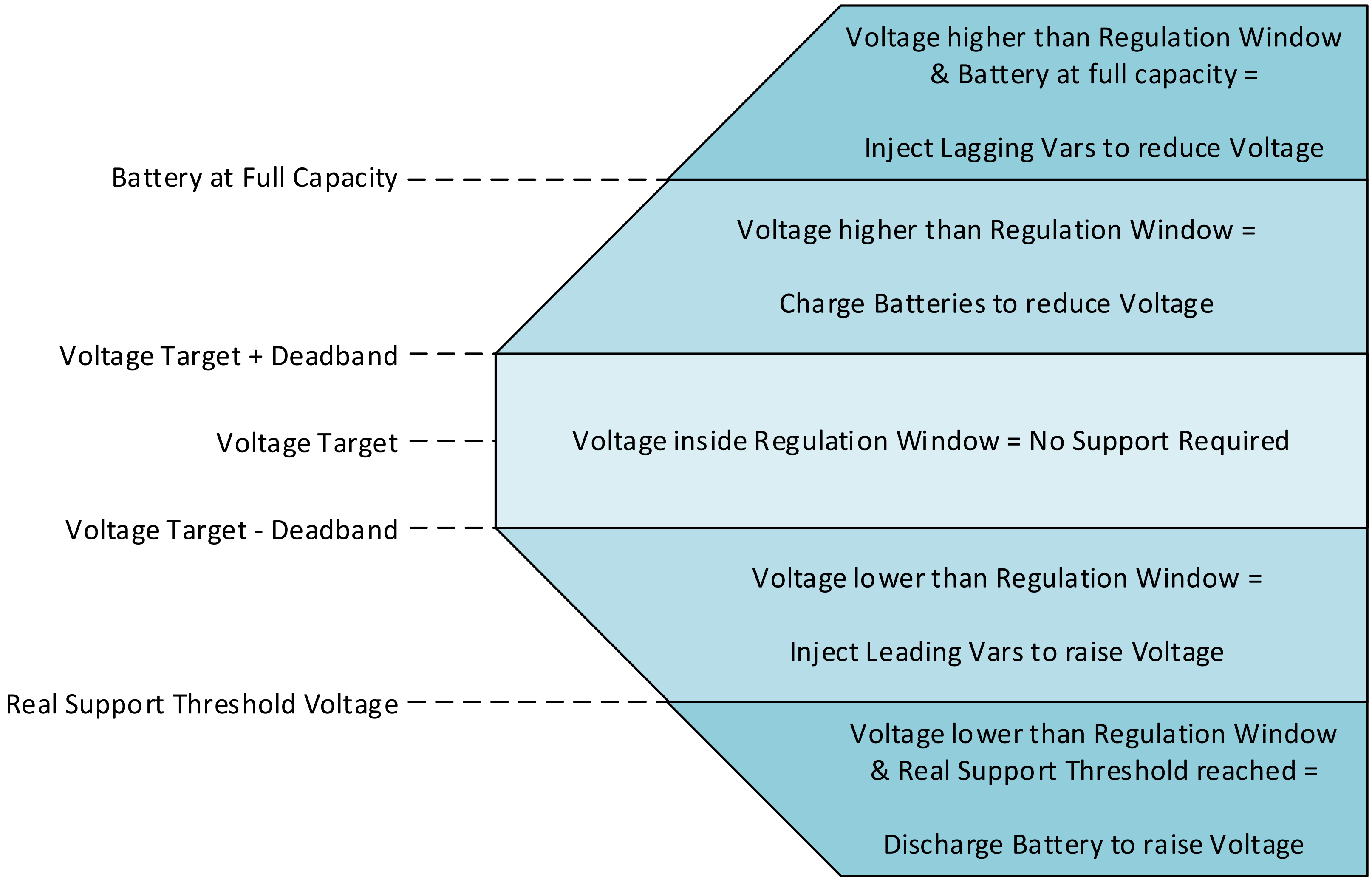


dSTATCOMs are capable of operating autonomously responding to the real-time grid dynamics, and hence doesn’t require centralised control

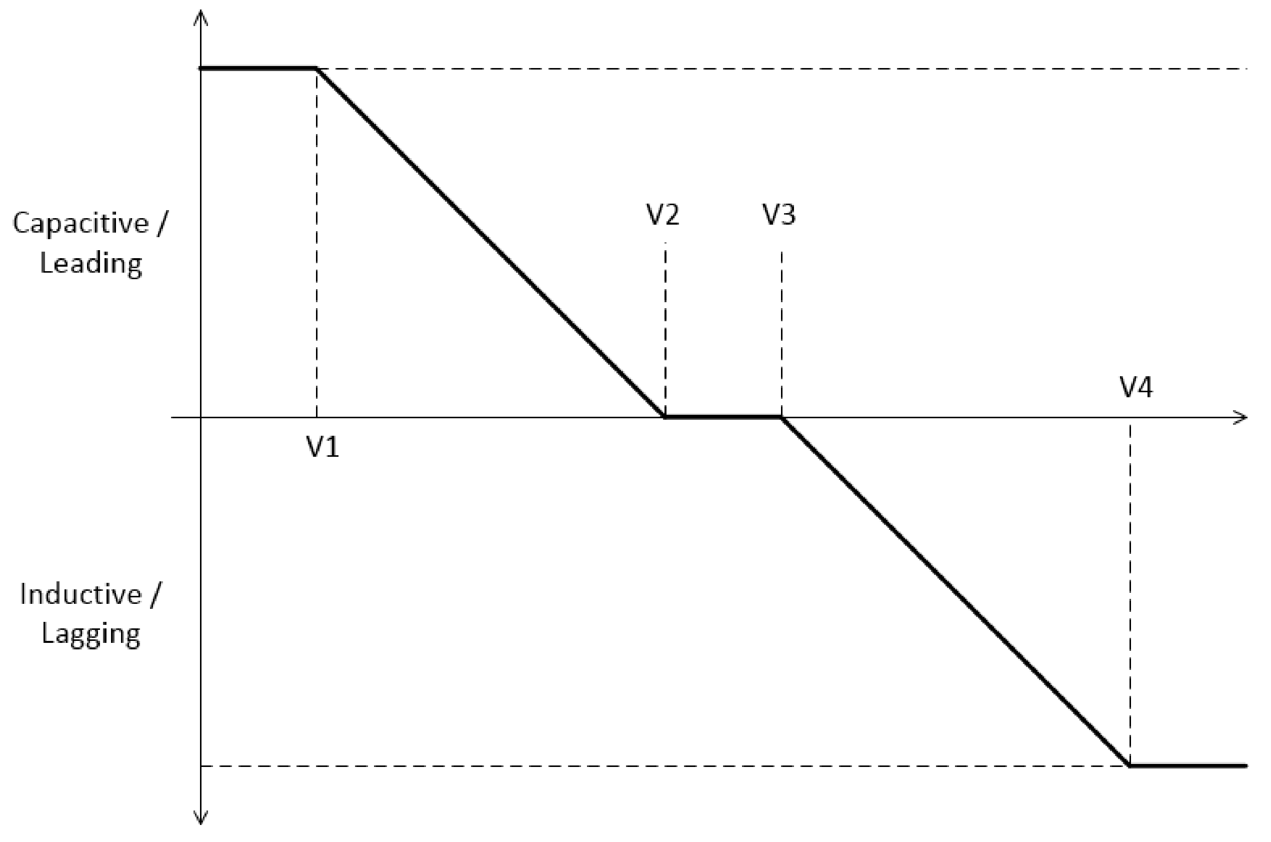
dSTATCOMs trial in LV feeders for voltage improvements

- Phase A – 5 kVAR; Phase B – 5 kVAR; Phase C – 2*5 kVAR

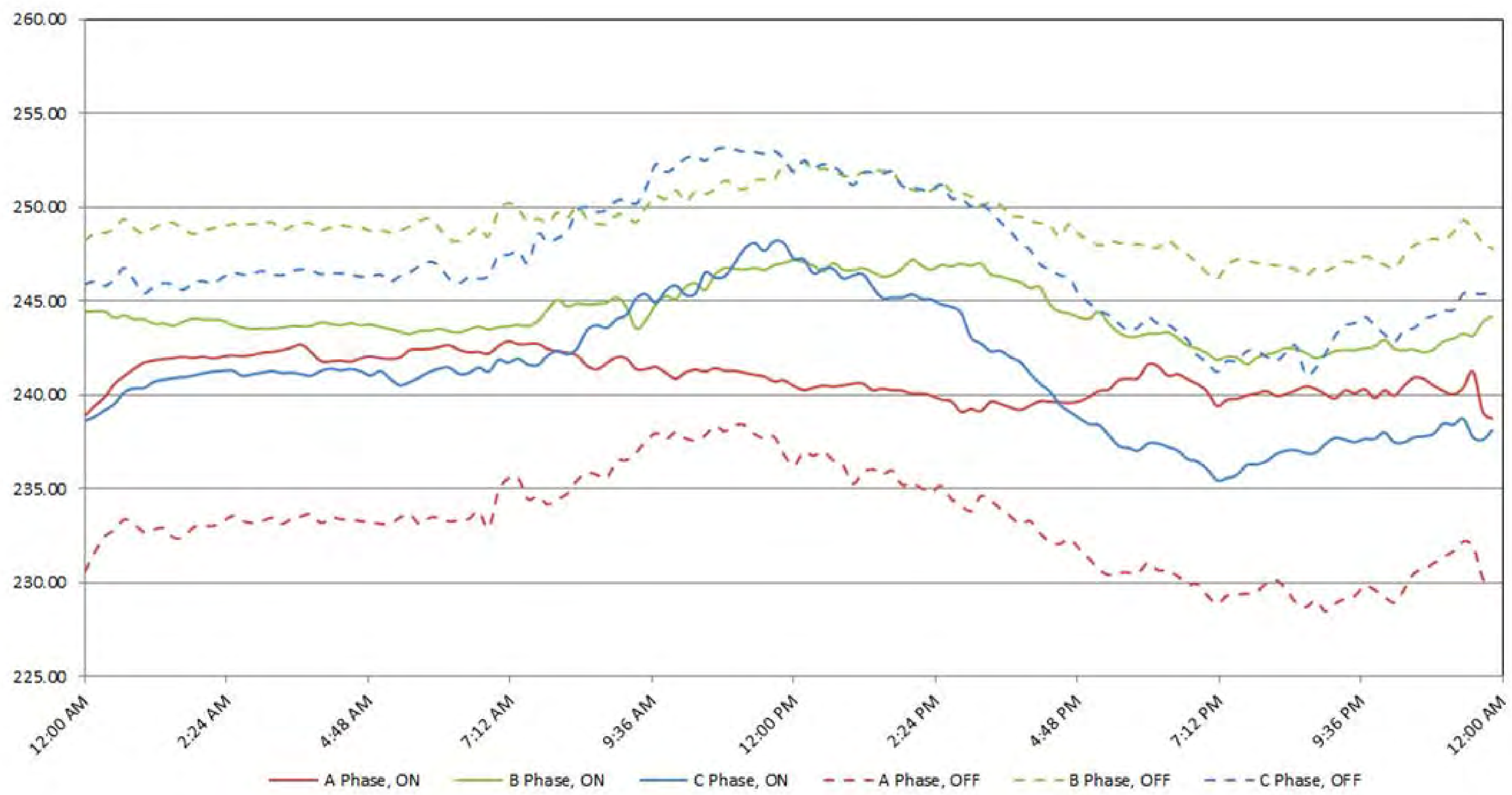
Voltage- Control mode of dSTATCOMs



Volt-Var control mode for dSTATCOMs



DSTATCOMs Trial

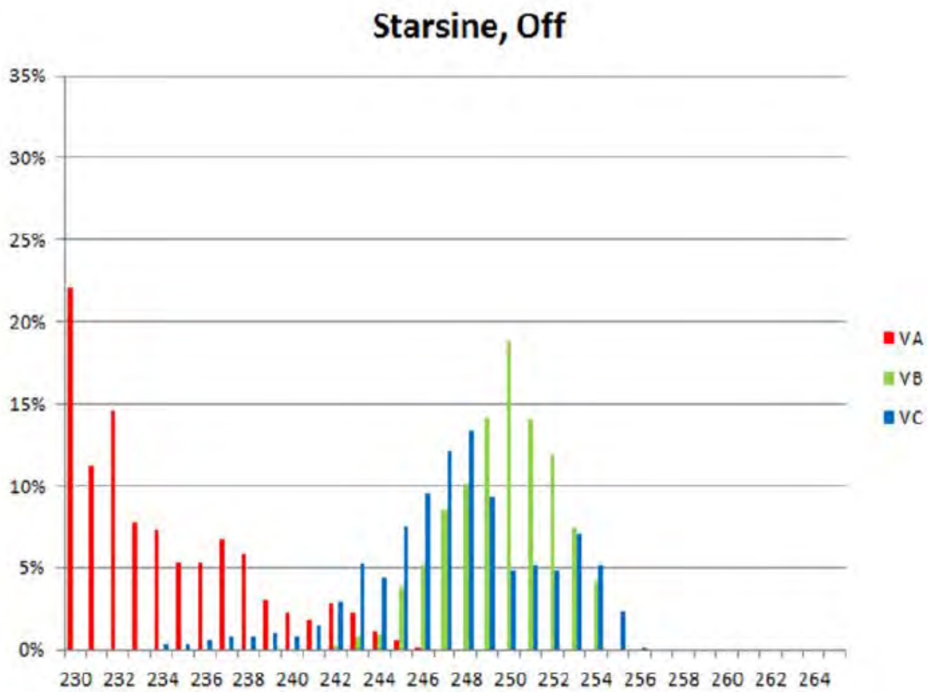


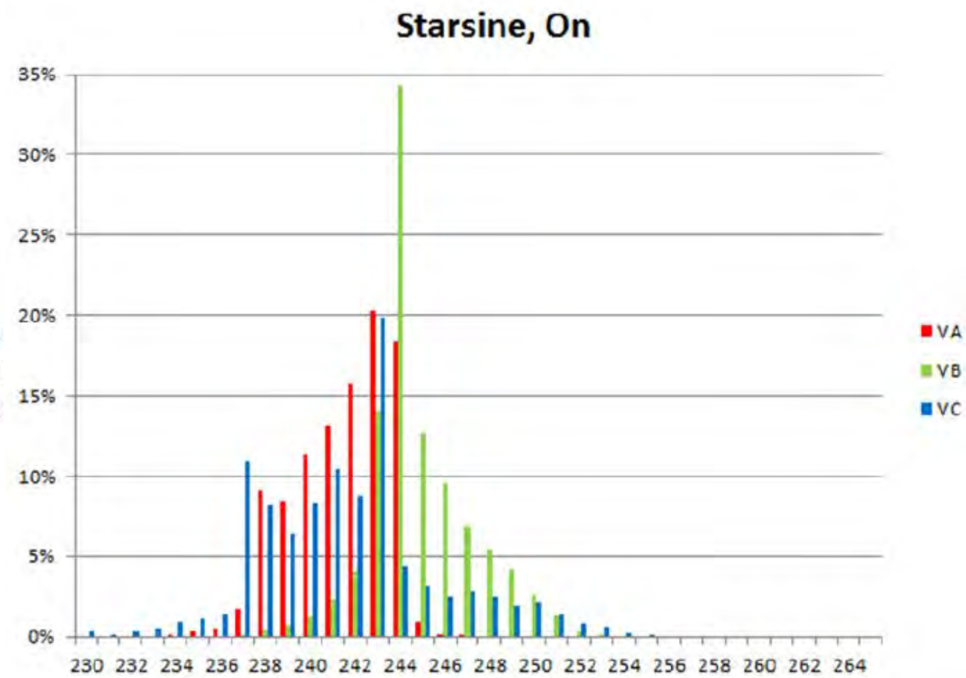
Average Voltage profile improvement with and without DSTATCOMs

DSTATCOMs Trial

Average reactive power contribution from the set of 4 DSTATCOMs

Improvement in the voltage profile with and without dSTATCOMs





- dSTATCOM units have greatly reduced day time high voltages and provided voltage support in the evenings

Conclusions

- distribution STATCOMs can be deployed in a number of ways
  - As a battery less reactive power device to provide voltage regulation and phase balancing
  - As a battery enabled device providing real and reactive power for voltage regulation and phase balancing
  - As a power factor correction device providing PF correction on Industrial and Solar Generation sites
  - As an energy management device to control integration of battery storage and renewable generation connection to the grid

Hold that thought for question time
at the end of this session ….

AMSC Gridtec Solutions: CIGRE 2017

smarter, cleaner
... better energy

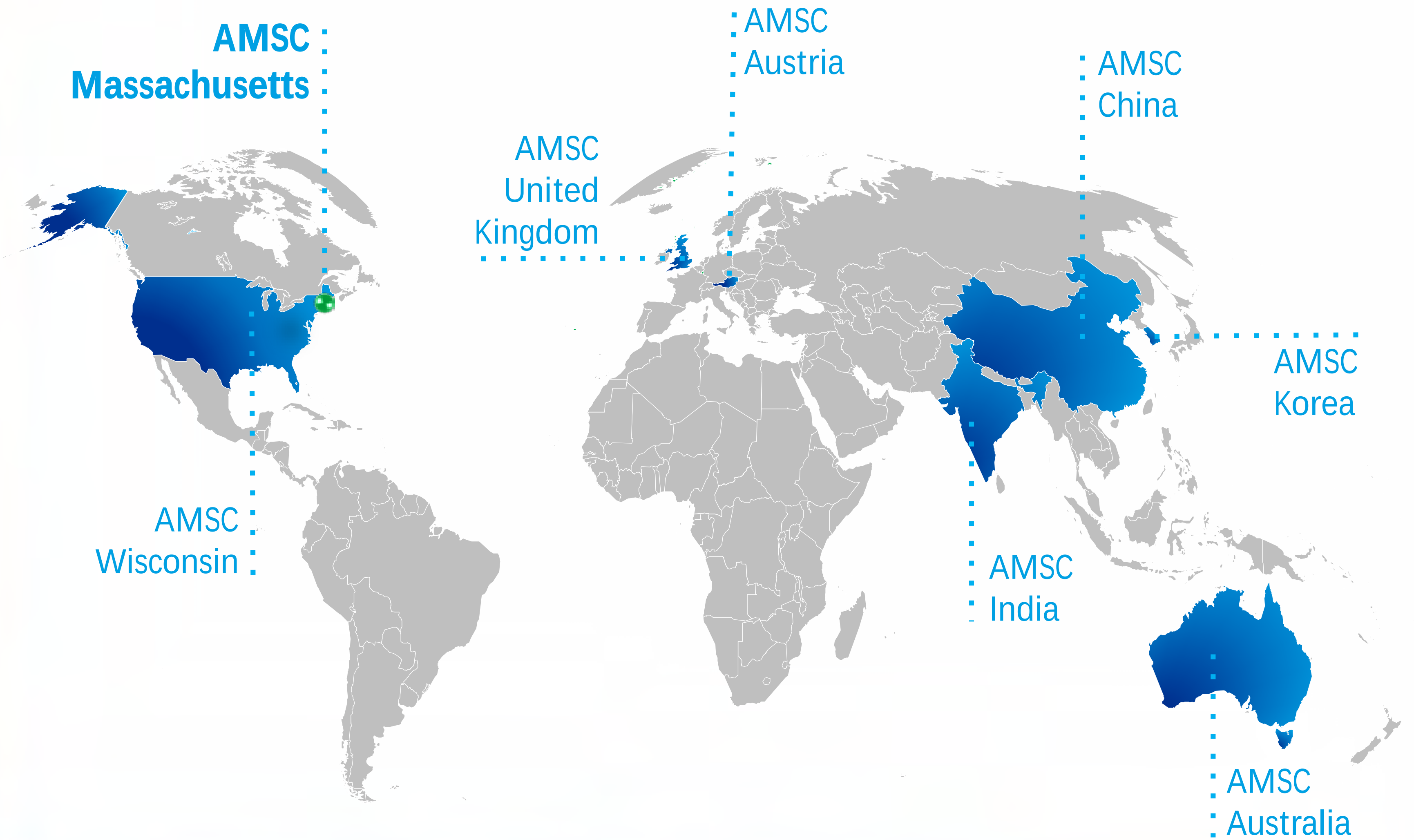
AMSC® (American Superconductor)

Corporate Background

- AMSC is a leading global manufacturer of solutions for electric grids
- AMSC solutions are powering over 14 GW of renewable energy and enhancing the performance and reliability in power networks in more than a dozen countries
- Founded in 1987 as a start-up – company founder from the Massachusetts Institute of Technology (MIT)
- Headquartered near Boston, Massachusetts with operations in Asia, Australia, Europe and North America

AMSC® Regional Offices

Sales and Service support worldwide



AMSC's Gridtec Solutions

Smart grid solutions from generation to end use

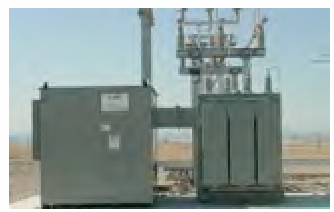
Engineering Services

- Power Quality Applications and Solutions
- Transmission Planning Studies
- Harmonic Analysis
- Voltage Stability Studies

Energy Generation

- Renewable Energy Plant Solutions
- Power Plant Generators

Transmission



- Dynamic Reactive Power Support
- Voltage Regulation
- AC Power Cables
- HTS Fault Current Limiters

Distribution

- Dynamic Reactive Power Support
- Power Quality Solutions
- AC Power Cables
- HTS Fault Current Limiters

End Use

- Power Quality Solutions
- Mine Interconnections
- Indoor HTS Power Cables

AMSC's Gridtec Engineering Services

Network Planning and Applications Group

Engineering Services → Energy Generation → Transmission → Distribution → End Use

AMSC's team of engineers provide over 85 years of combined utility transmission planning and engineering experience

- Power System Engineering Studies
- Grid Code / Requirements Assessments
- Equipment Specification / Review
- Modeling & Applications Support
- HTS Cable and FCL Siting and Impact Studies

Phase 1 Feasibility → Phase 2 System Impact → Phase 3 RFP/Tech. Spec → Phase 4 Rating & Compliance → Phase 5 Capability

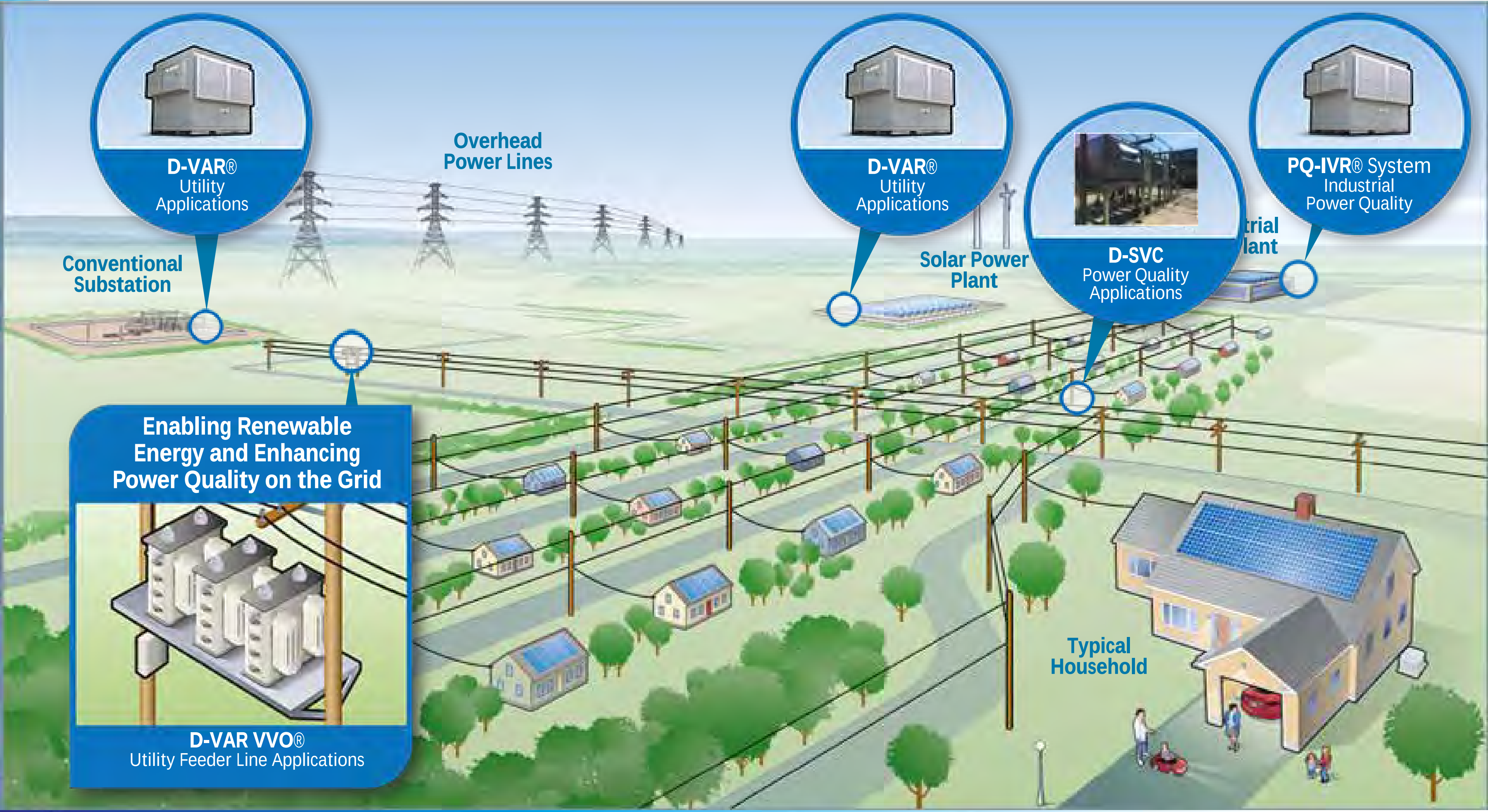
AMSC Planning & Engineering Services

- ***AMSC Support Capability for Systems Engineering***
  - Steady-state load flow (power flow) studies
  - Dynamic and stability analysis
  - Harmonics and resonance scans
  - Power transfer capability studies
- ***Planning Tools (Software)***
  - PTI PSS/E Load flow and Stability
  - DIgSILENT load flow, stability, harmonics, short circuit
  - PSCAD and RTDS
  - GE PSLF Load flow and Stability
- ***Global Experience***
  - Studies performed for wind farms, industrial plants and utilities worldwide

Validated models of D-VAR® System available

AMSC FACTS Solutions

Enabling Renewable Energy integration, Enhancing Power Quality and Voltage Stability of the Electric Grid



AMSC FACTS Solutions

Smart, Modular and Easily Configurable Systems

D-VAR® STATCOM Systems

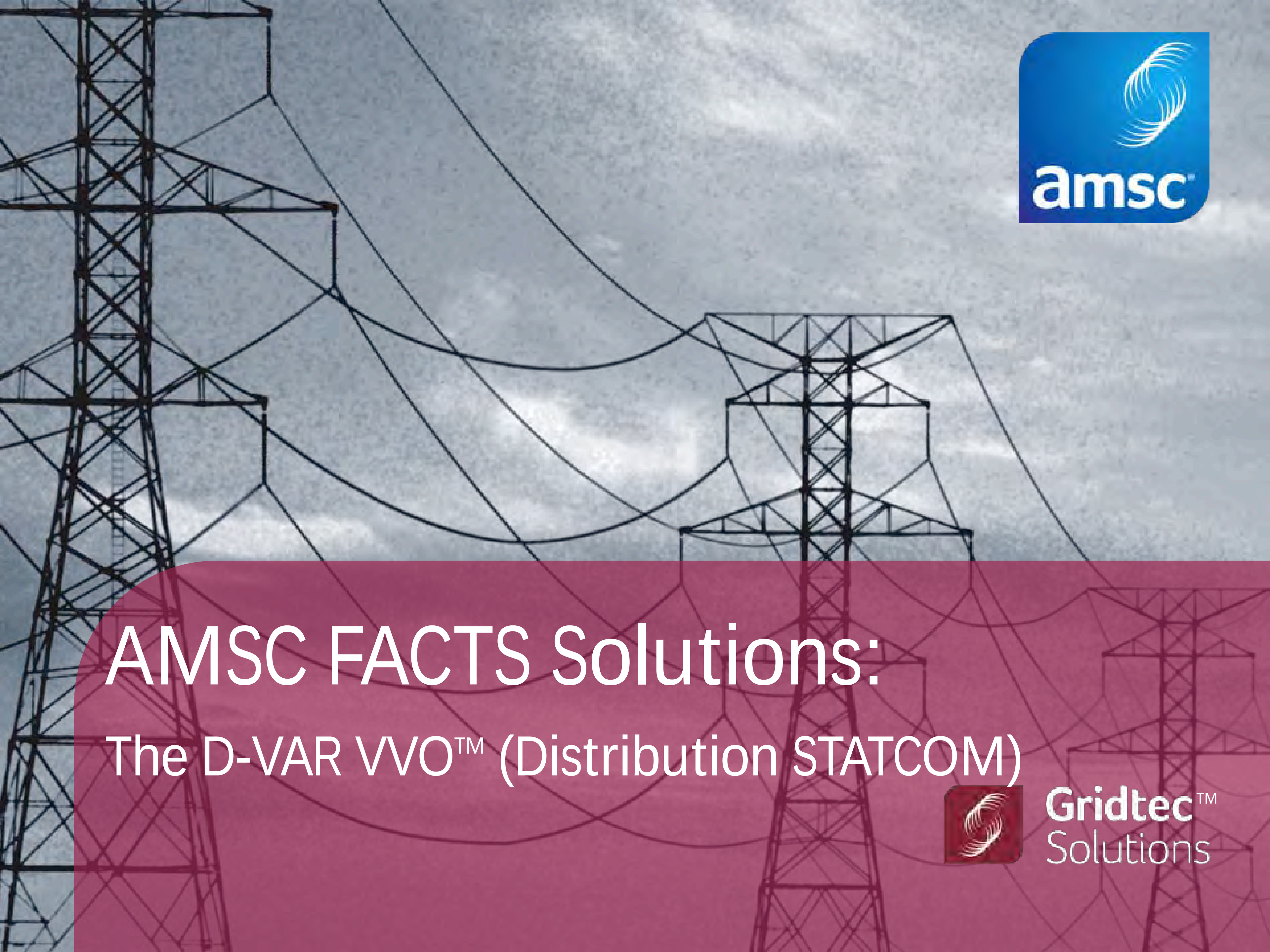
- Air cooled, IGBT based power electronic reactive current device for connections up to 66kV.
- State of the art controls and features.
- Configurable from a few MVArs to 100s of MVAr Systems
- +150 systems deployed all over the world

D-SVC™ Systems

- Thyristor Switched Shunt Capacitor based system up to 15kV direct connect.
- Cycle by cycle switching of banks.
- Ideal for power quality applications requiring dynamic capacitive compensation.
- Configurable from 500kVAR to 10s of MVAr

D-VAR VVO™

- 15kV Class direct connect STATCOM.
- 500kVAR and 1MVAR
- 3 and 1 Phase
- Feeder level solution
- Address PV and DG issues on long distribution feeders


amsc
AMSC FACTS Solutions:
The D-VAR VVO™ (Distribution STATCOM)
Gridtec™
Solutions

The D-VAR VVO™ STATCOM

PV Capacity + CVR Control + Power Quality + Volt VAR

First of its kind Distribution STATCOM

- Direct-connect *Power Electronic* device
- Pole mounted (standard H pole)
- Acoustically quiet
- Tamper proof enclosure (sealed)
- No routine maintenance (no mechanical switching, no pumps, fans, or filters)
- Standard Utility 15 kV protection
- Utility owns and operates
- Utility selects optimal location
- Optional Pad mounted version

Example of an above ground feeder installation

Connects up to all 15kV class distribution Systems

The D-VAR VVO™ STATCOM: Applications

PV Capacity + CVR Control + Power Quality + Volt VAR

Case	Value
• Maximize PV & DG Hosting Capacity	ü Avoid/delay major upgrades in voltage constrained feeders with growing PV
• Power Quality	ü Quickly improve service quality in areas with voltage flicker and PQ violations
• Energy Efficiency/Conservation Voltage Reduction	ü Reduce demand and/or consumption by optimizing voltage across feeders
• Small Solar/Wind Plants	ü Minimize use of dedicated feeders ü Meet interconnect requirements quickly

A versatile tool to strengthen and maximize utilization of existing distribution circuits

AMSC FACTS Solutions:

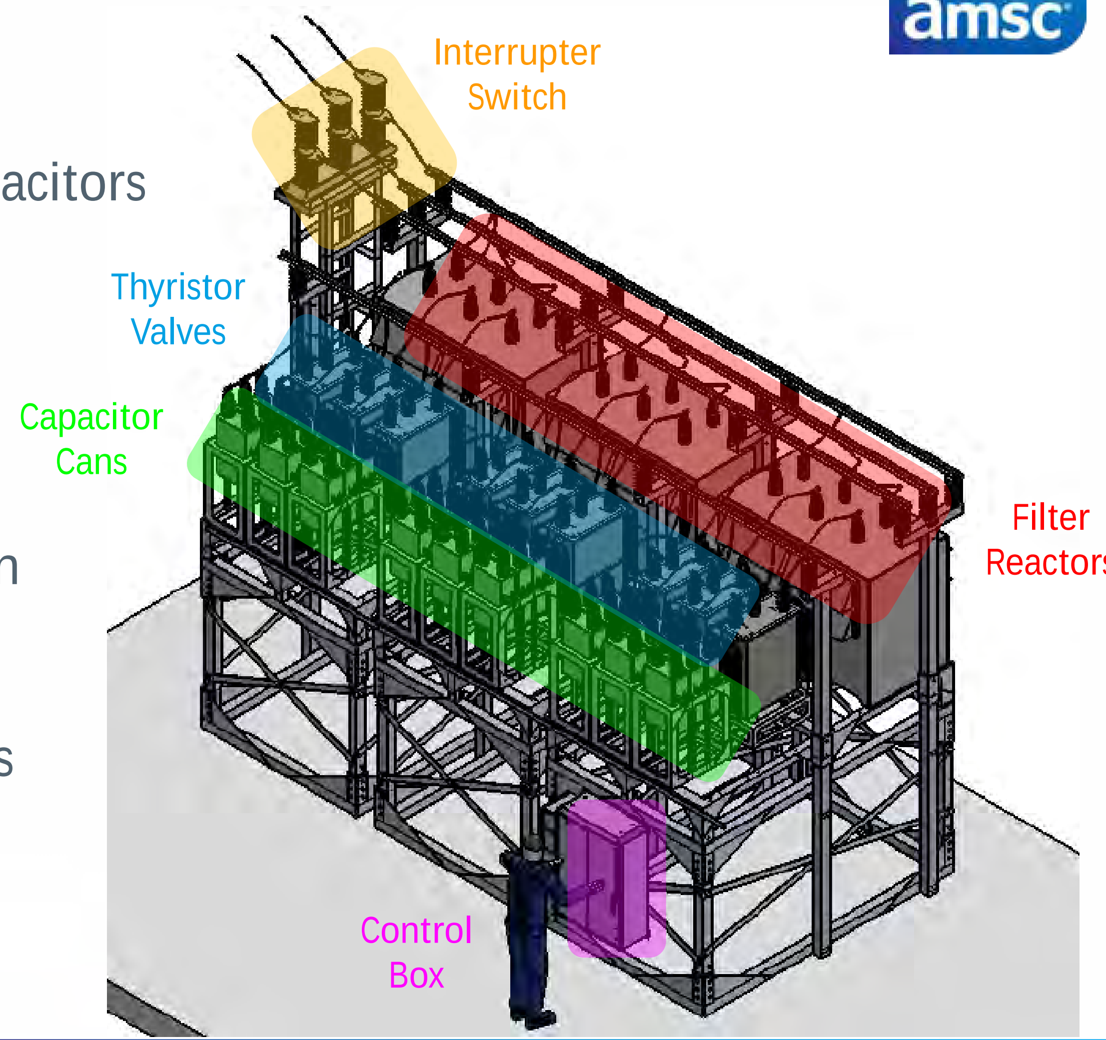
The D-SVC™ (Distribution Static VAr Compensation)

Gridtec™ Solutions

The D-SVC™ System

Distribution Static VAr Compensator

- 15kV Thyristor Switched Capacitors
- Factory sealed modules
  - Oil-filled
  - Field-ready
- Standard outdoor Installation
  - Designed for -40 to +40°
- Standard utility connections



Cost effective power quality solution for 15kV class distribution system

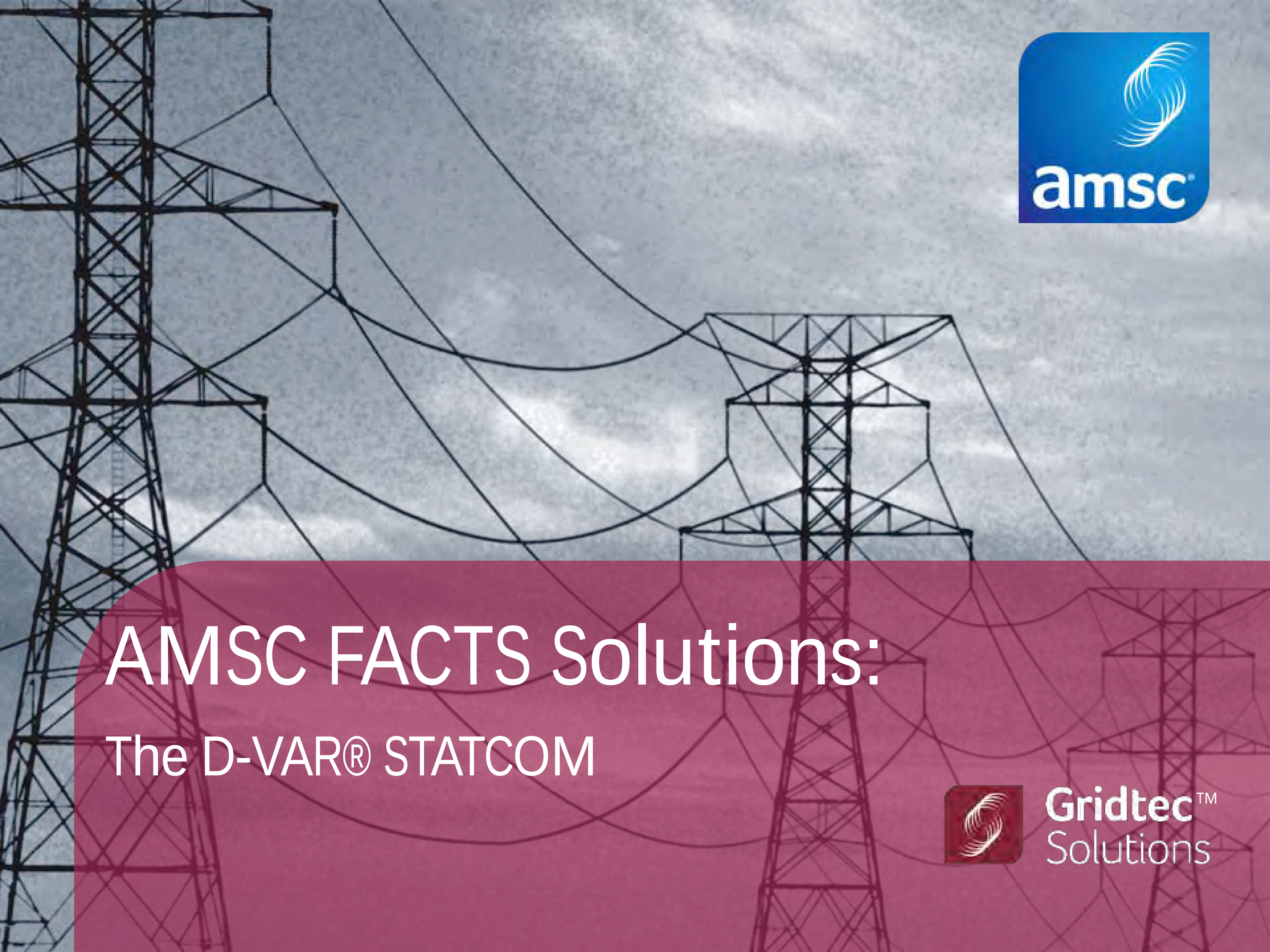
The D-SVC™ System

Standard Outdoor 3 step 3.5MVAR SVC Rack Mount (Typical)

The D-SVC™ System: Applications

Solves power quality problems caused by following types of loads

- Pumps & Pipelines
- Compressors
- Quarries
- Crusher/ Shredders
- Sawmills
- Ski resorts
- Arc Furnaces
- Welders
- Water Treatment Plants
- Feed Pelletizers
- Rolling Mills
- Wind Tunnels
- Pulp & Paper
- Refineries
- Hoists & Dredges
- Mining



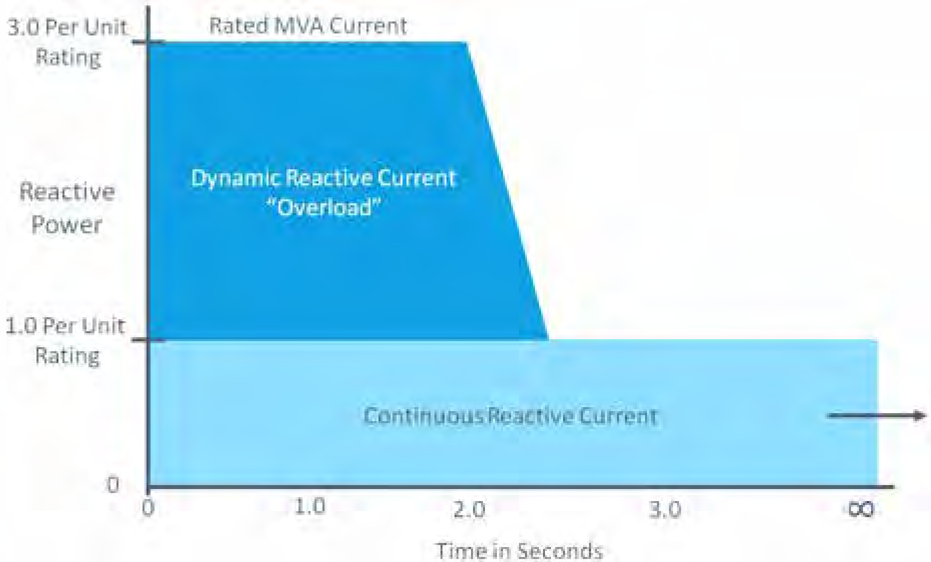
AMSC FACTS Solutions:

The D-VAR® STATCOM

Gridtec™ Solutions

The D-VAR® STATCOM System

- Provides sub-cycle dynamic reactive capability – both leading and lagging
- Has short term overload capability of 3.0 times its continuous rating
- Seamlessly switch other shunt devices and is in communication with the utility system operations & control center via SCADA
- IEEE519 Compliant Harmonic performance



The D-VAR® STATCOM

Filters

Front Louvers

Exhaust Louvers

Checks: Filters clean/replace, general condition, louvers, fans, exhaust passages, check heater operation

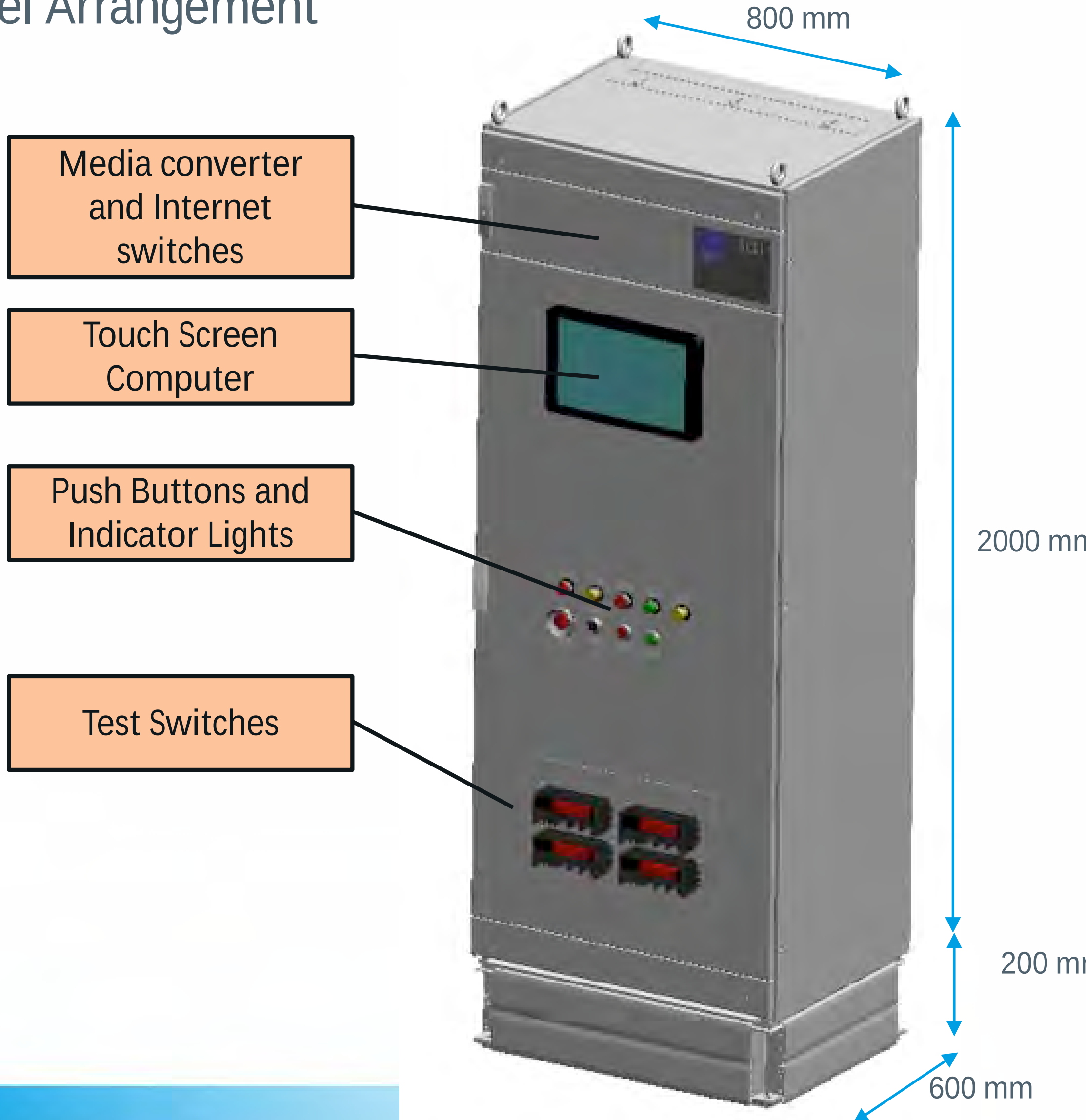
- *Forced (ambient) air cooled systems*
- *Simple Installation requirements*
- *Installed in varied environmental conditions*
- *1 or 2 transformer configurations*
- *Short lead times (5 - 7 months)*

Easy to Maintain – 24 x 7 Monitoring by AMSC Available

The D-VAR® STATCOM System - Master Controller

2000 x 800 x 600 mm Custom Panel Arrangement

Quick Access to touch screen computer (HMI),test switches, media converters and internet connections and switches



Check with Oly

The D-VAR® STATCOM System - Experience

153 Systems sold worldwide since 2000

- **107 D-VAR® Systems sold for wind and solar interconnections**
  - Connecting wind farms employing Vestas, Gamesa, RePower, Mitsubishi, GE, Siemens and Suzlon Turbines.
  - 52 installations with D-VAR Controller as Master Controller for the complete plant working with Park Controllers.
  - Supporting connection of more than 9.5 GW of wind generation to the grid.

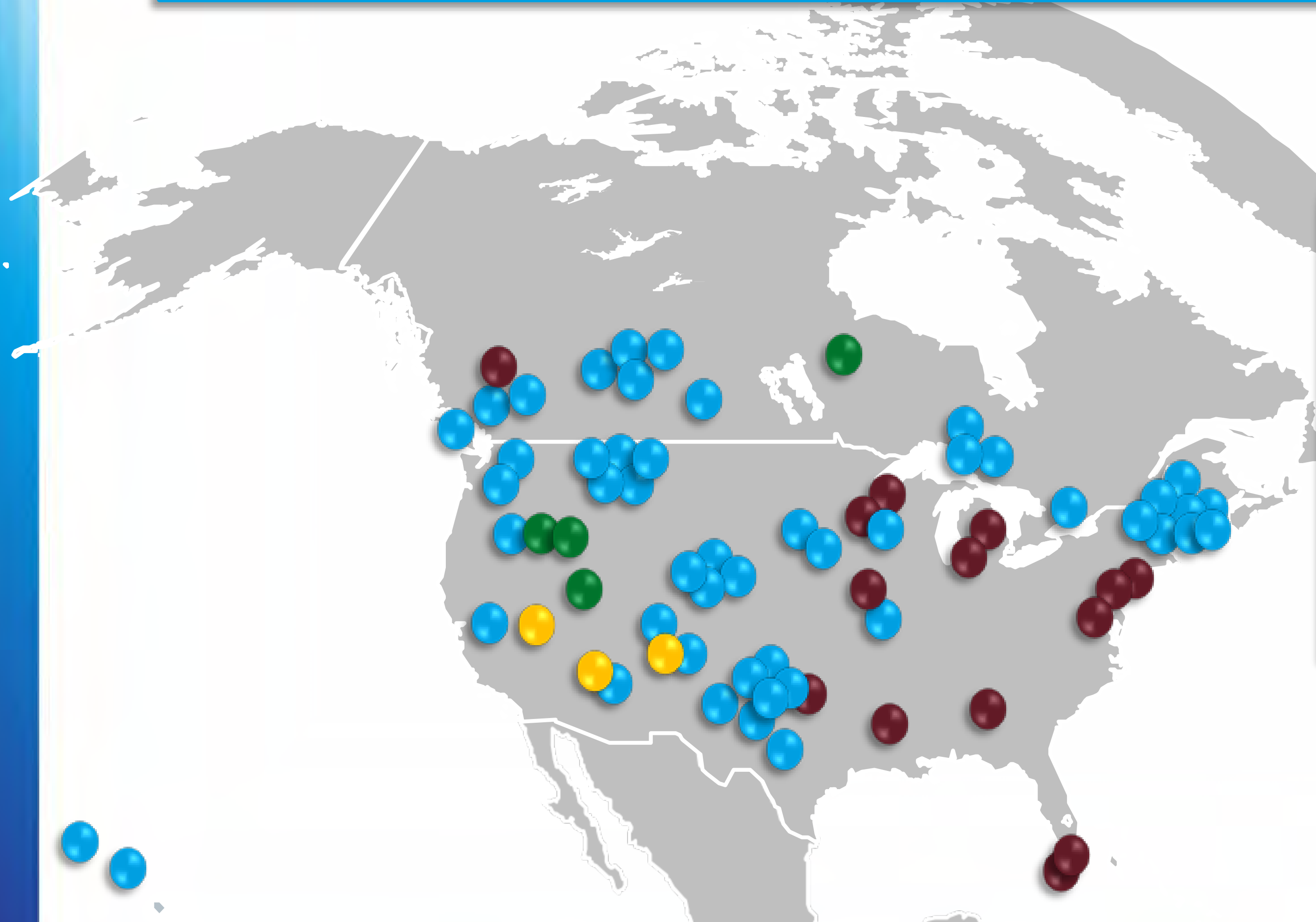
- **46 D-VAR Systems sold for Utility Grid Voltage Support/Power Quality Applications**
  - Grid Voltage Support and post-fault voltage recovery
  - Semiconductor Fabs
  - Mining Applications

Substantial experience with grid connected systems worldwide

The D-VAR® STATCOM Experience

North America – 85 Systems Sold

Utilities Industrials Wind Farms Solar Plants



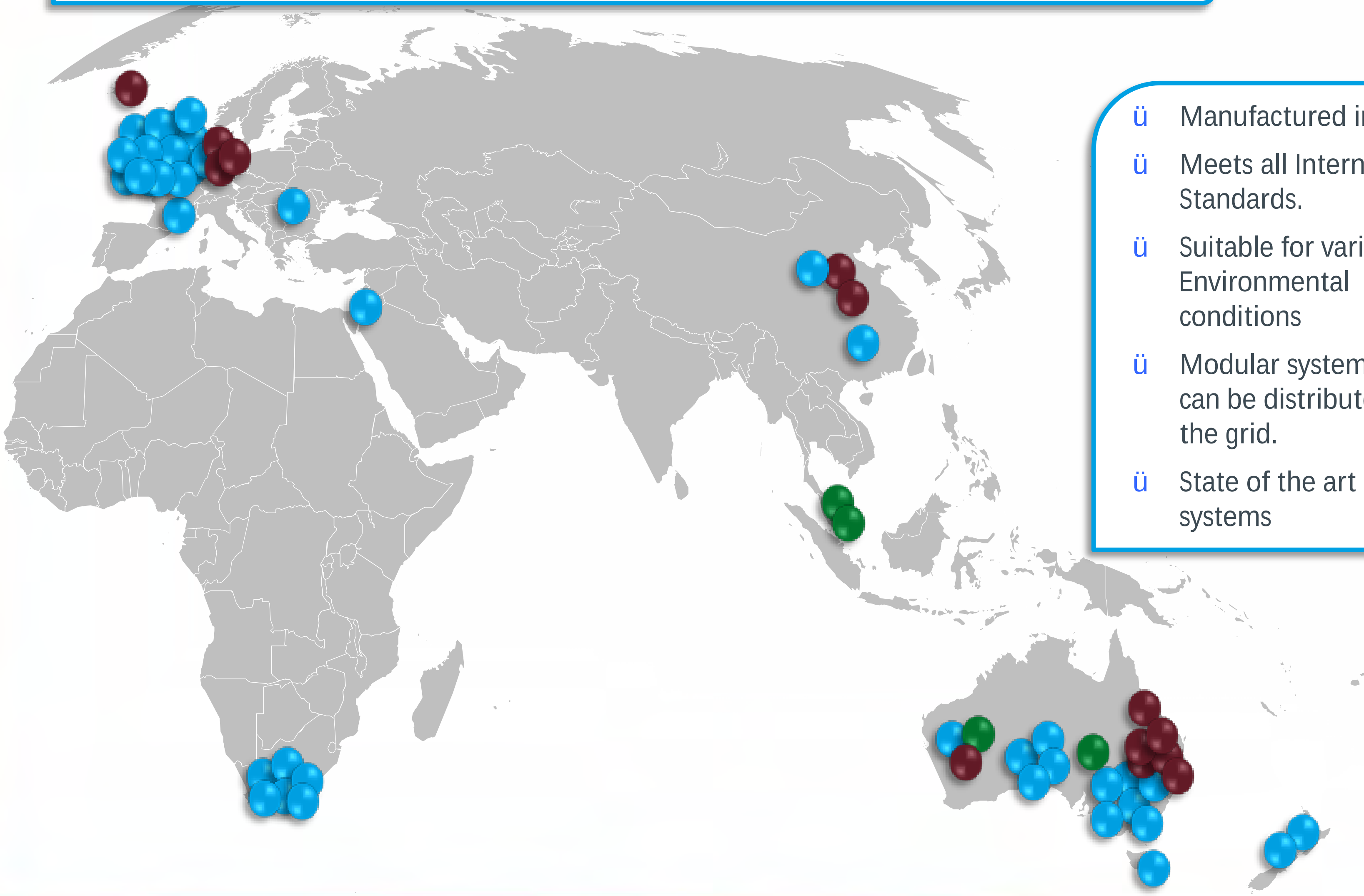
- ü Manufactured in USA.
- ü Meets all International Standards.
- ü Suitable for varied Environmental conditions.
- ü Modular systems that can be distributed in the grid.
- ü State of the art control systems

12 Systems in process of delivery and installation currently

The D-VAR® STATCOM Experience

Rest of the World – 68 Systems Sold

Utilities Industrials Wind Farms Solar Plants



- ü Manufactured in USA.
- ü Meets all International Standards.
- ü Suitable for varied Environmental conditions
- ü Modular systems that can be distributed in the grid.
- ü State of the art control systems

The D-VAR® STATCOM System - Experience

No. of Systems and Units sold worldwide

Region	No. of Systems Sold	No. of 4MVAR Units (PME)
United States	65	180
United Kingdom	27	58
Canada	20	58
Australia	21	74
China	5	8
New Zealand	2	3
South Africa	6	9
France	1	1
Romania	1	3
Singapore	3	22
Iceland	1	3
Ireland	1	1
Middle East	1	6
Total	**154**	**426**

12 D-VAR Systems in process of delivery and installation

The D-VAR® STATCOM

Installation Example: Renewables

amsc

Gridtec™ Solutions

Challenges of Renewable Plant Integration

Resource Variability

- Power output is inherently unpredictable
- Power sources located at non ideal locations
- Presents system operator challenges

Grid Impacts

- Potential for transmission congestion issues
- Drives need for stringent connection codes and procedures
- Level of renewable penetration

Different Technology

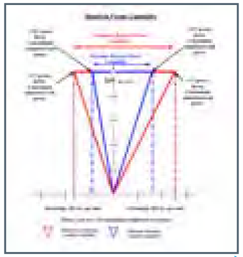
- Different technologies employed and spread in the system with varying capabilities employed
- Ancillary equipment with advanced controls typically required

Firm Grid Codes with fully defined requirements in the areas of:

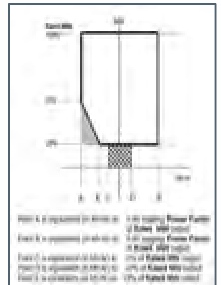
- Voltage Ride Through /Dynamic Stability
- Power Factor Capability
- Control Objective
- Power Quality
- Compliance Validation

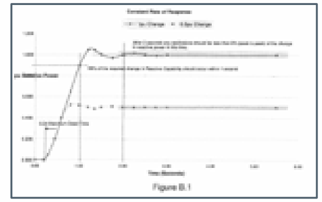
World Wide Grid Code Requirements

To alleviate the growing impacts of renewables on the grid

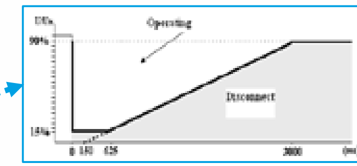


Reference: AESO ISO Rules Part 500 - Facilities Division 502 – Technical Requirements Section 502.1 – Wind Aggregated Generating Facilities Technical Requirements August 10, 2010

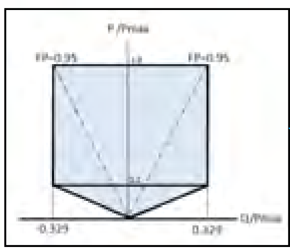


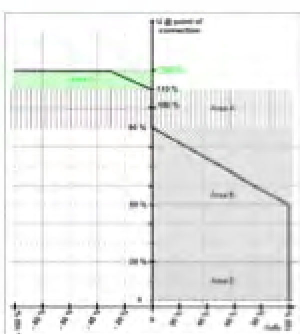


Reference: UK Grid Code, December 13, 2013

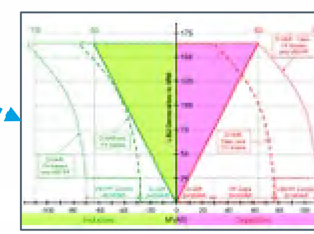


Reference: Romania - **Technical conditions for connection to the public electrical grids for electrical wind power stations, March 4, 2009**





Reference: ESKOM Grid Connection Code for *RPPs* in South Africa - Version 2.8, July 2014



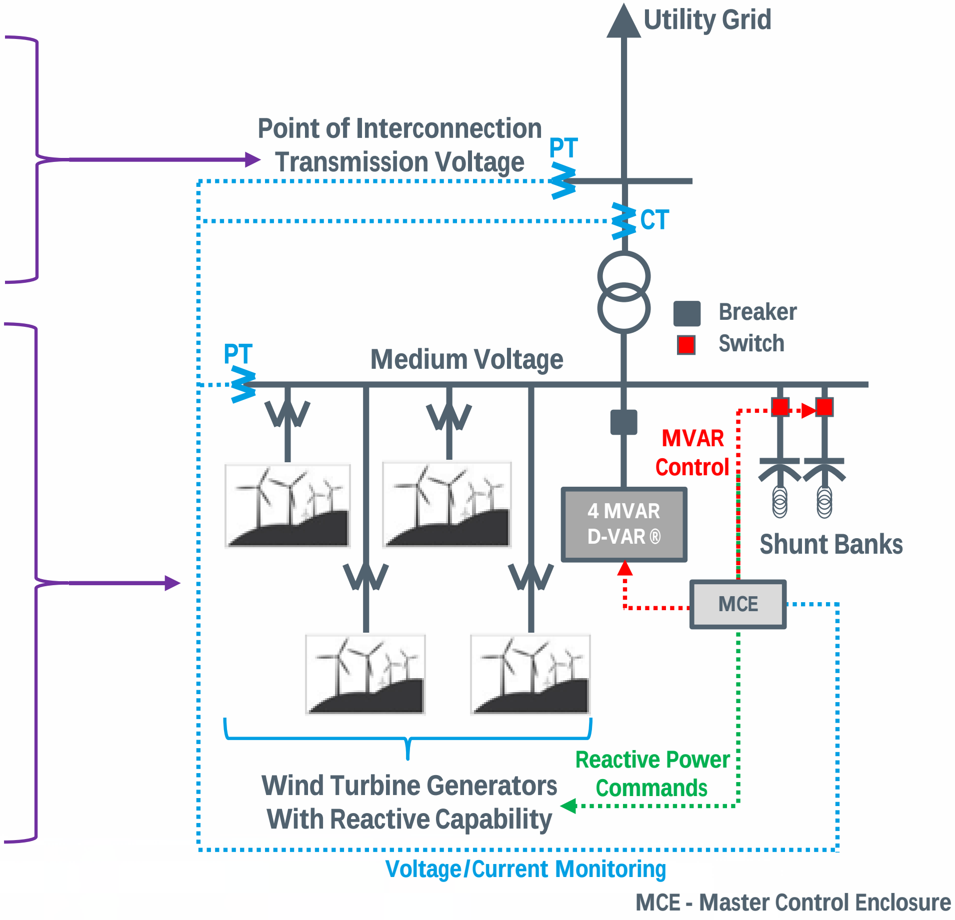
Reference: ESCOSA Electricity Transmission Code, July 1, 2008

Grid code requirements vary from region to region.

World Wide Grid Code Requirements

Requirements met using a variety of reactive resources

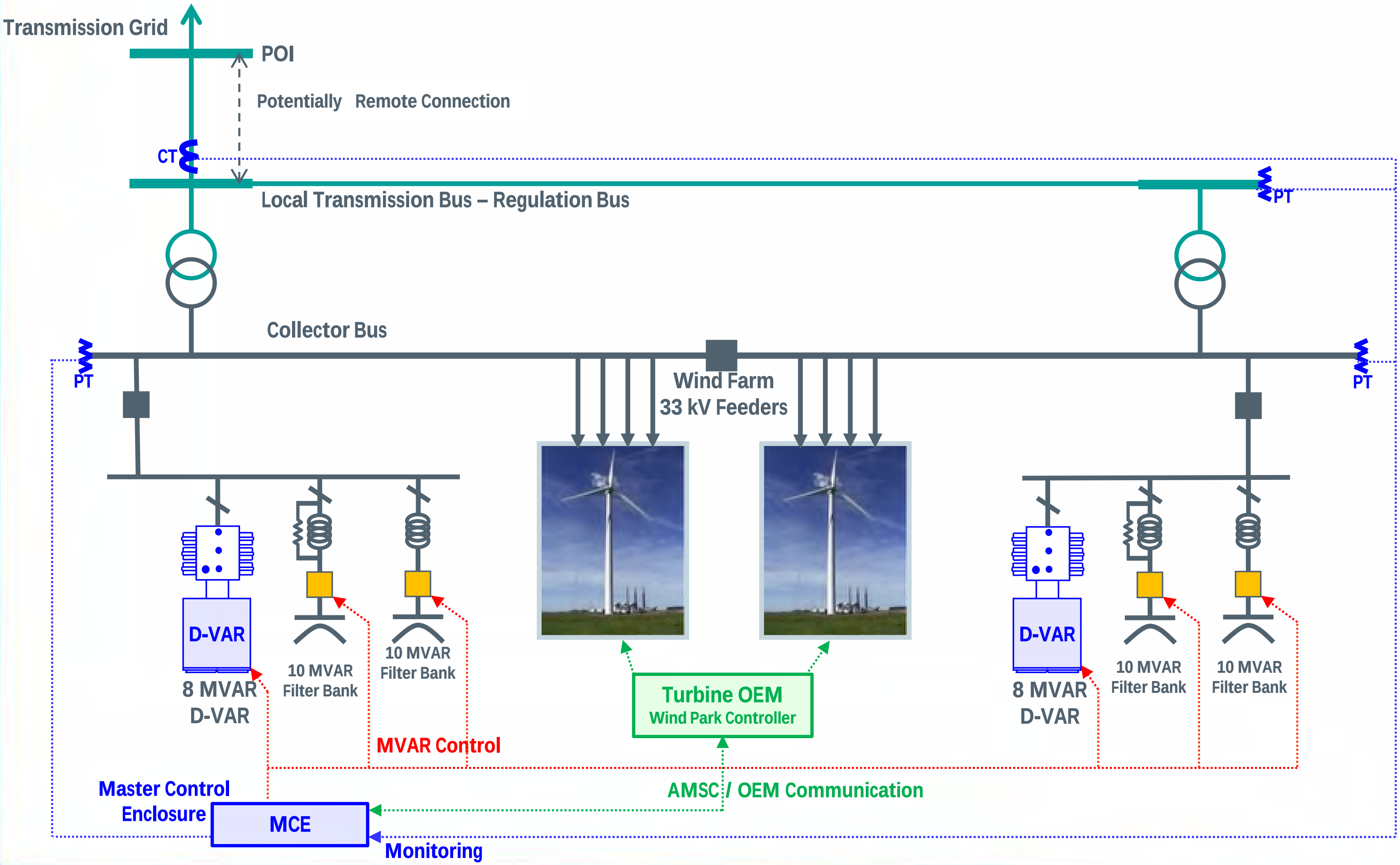
- The Grid Code Requirements are imposed at the Point of Interconnection of the Wind Farm to the Transmission Grid
- Variety of reactive resources are required to fully meet the grid code requirements
  - Often the assistance of STATCOMs are required
  - Creative control systems have been implemented to integrate all reactive resources to meet the various grid codes

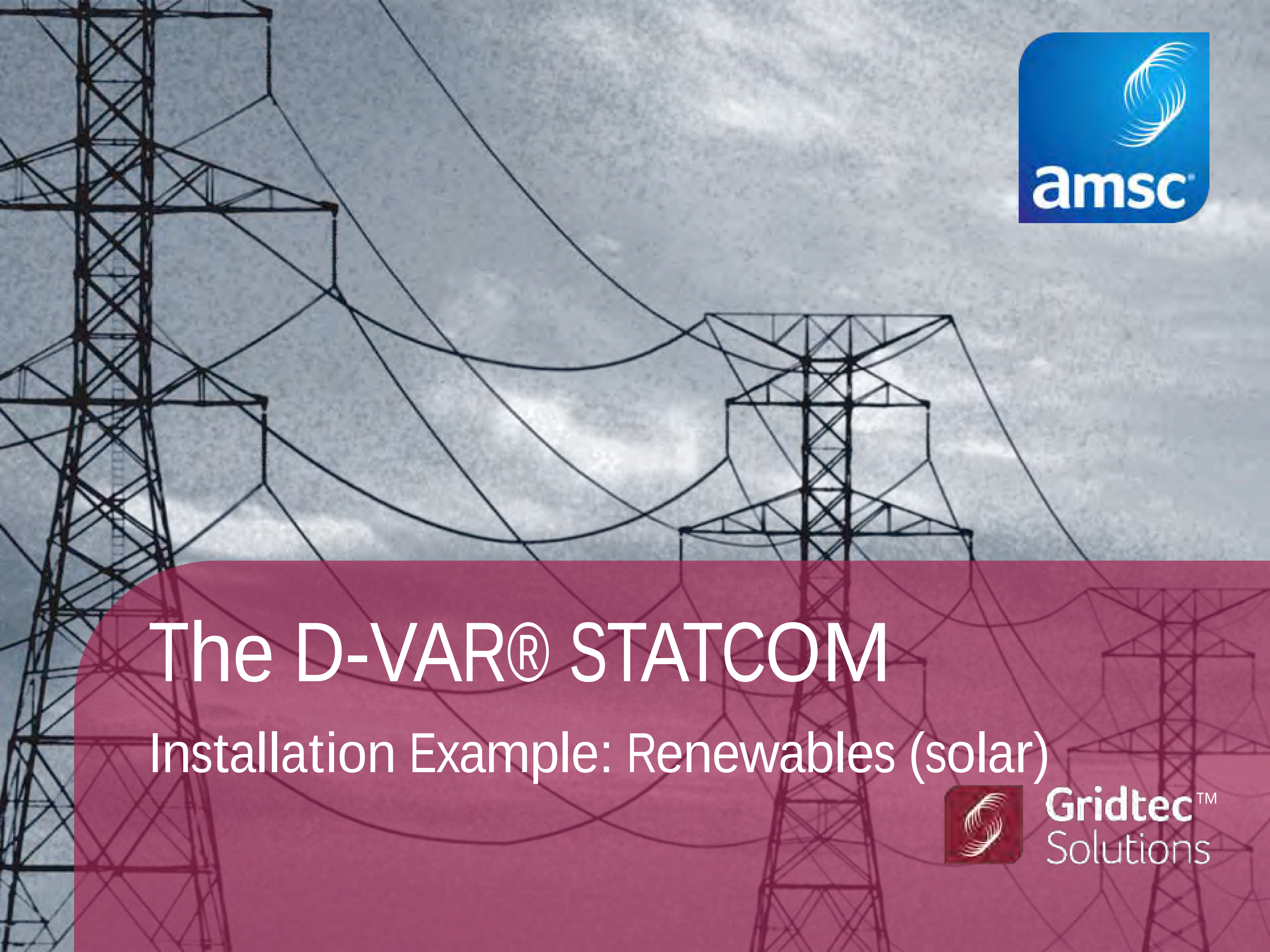


Creative controls allow multiple reactive resources to assist in meeting the various grid code requirements.

Wind Farm D-VAR® System Connection

Application: Wind Farm Voltage & PF Control and Utility Voltage Support

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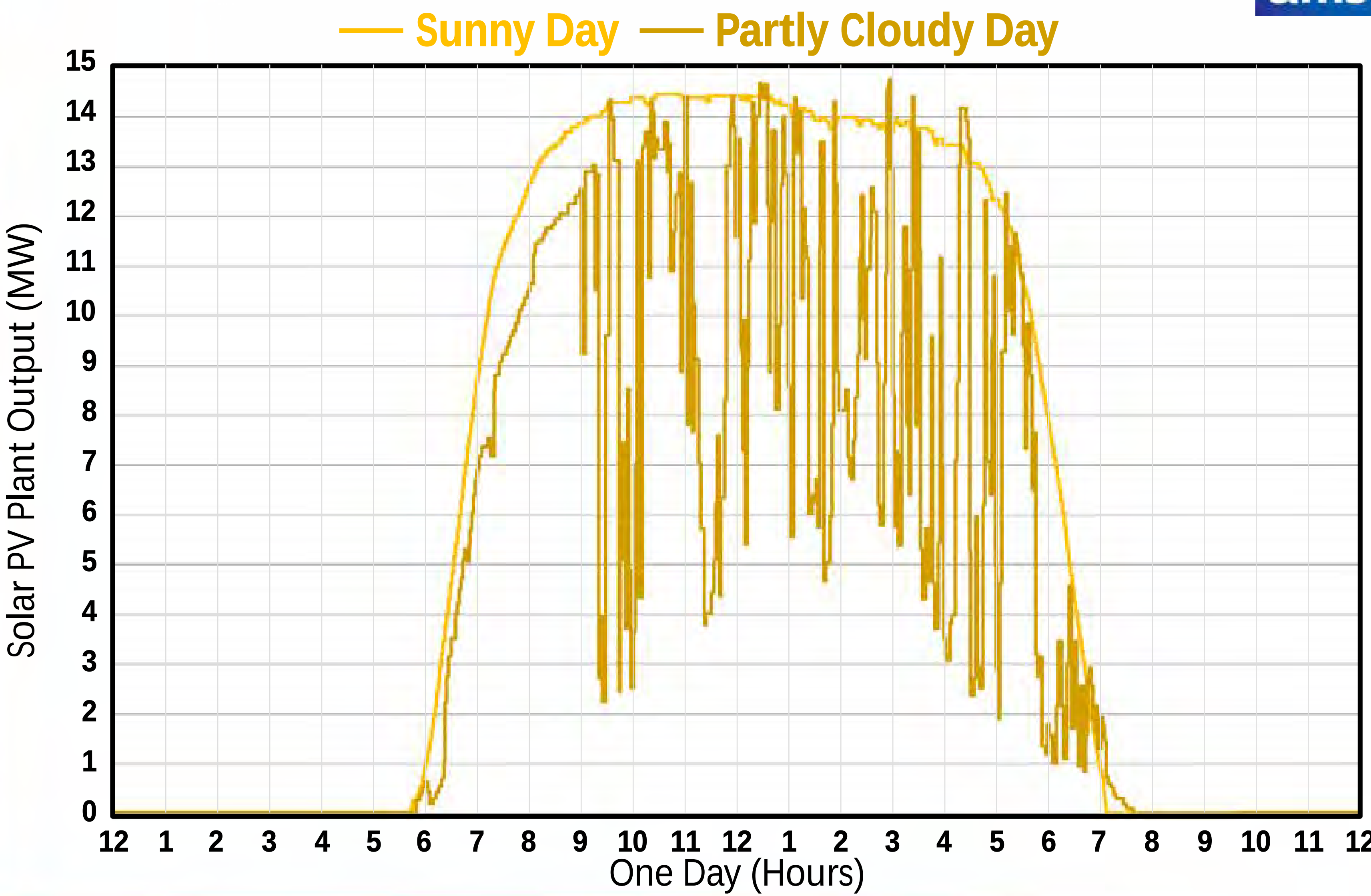
The D-VAR® STATCOM
Installation Example: Renewables (solar)
Gridtec™
Solutions

Variations in Solar PV Plant Output

Actual Field Measurements - PV Solar Generation (MW)



Solar Plant Application Objectives

Goals:

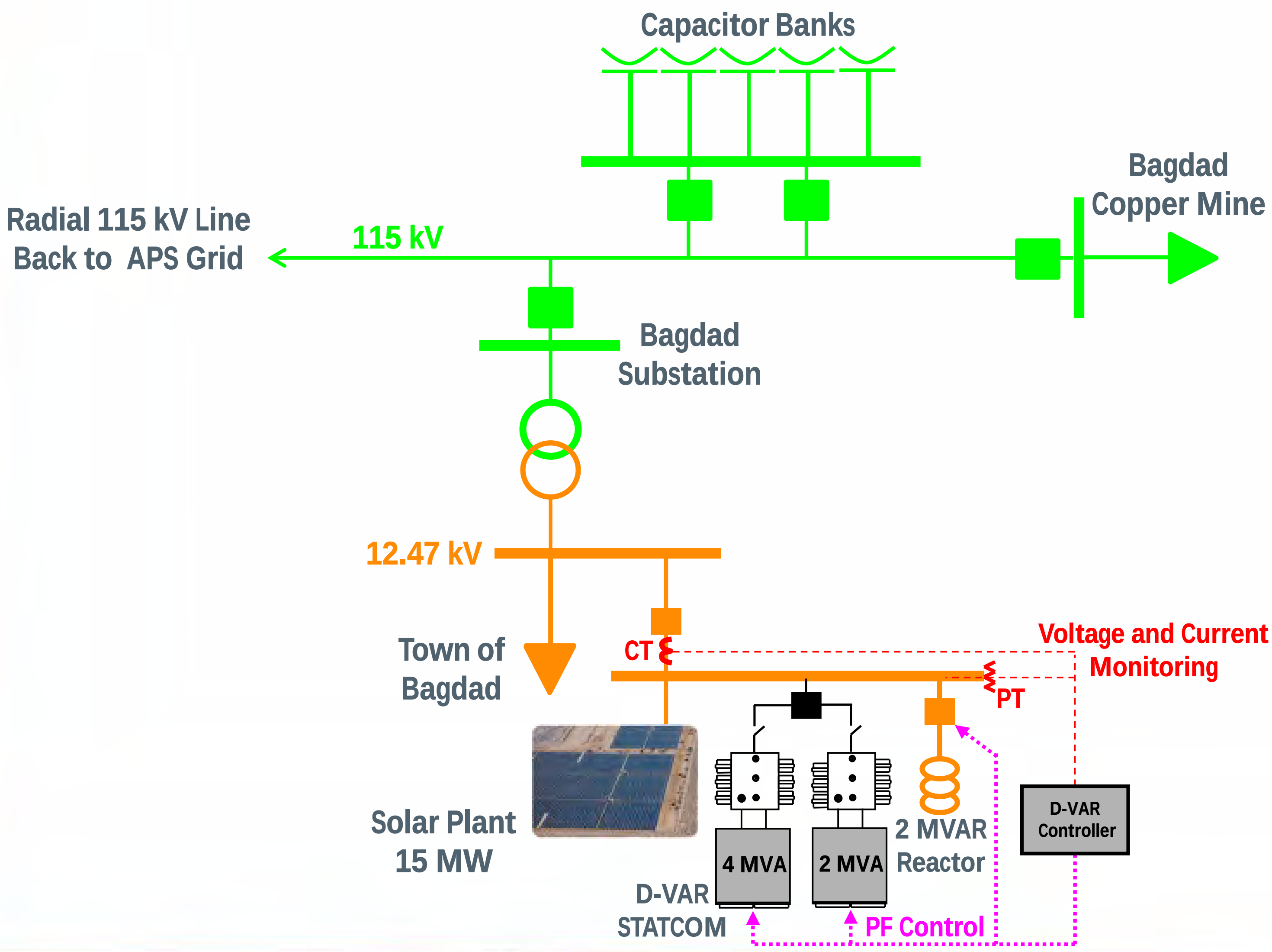
- Mitigate voltage deviations at the Bagdad 115kV bus caused by irradiance intermittency or unexpected loss of generation to within 0.5% of pre-event voltage levels.
- Use a power factor based control approach to achieve the control objective of regulating the 115kV bus voltage for gradual changes in solar plant output only.

D-VAR® System Capability Purchased:

Steady State:	±6 MVAr and 2 MVAr Reactor
Dynamic:	±16.02 MVAr (6MVAr x 2.67 overload)

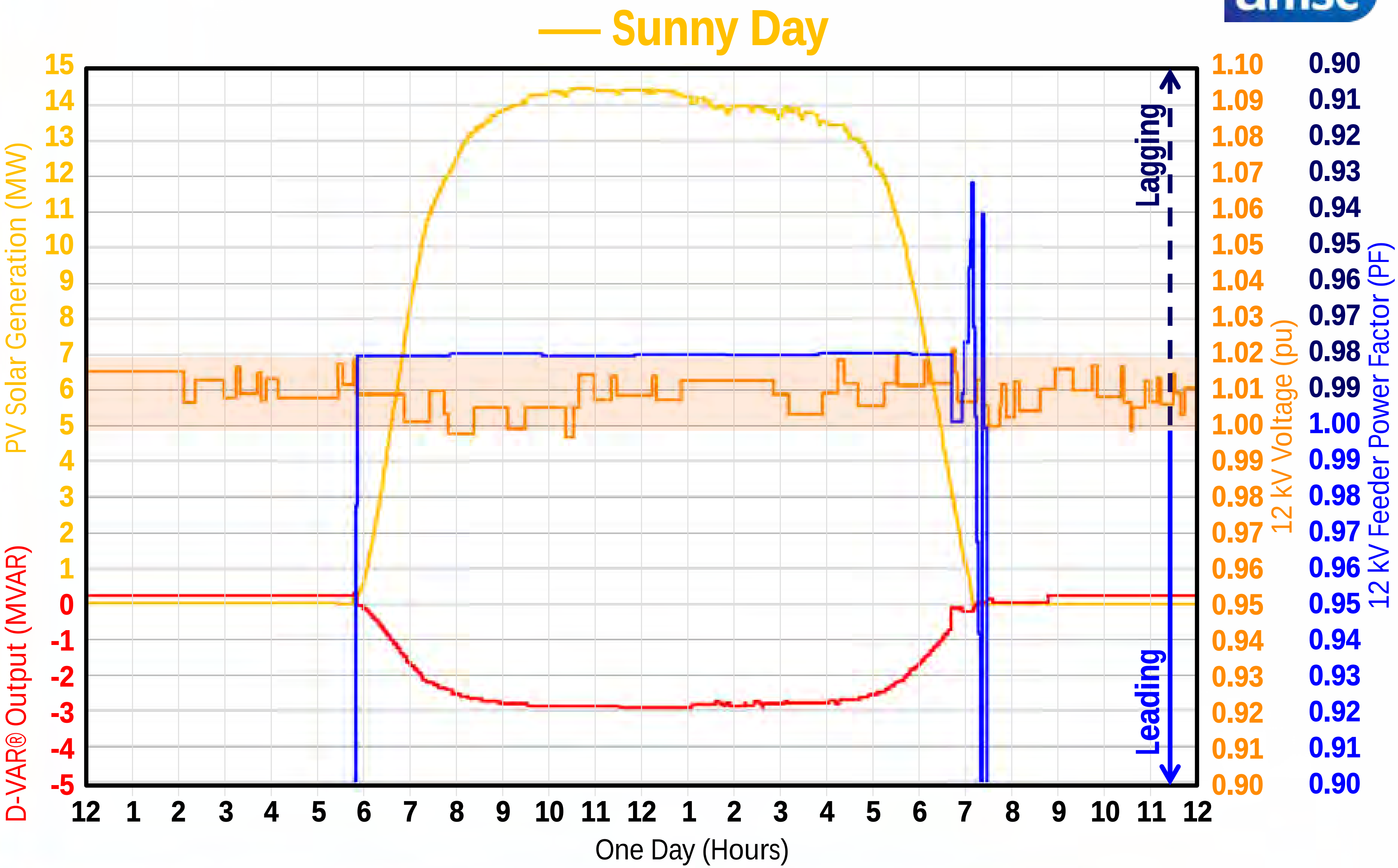
Solar Plant: Area One-Line Diagram

Surrounding System with the D-VAR® STATCOM



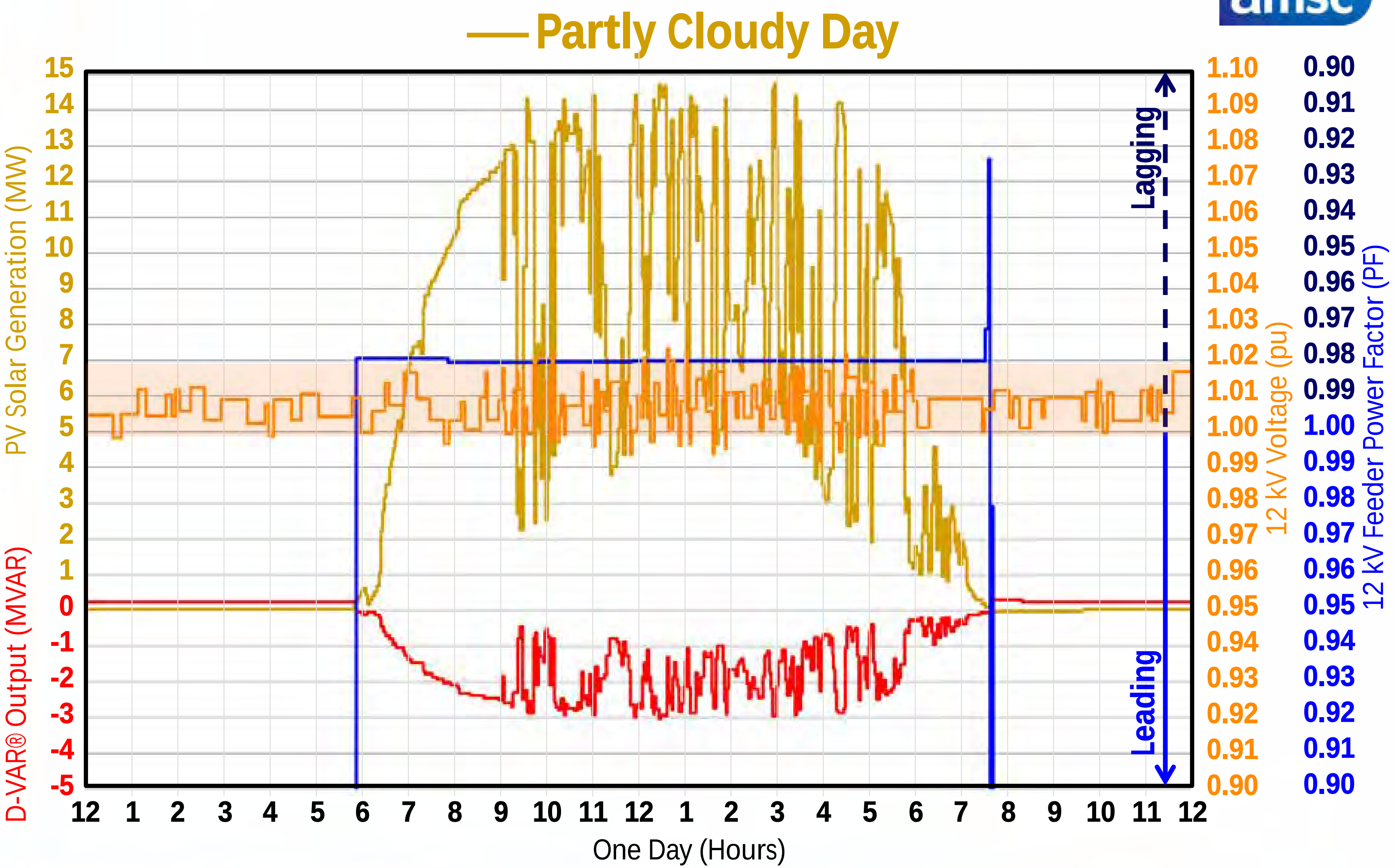
Solar Plant Output Variations - Sunny Day

Actual Field Measurements



Solar Plant Output Variations - Cloudy Day

Actual Field Measurements



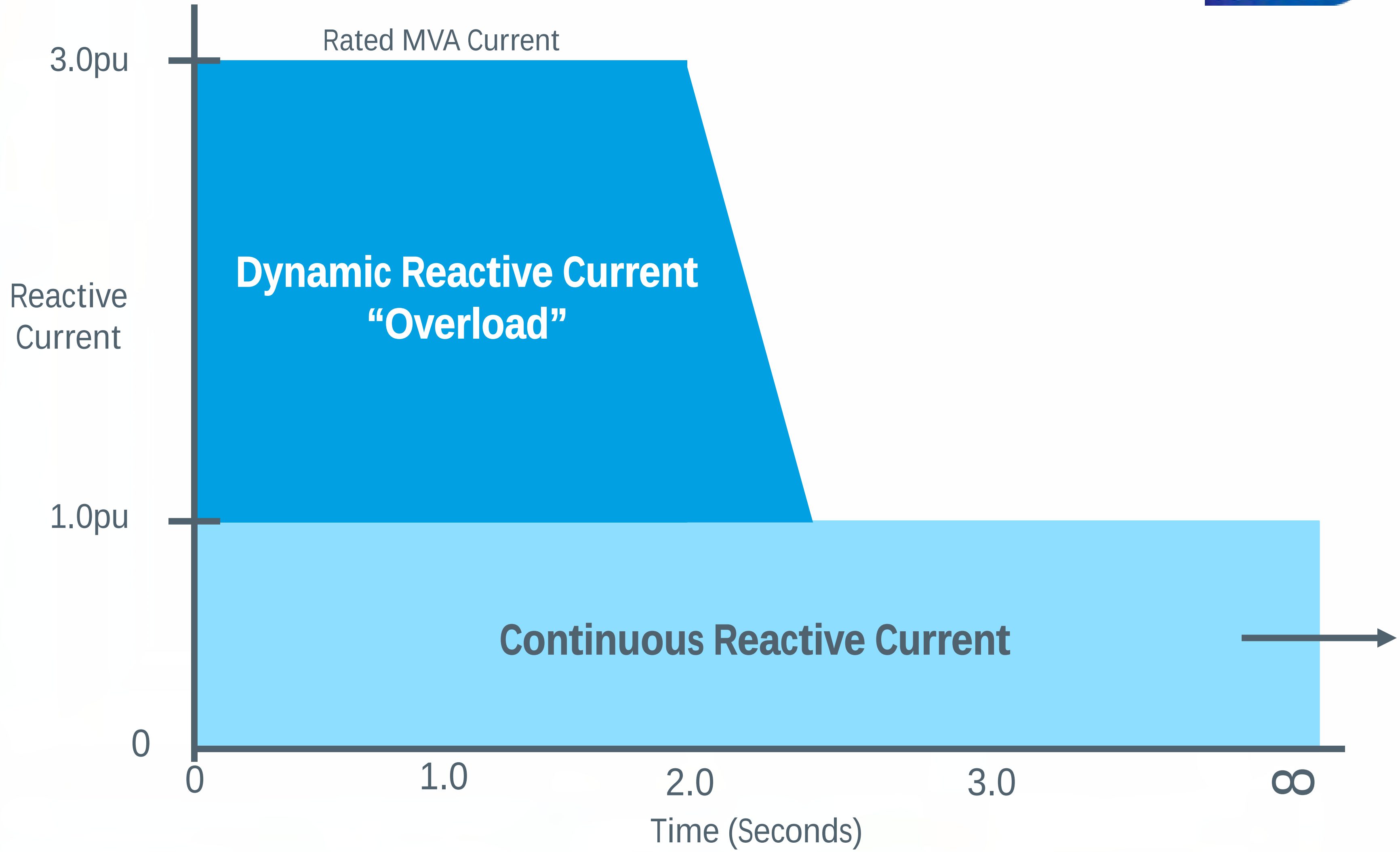
The D-VAR® STATCOM

Installation Example: Utility

amsc

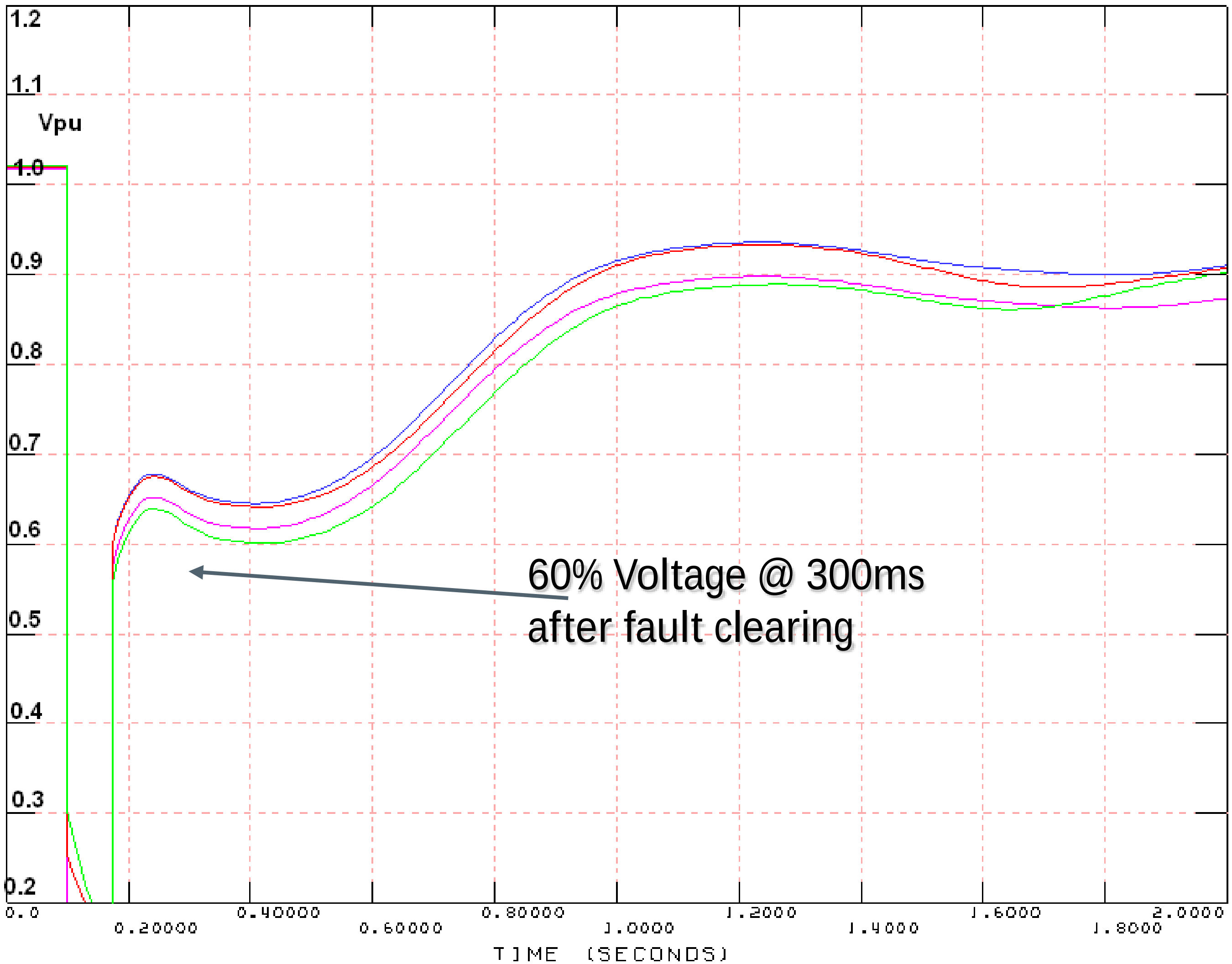
Gridtec™ Solutions

Leveraging the Short Term Overload Capability

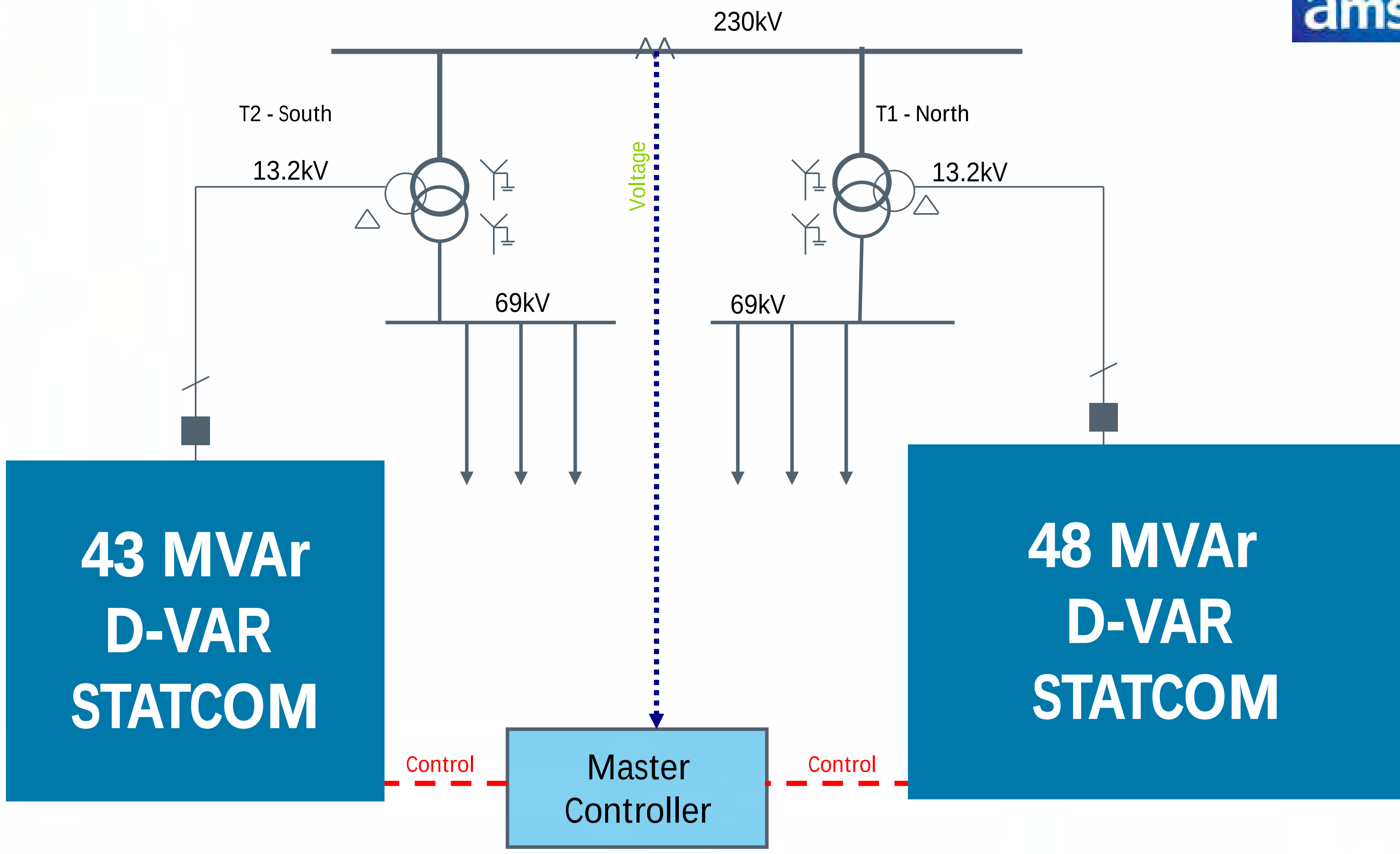


Midwest Utility – Problem Statement

Post-fault delayed voltage recovery

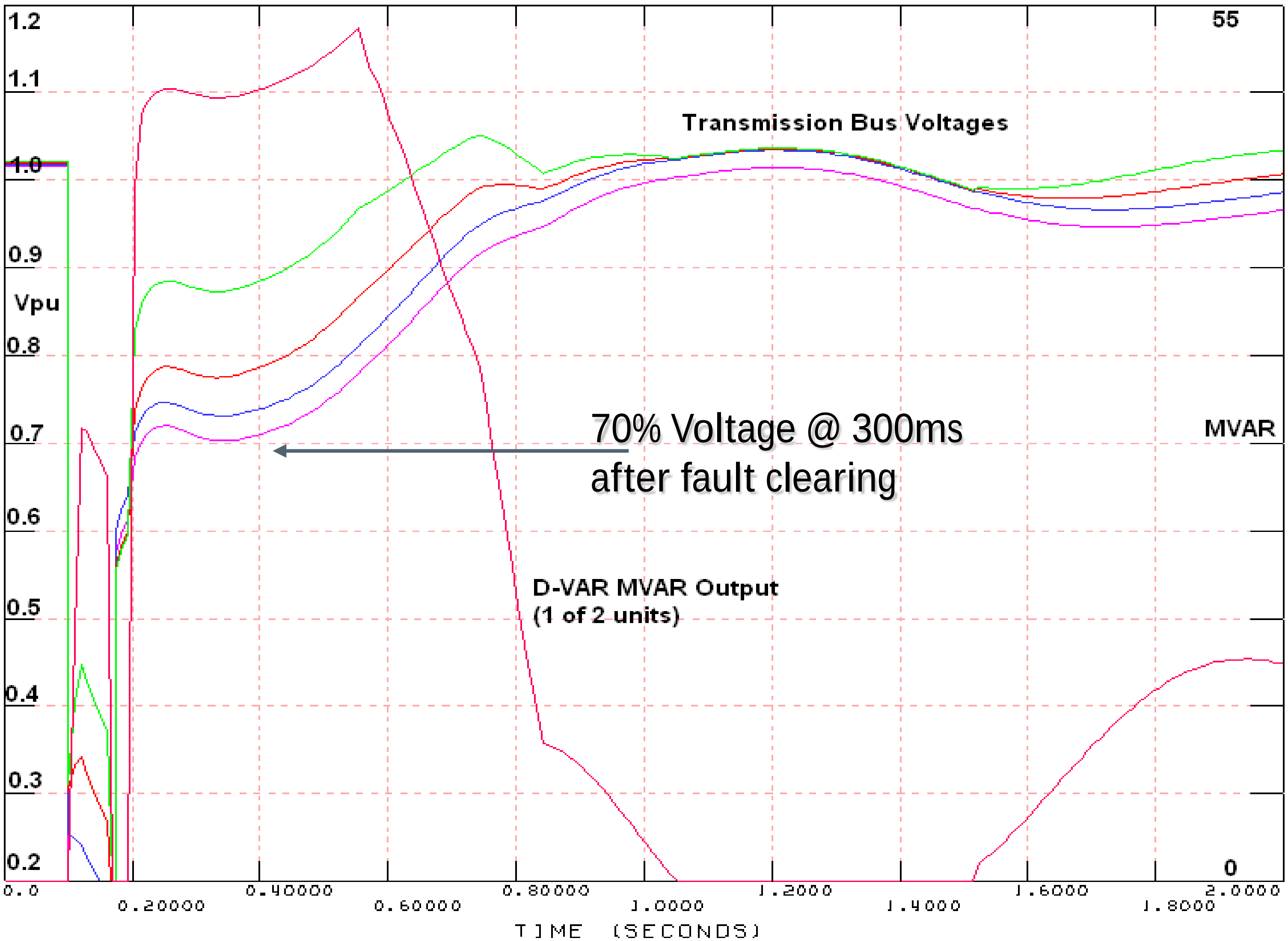


+/-91MVAr D-VAR® STATCOM System



Midwest Utility – The Solution

Response with 91 MVAR D-VAR® STATCOM System



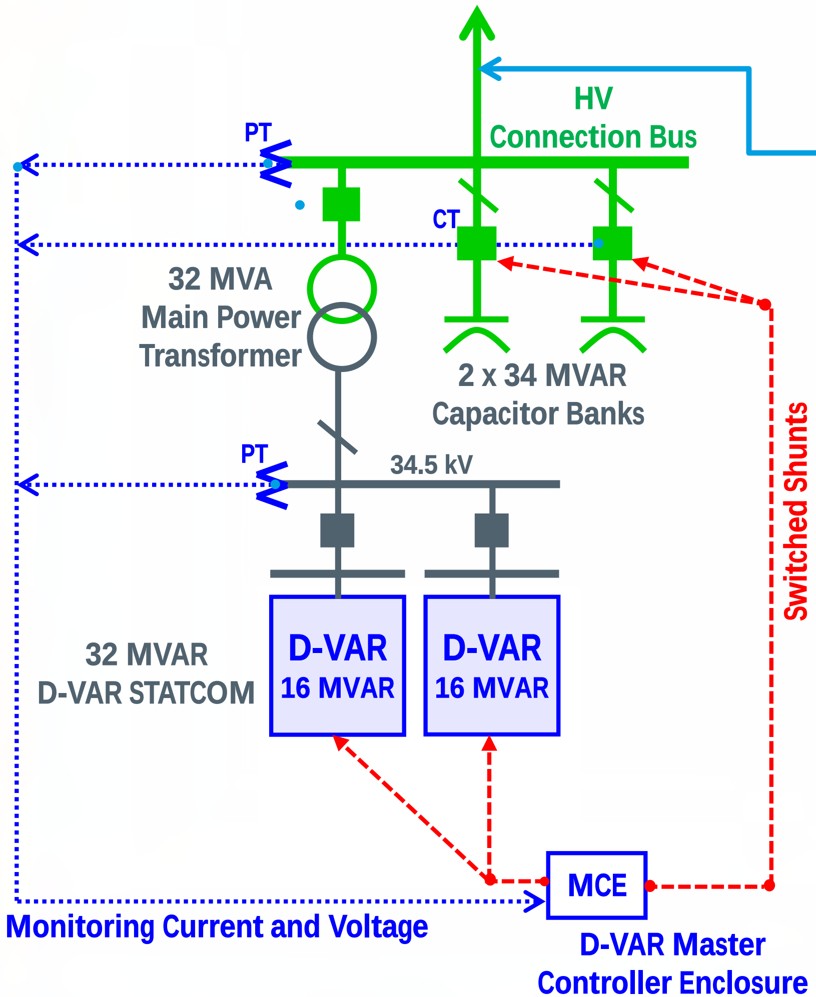
STATCOM Technology:

Adoption with Hybrid Systems on the Rise

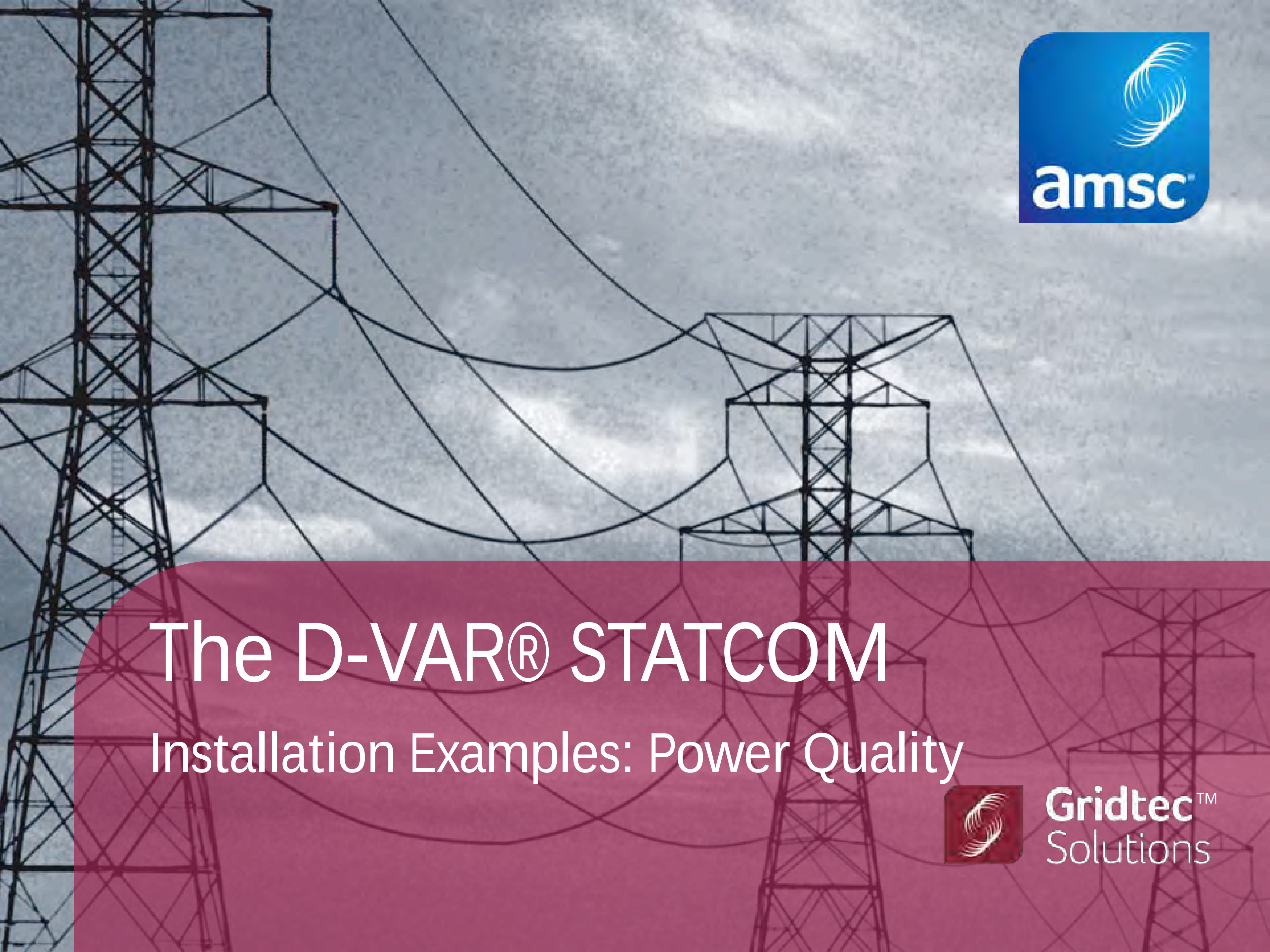
- SVCs and STATCOMs usually add shunt banks to their operating capability
- STATCOMs with shunt banks are typically called Hybrid STATCOMs
- All the benefits of the STATCOM with the added extended range of the shunt banks under the STATCOM's control
- FACTS installation around the world are in the process of replacing the SVC's TCR with a STATCOM for harmonic, speed of response, and cost issues

The AMSC D-VAR® STATCOM

±100 MVAR (Continuous) Hybrid D-VAR Configuration



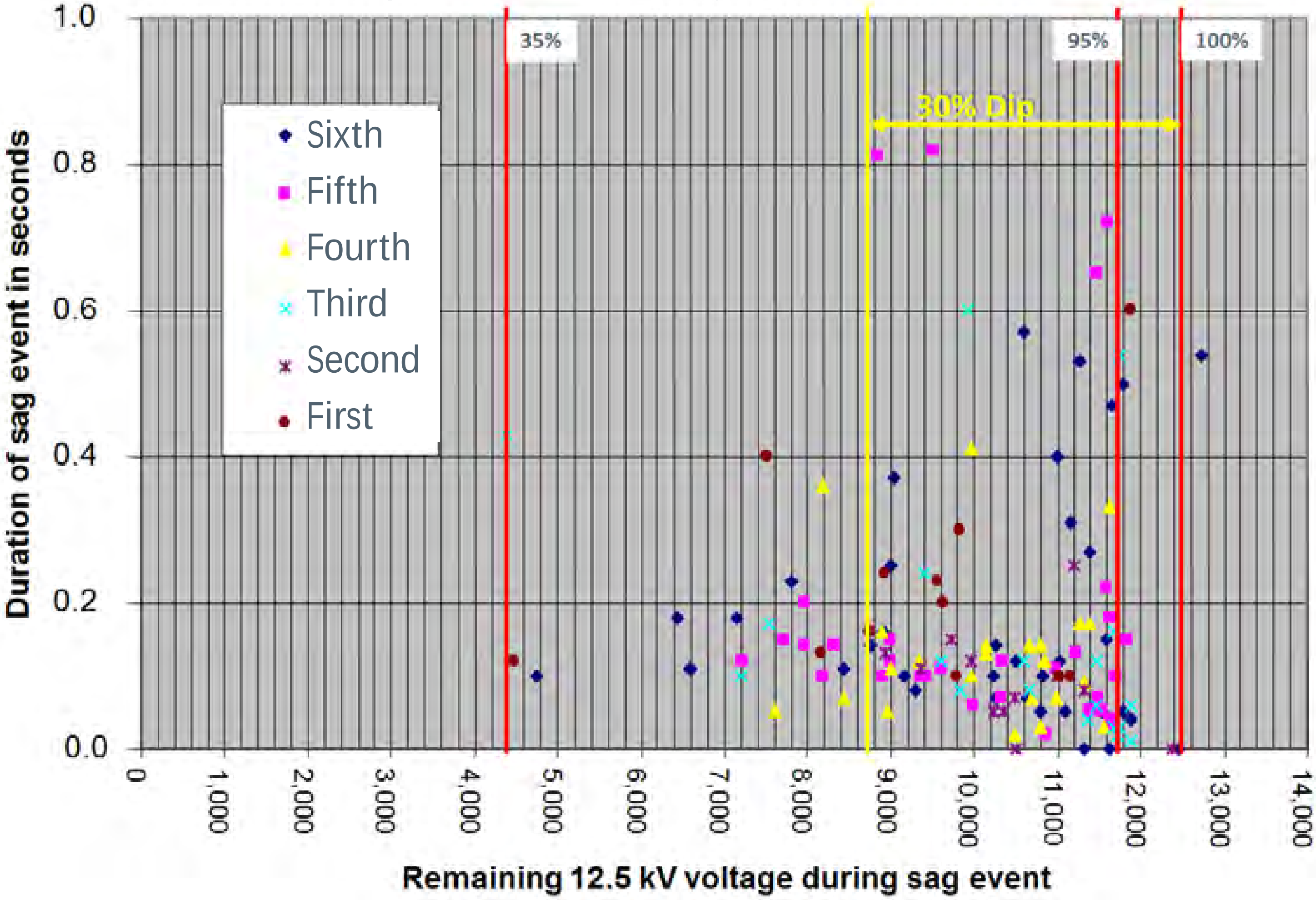
MVAR Output Capability (@1puV)	Steady State	Dynamic
D-VAR STATCOM	±32	±96
Capacitors	+68	+68
Total System	**+100/-32**	**+164/-96**


amsc
The D-VAR® STATCOM
Installation Examples: Power Quality
Gridtec™
Solutions

The AMSC PQ-IVR® System

Mitigates Critical Process Interruptions due to sags in supply system

Example collection of sag data at an industrial facility



The AMSC PQ-IVR® System

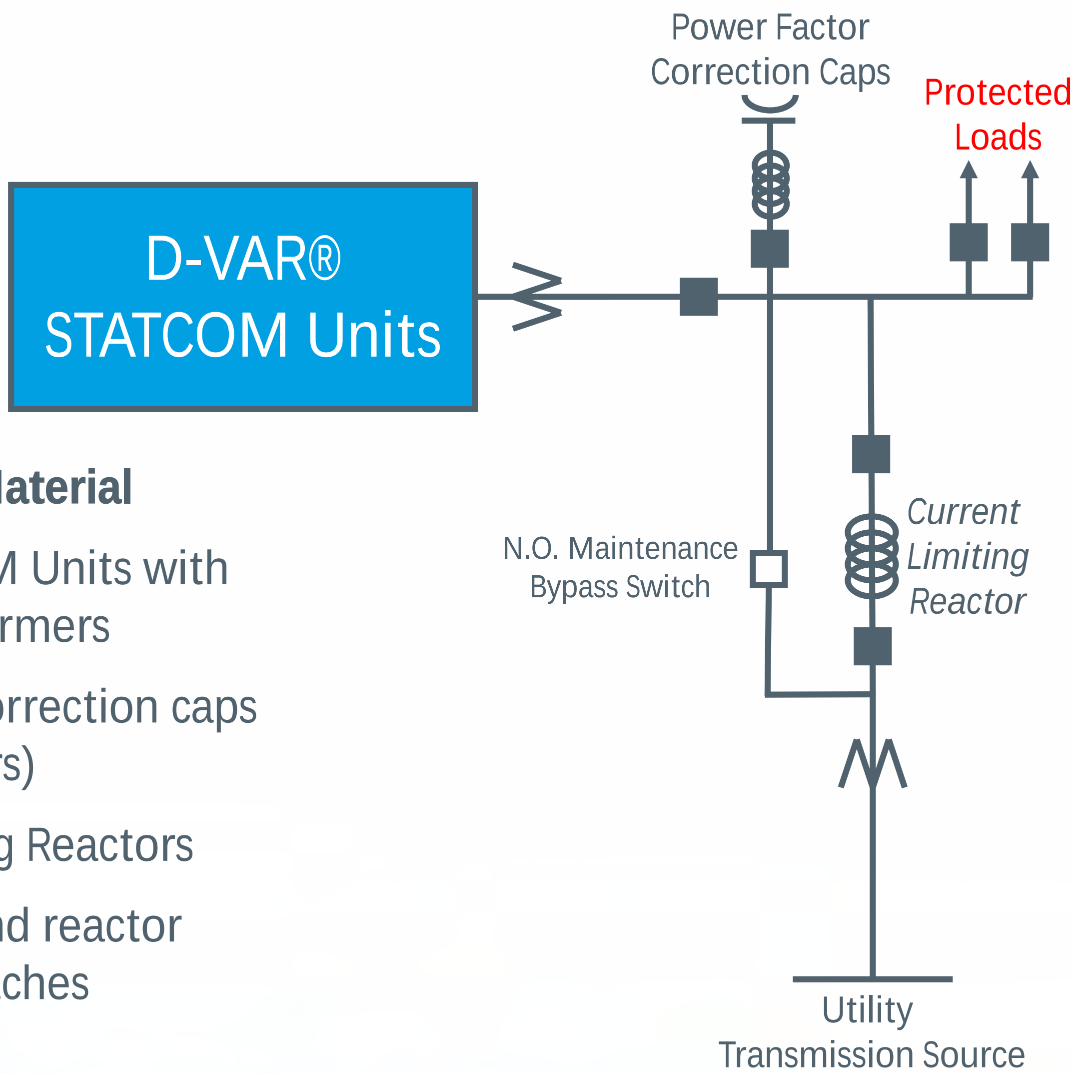
Analysis of Voltage Sag History – case for adding protection

- > 375 events recorded over 7+ years.
- > 150 voltage events impacted production.
- The number of annual production impacting events has more than doubled.
- > 98% of production impact is from voltage sags and < 2% from voltage swells.

The number of production impacting events and the cost of these events warranted installing a PQ solution

The AMSC PQ-IVR® System

Key Components



Bill of Material

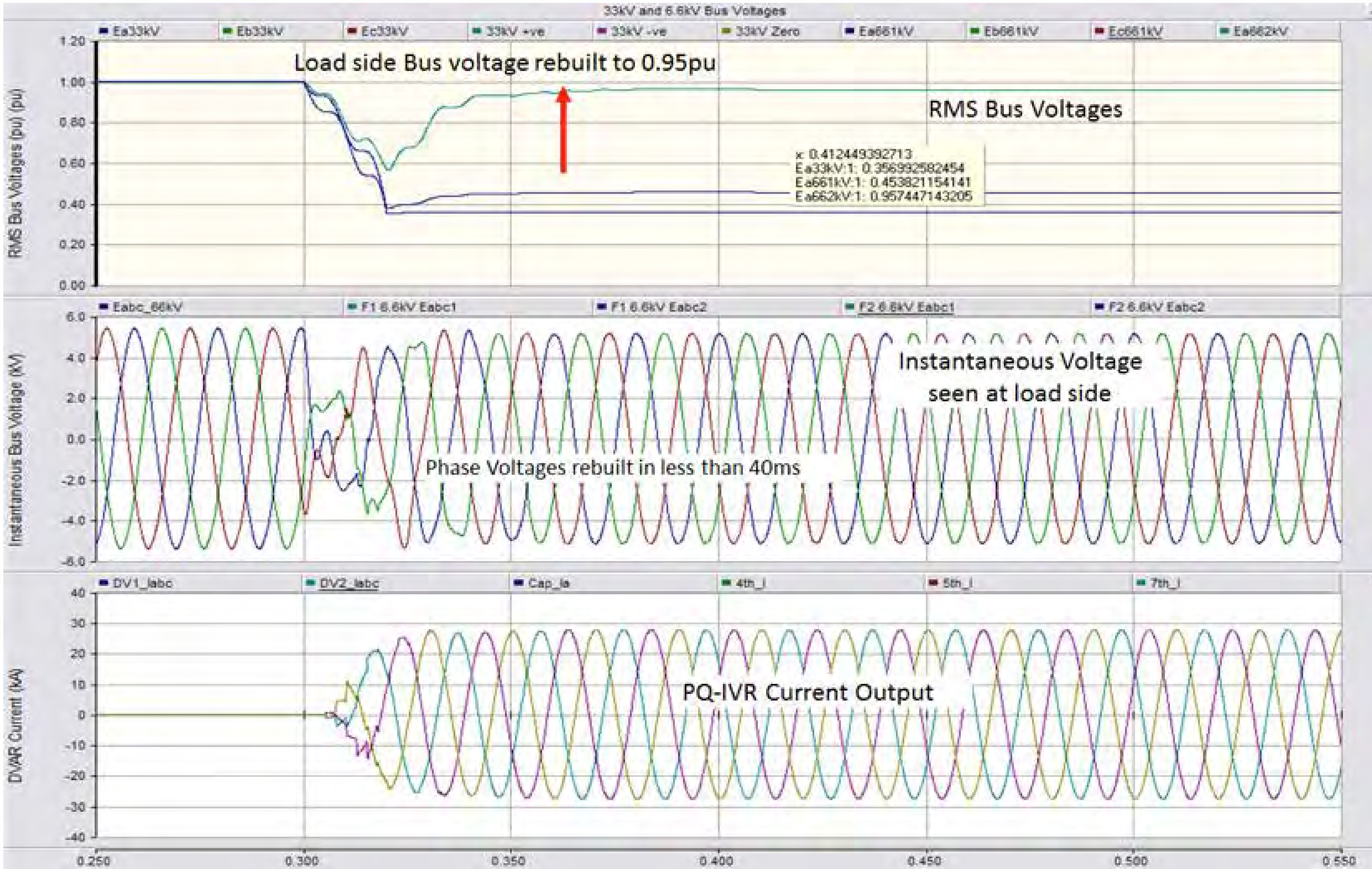
- D-VAR STATCOM Units with step-up transformers
- Power factor correction caps (harmonic filters)
- Current Limiting Reactors
- MV breakers and reactor disconnect switches

The AMSC PQ-IVR® System – System Analysis

PSCAD / 3-Phase Fault / No PQ-IVR® Solution In-Service

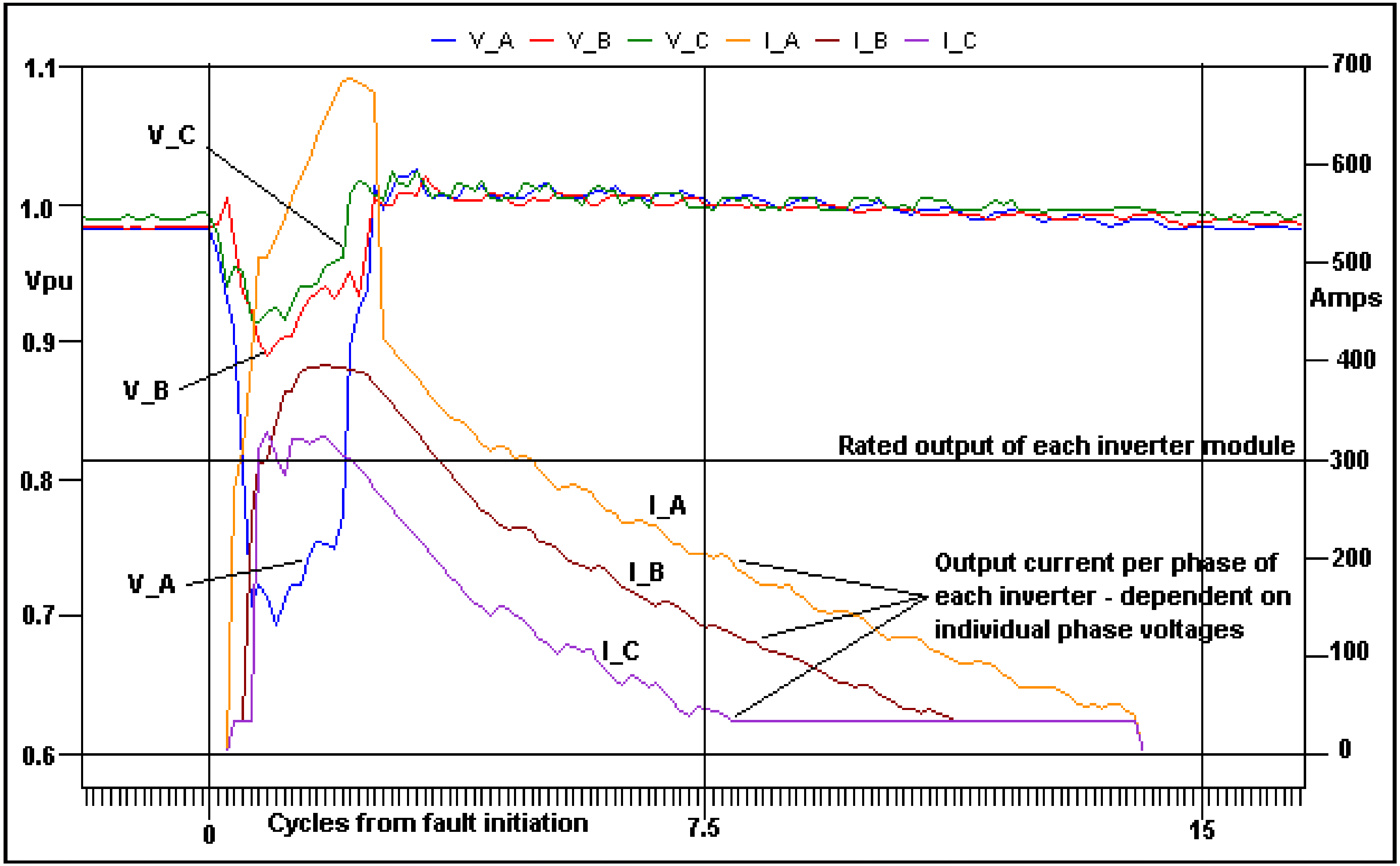
The AMSC PQ-IVR® System – System Analysis

PSCAD / 3-Phase Fault / with PQ-IVR® Solution In-Service



The AMSC PQ-IVR® System
– Speed of Response

Example response of D-VAR STATCOM to unbalanced fault



CONNECTION OF WIND FARMS TO WEAK AC NETWORKS

Dr. Mark Davies

AP B4/C4 Joint Seminar 9.11.2017

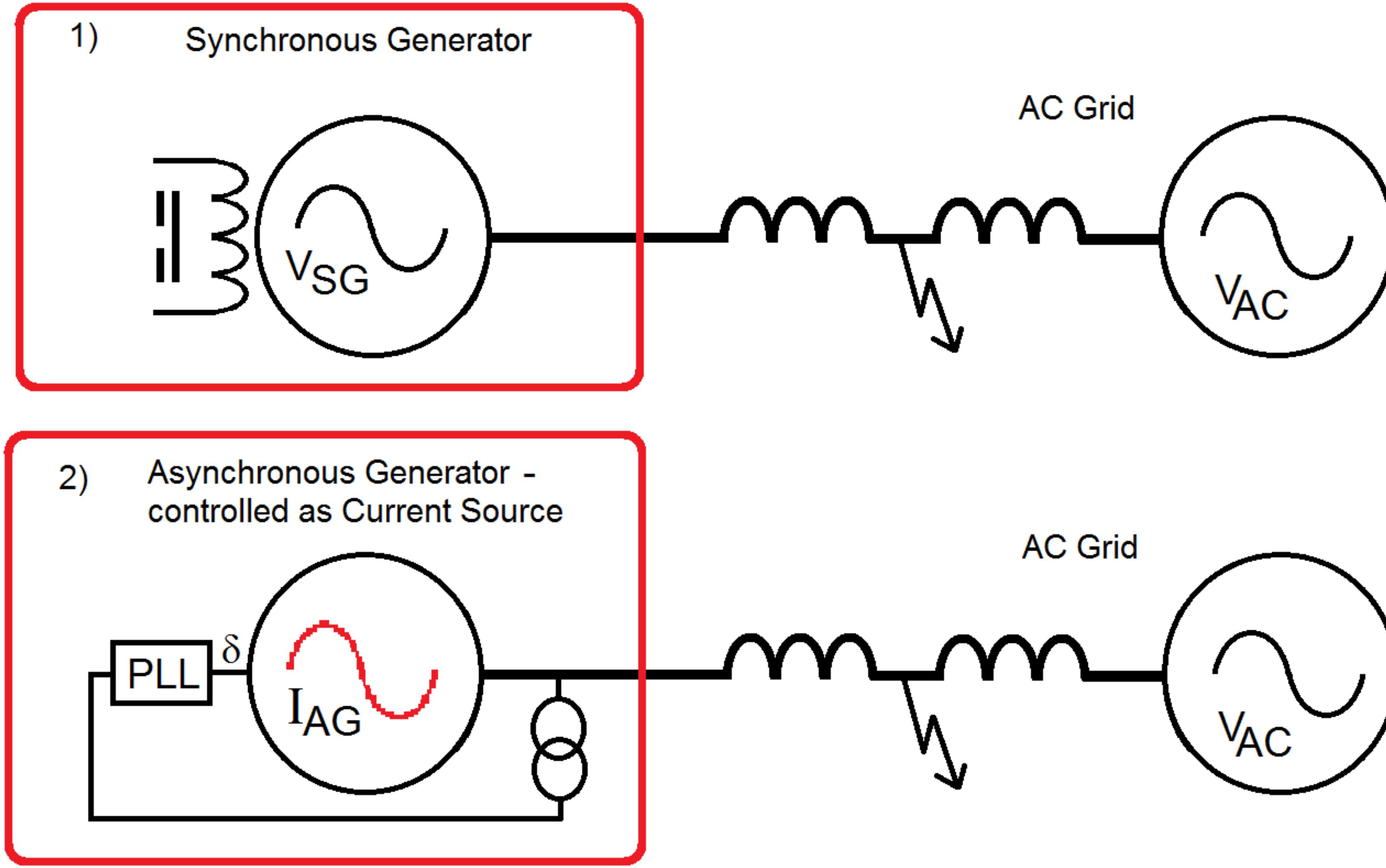
TasNetworks
Delivering your power

Intermittent renewables (e.g. windfarms) are predominantly Asynchronous Generators (AG)

- Windfarm AGs have an intermittent energy source
- AG traditionally offer less “services” than Synchronous Generation (**SG**)
- AG is generally dominated by power electronics which gives a *digital* connection cf. with the *analogue* connection of SG.

This means that the issues with AG vary depending upon the time-scales under consideration. Some issues are easily understood but many require complex scientific and engineering solutions.

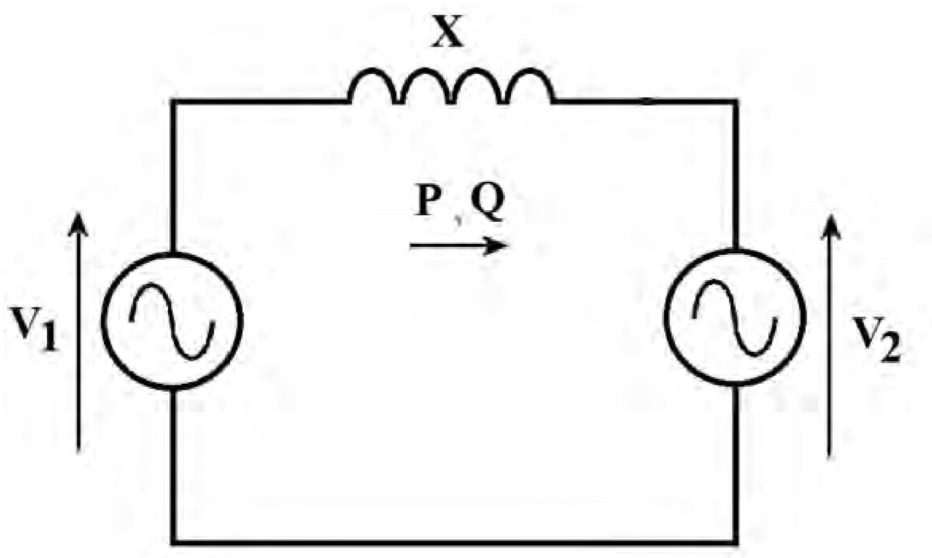
Fault ride through issue due to transition from SG to AG



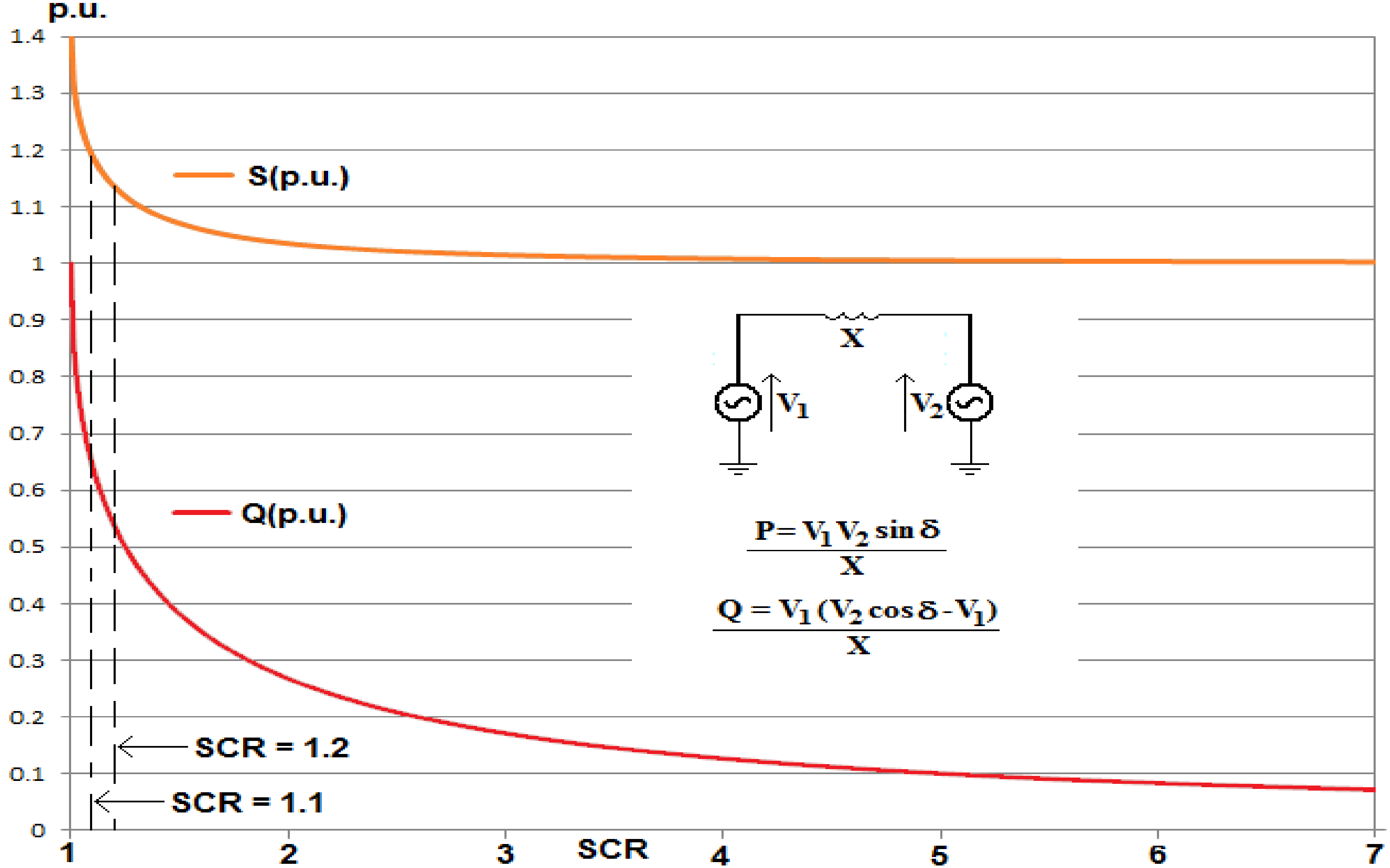
AG issues on weak AC Networks

A basic understanding is given by considering the familiar "transmission equations"

$$P = \frac{V_1 V_2 \sin\delta}{X} \qquad Q = \frac{V_1 (V_2 \cos\delta - V_1)}{X}$$

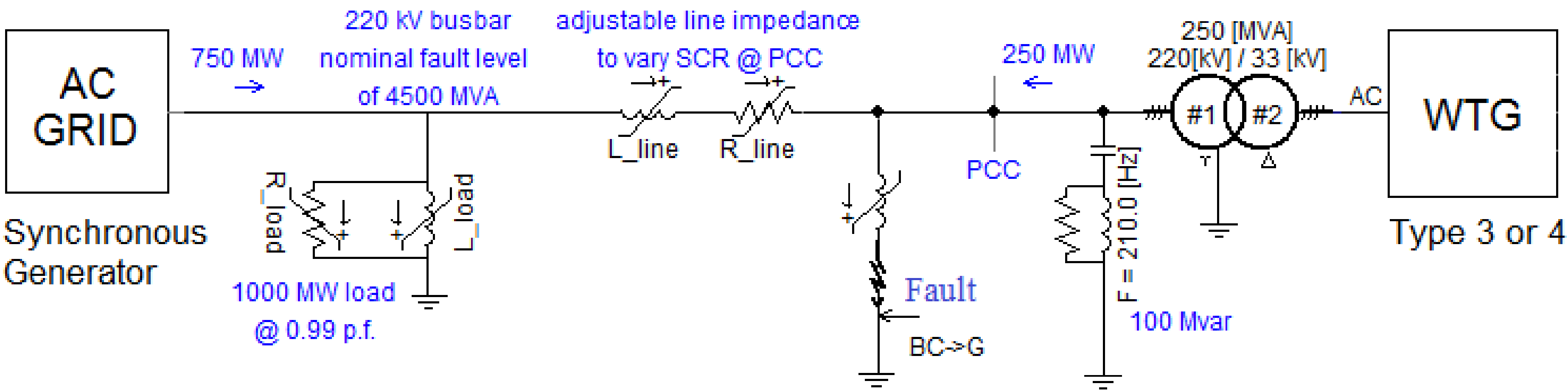


What do these equations tell us ?



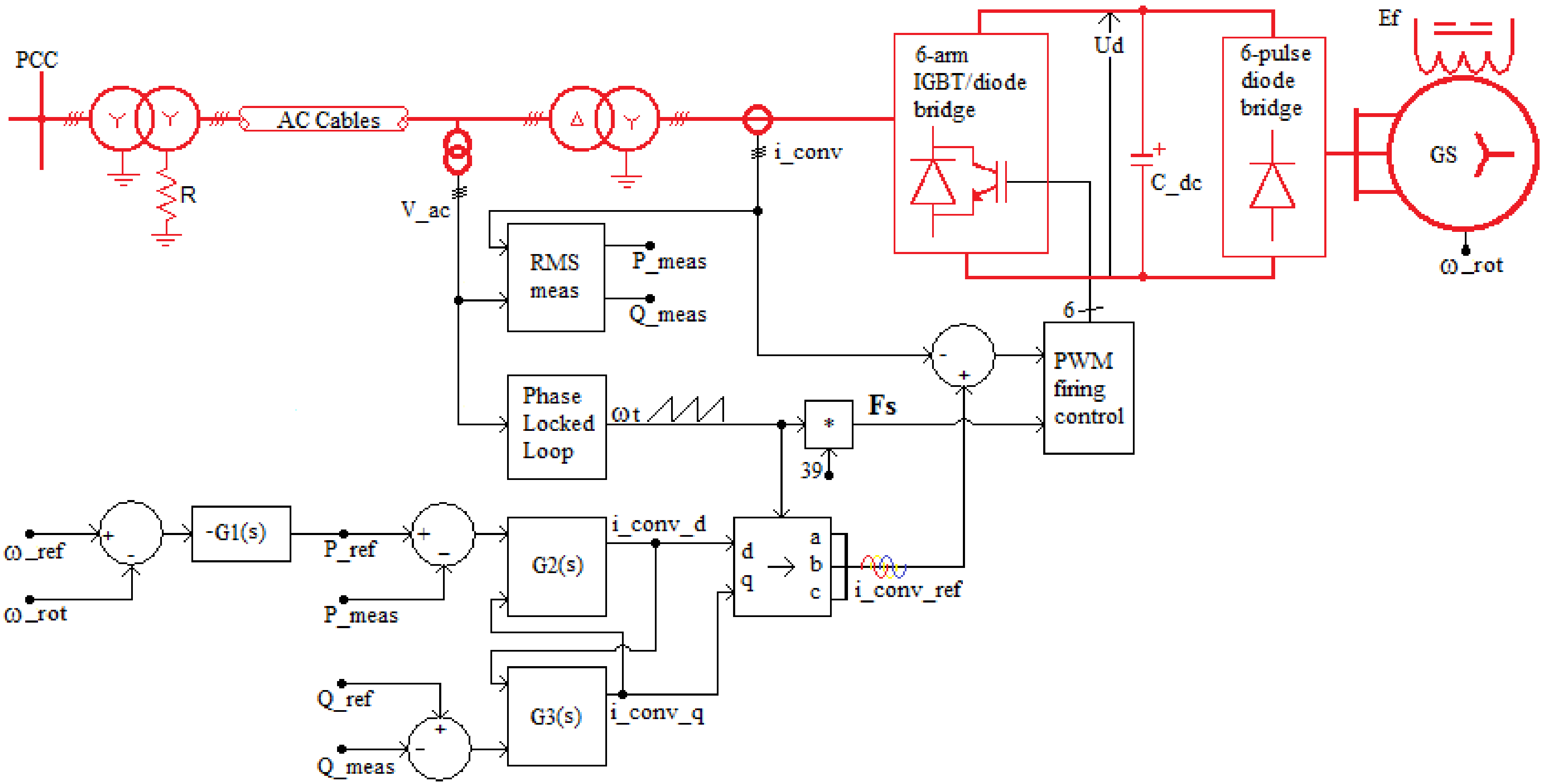
Short Circuit Ratio (**SCR**) = $\frac{\text{Fault MVA @ PCC}}{\text{WPP rating (MW)}}$

Cigre assessed the impacts on weak AC networks



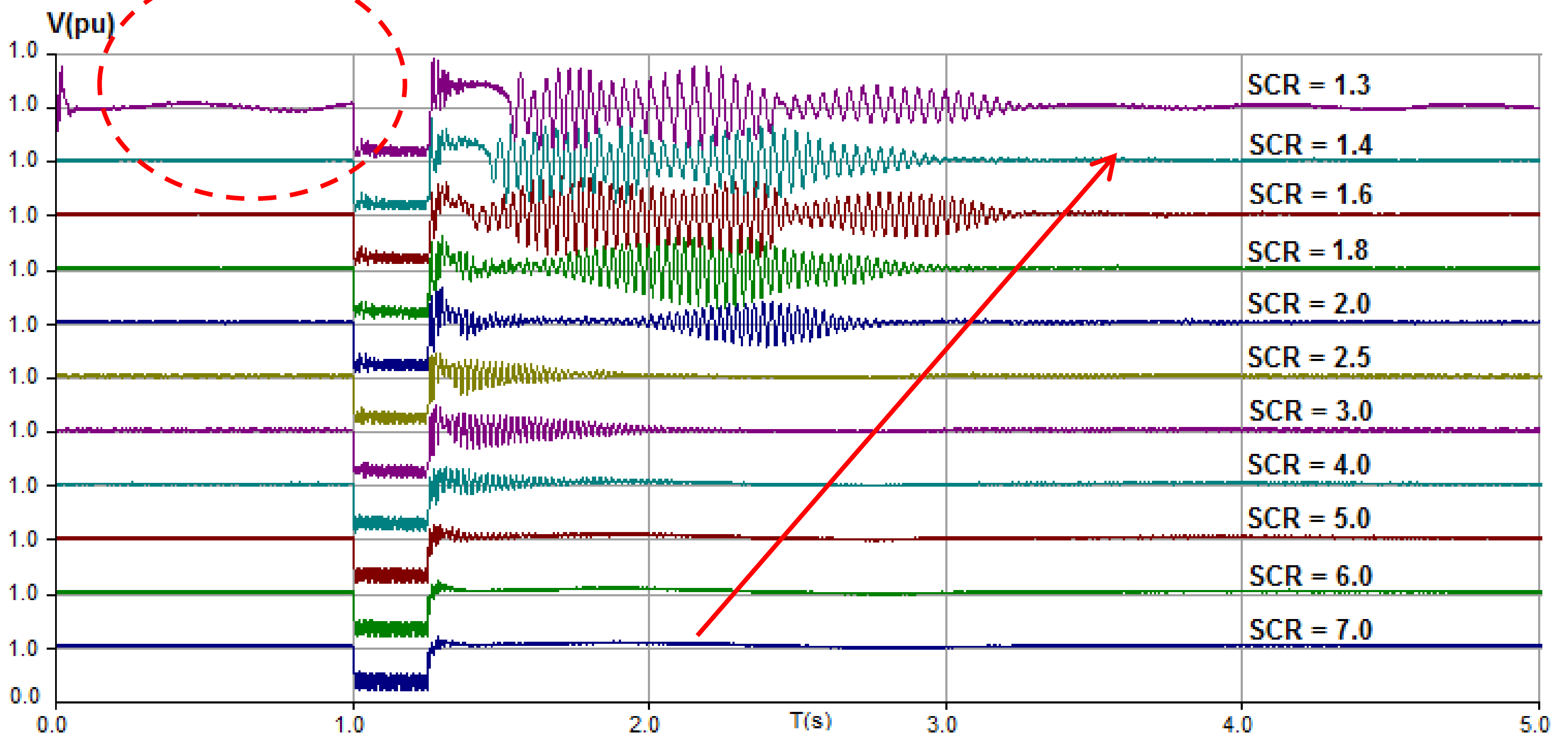
- Cigre set up WG B4.62 to investigate the problems (Brochure 671)
- A benchmark circuit (above) was agreed upon to assess the performance of asynchronous wind turbine generators (**WTGs**) on a weak point of common coupling (**PCC**)
- System strength was set by altering the line impedance
- Fault ride through (**FRT**) was tested with 2pg faults of 0.25 s

Generic WTG models were used to set a Benchmark



Model of generic Type 4 WTG used for benchmark studies

Generic WTG model FRT performance



Voltage response at PCC for local 2pg fault of 250 ms duration

As SCR decreases, stability margin is reduced:

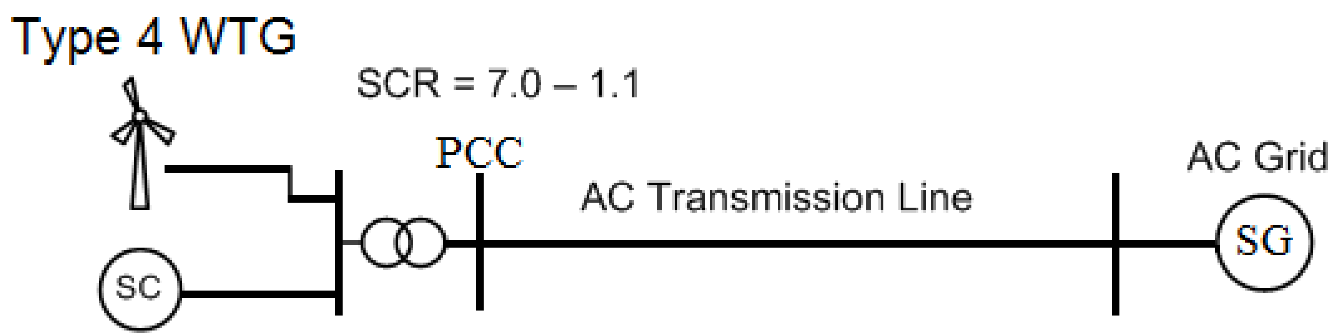
1. WPP model struggles to recover from FRT
2. Increasing voltage transients are evident post-fault clearance

Methods to improve performance at low SCRs

Four "enabling technologies" were selected to investigate their ability to improve Type 4 WTG performance at low SCRs:

1. Addition of Synchronous Compensators (SC)
2. Addition of STATCOM
3. Use of remote synchronising reference (PMU)
4. Use of decoupled local Phase-Locked Oscillator

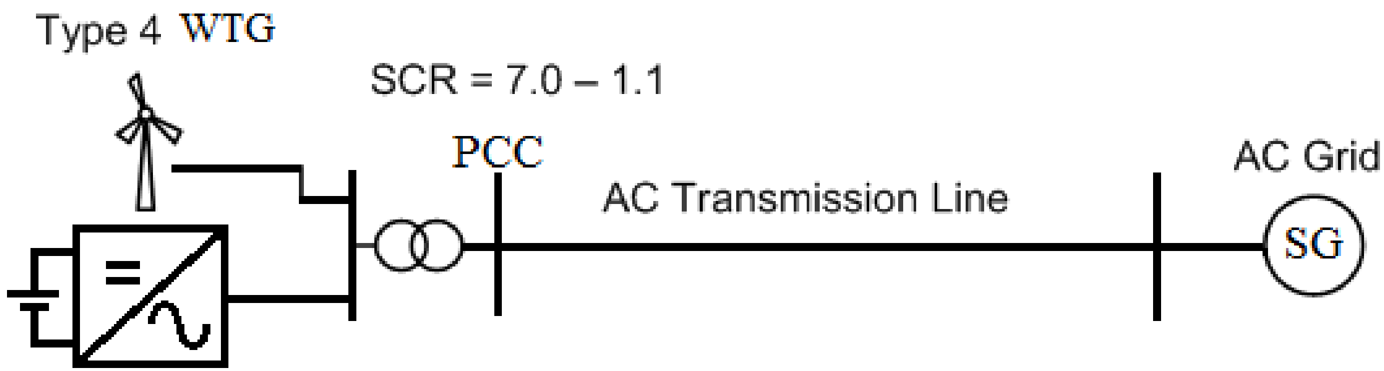
Simulation results Type 4 WTG + 50 MVA SC



Isolated WPP with voltage/inertial support from Synchronous Compensator

- Stabilises voltage and provides a local Q response (machine timeframe)
- Active power exchange with SC rotor helps stabilise voltage angle
- SC improves stability (fault ride through response) for all cases
- Addition of SC appears capable of stabilising WPP for SCR down to 1.3
- This is an improvement of approximately 30%

Simulation results Type 4 WTG + 50 Mvar STATCOM

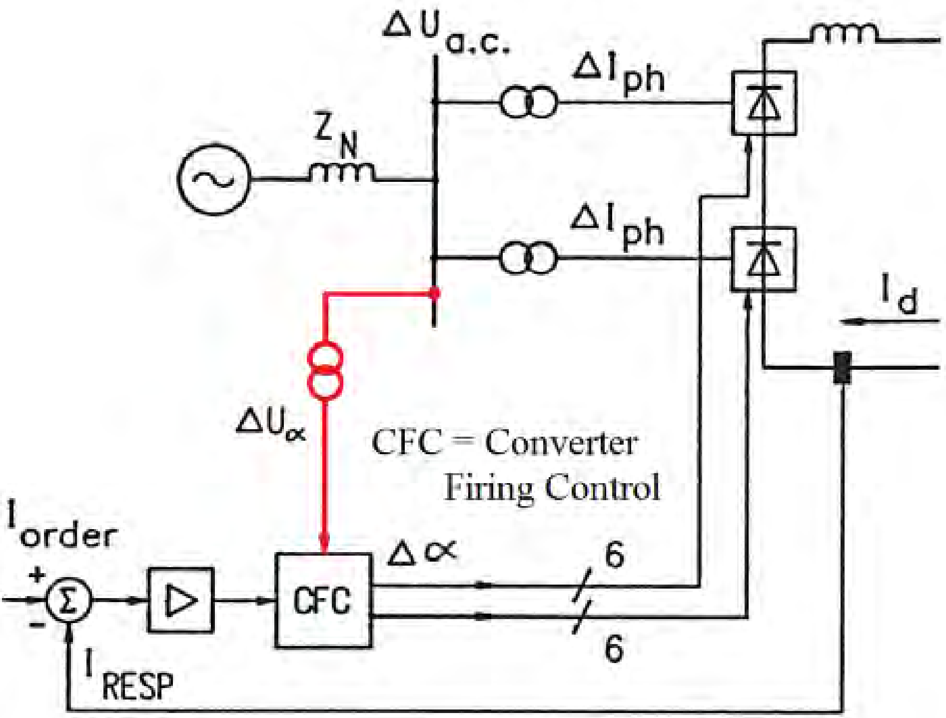


- Stabilises voltage and provides a fast local Q response (converter timeframe)
- Faster control of voltage compensates for inability to exchange P
- STATCOM improves stability for all cases, very similar to SC
- STATCOM appears capable of stabilising WPP for SCR down to 1.3
- This is an improvement of approximately 30%

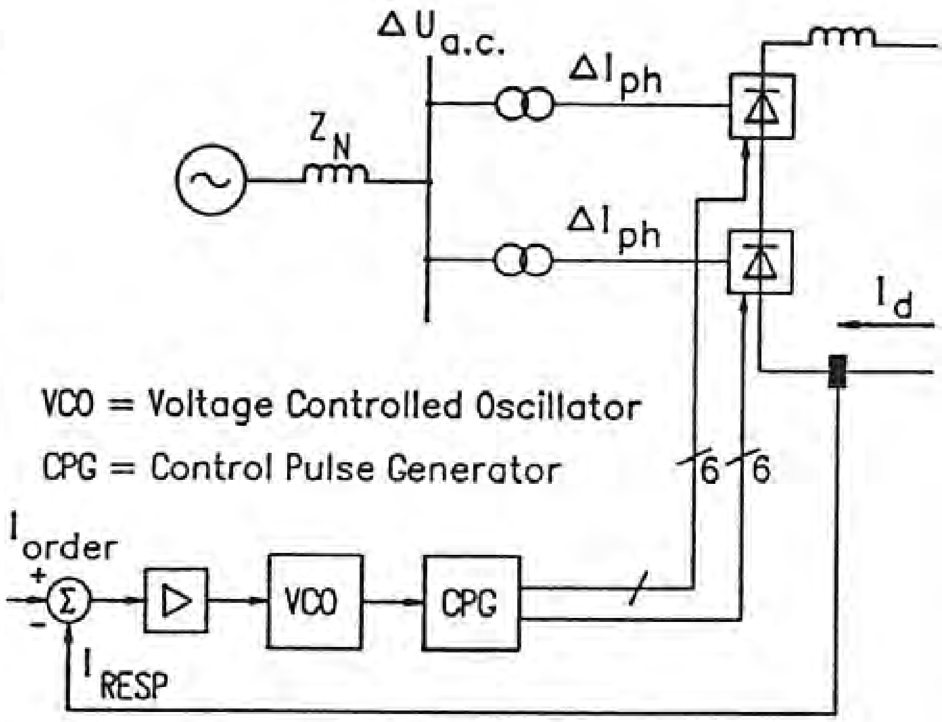
SC versus STATCOM

- Assessment on a weak radial connection showed similar improvements for SC and STATCOM
- Inertial requirements of AC system not assessed
- Considering FRT of the WTG the SC reduces the apparent X, i.e. increases the SCR transiently.   Whereas the STATCOM supplies the fast Q needed for stability – lessens WTG requirements.
- It is not true that SCs are essential for very weak systems - offshore WPPs of 1 GW have been commissioned without any synchronous machines.

Explanation of PLL "delay" effect on HVDC



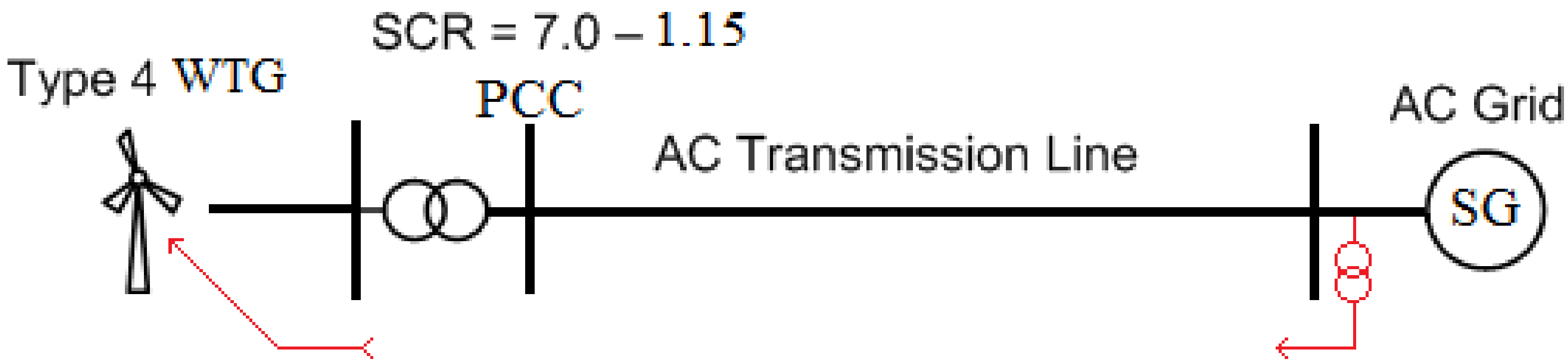
Phase-Locked Loop Based Control System



Local Oscillator Based Control System

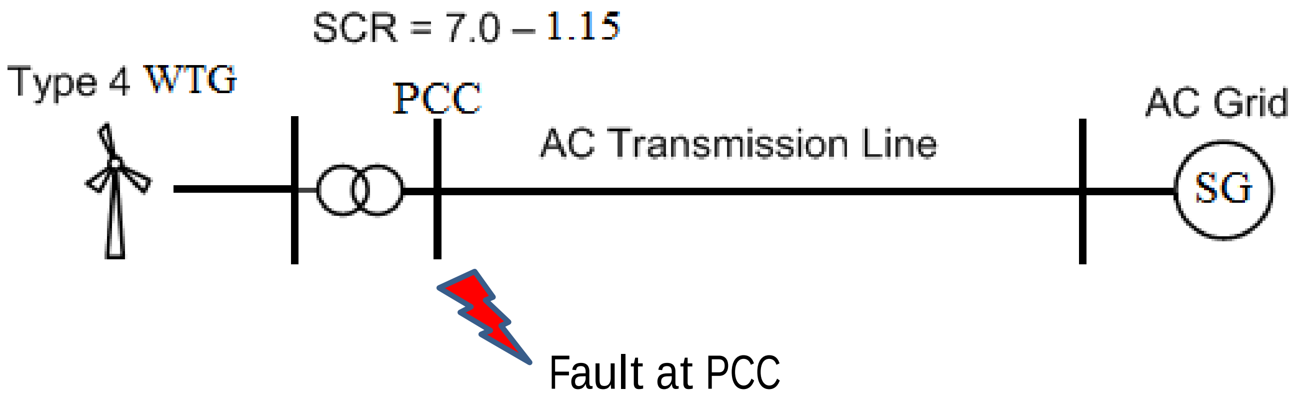
Extract from Cigre 68/IEEE 15.05.05 - HVDC Interaction with low SCR AC Systems - 1992

Simulation results Type 4 WTG + PMU signal



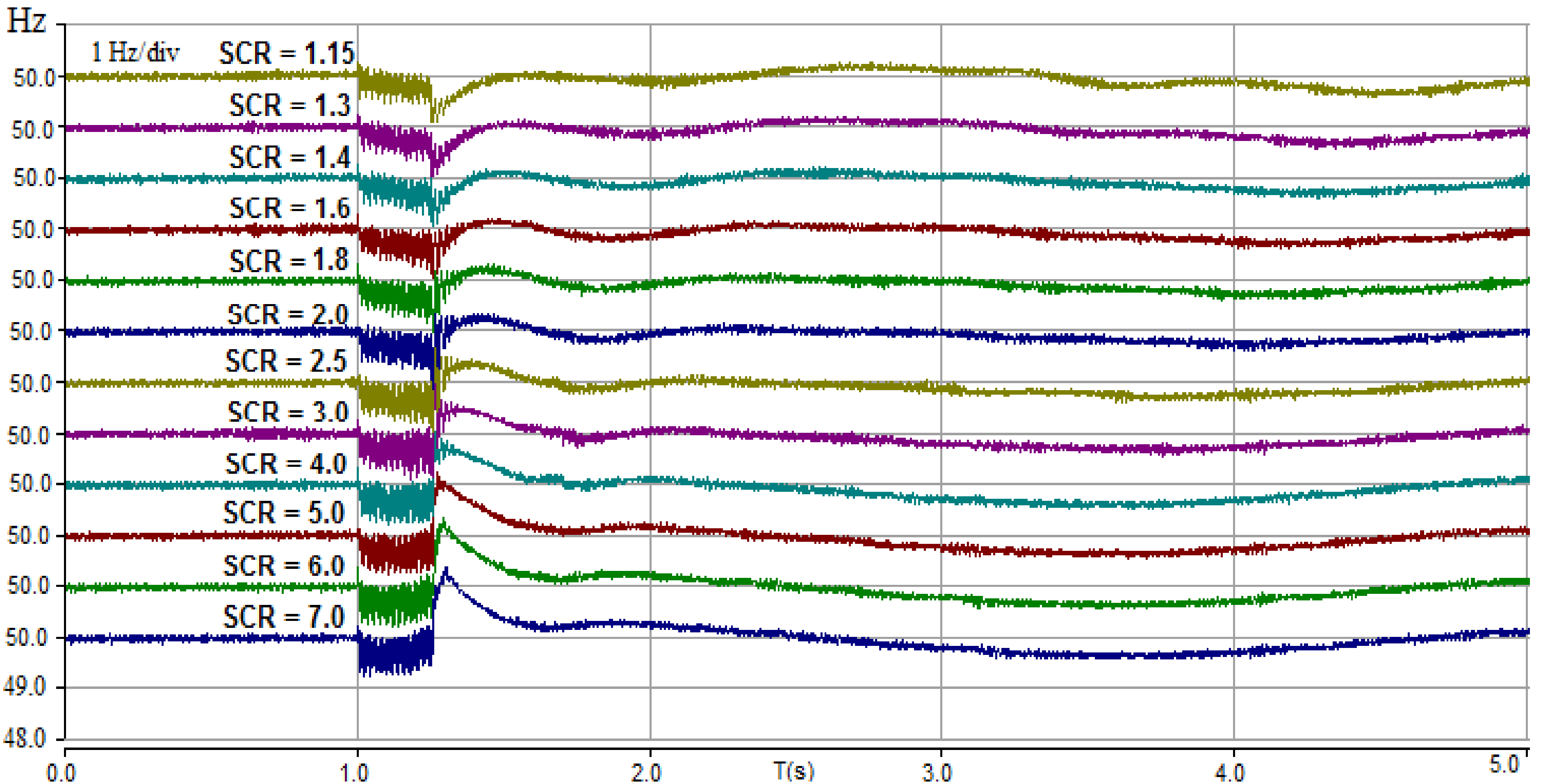
- What is the benefit?
- Effectively 'decouples' the WTG and its PLL from its own impact on the PCC voltage angle – now referencing a strong signal for synchronisation.
- This method appears capable of stabilising WPP for SCR down to 1.3
- Method works for weak 'radial' networks but cannot assist for a general degradation of system strength
- Signal latency needs to be considered

Simulation results Type 4 WTG + local oscillator



- PLL replaced with a higher bandwidth local oscillator (faster control)
- Core advantage relates to re-synchronising with fast changing and distorted voltage phase angle
- Change in synchronous speed of AC grid will depend on SCR
  - Strong connection – AC grid accelerates
  - Weak connection – AC grid decelerates depending on WPP ‘P’
- This method appears capable of stabilising WPP for SCR down to 1.15
- Not without challenges – need to protect power electronics from over current

Frequency at the PCC – high or low?



Difficult to design a PLL that is robust for synchronising frequencies that can be high, low or unchanged post fault clearance

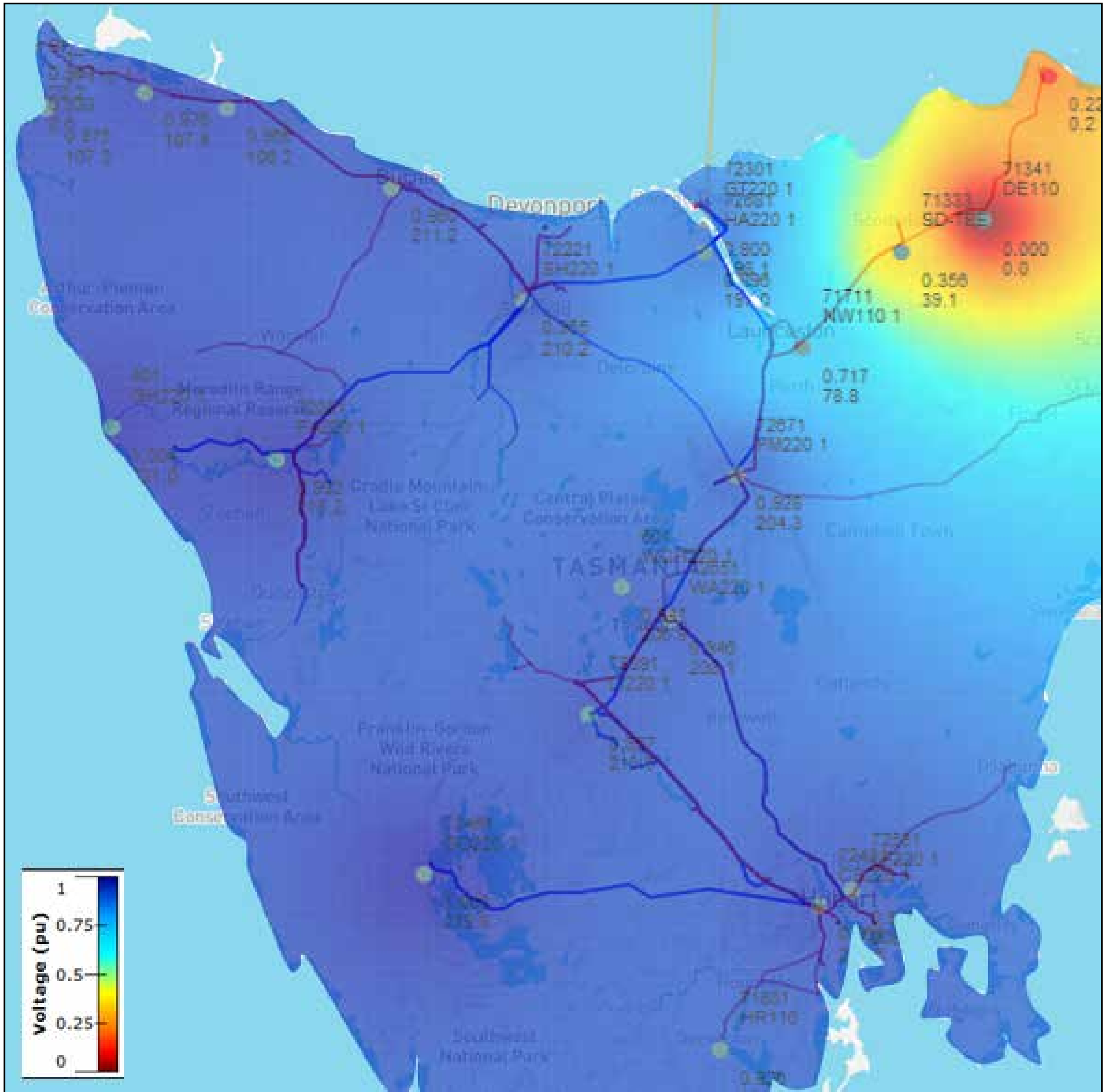
Conclusions from Cigre assessment

Generic Type 3 & 4 WTGs show issues with SCRs < 2.0 but:

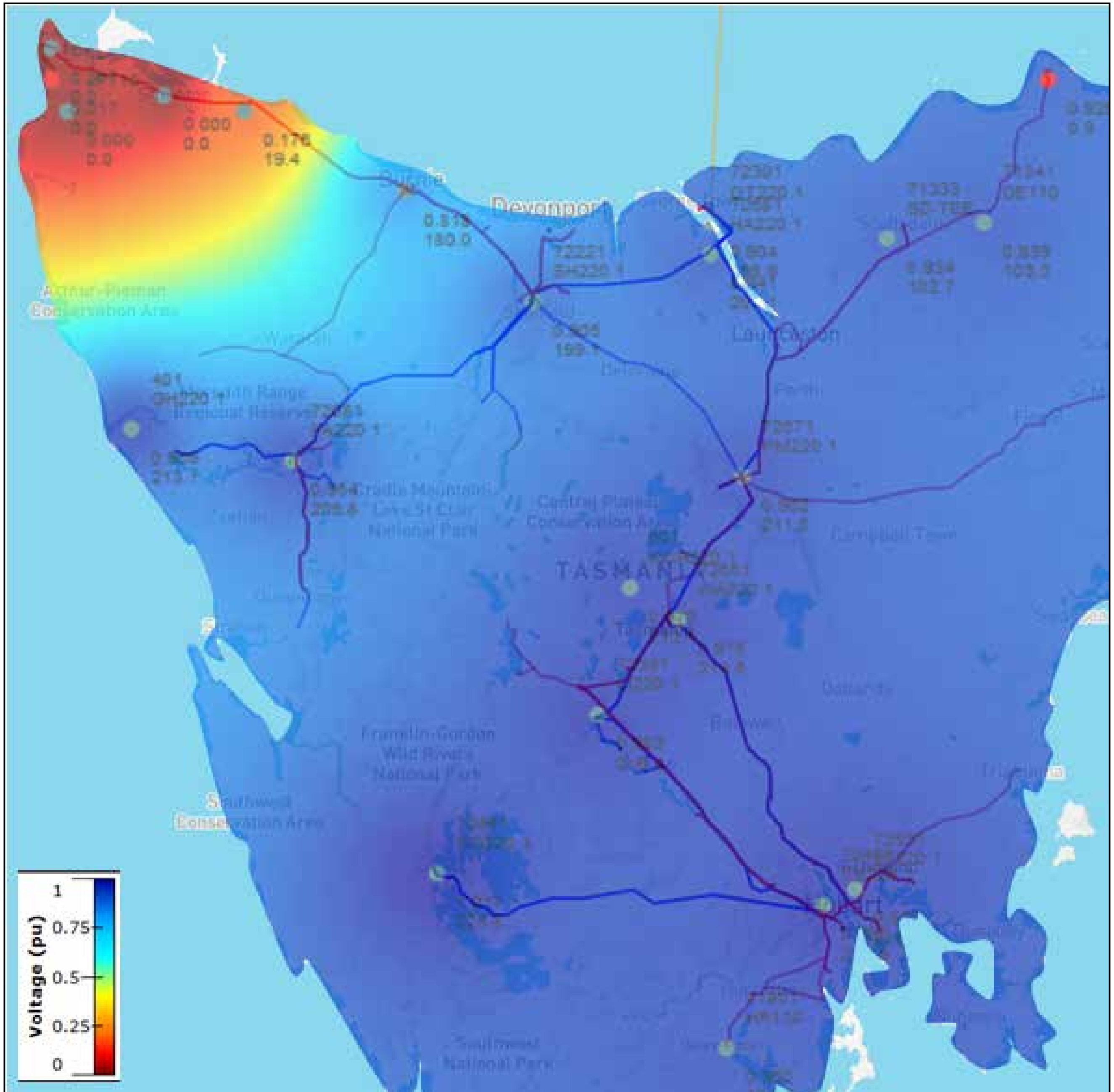
1. The following “enabling technologies” help:
    - i. SCs, STMs or PMU reference improve by about 30 %
    - ii. A local phase-locked oscillator improves by about 40 %
2. As AG penetration increases the “available” fault level and hence SCR will reduce for existing WTGs.
3. Connecting high performance technology now will greatly benefit power systems of the future.

How is Brochure 671 guiding TasNetworks ?

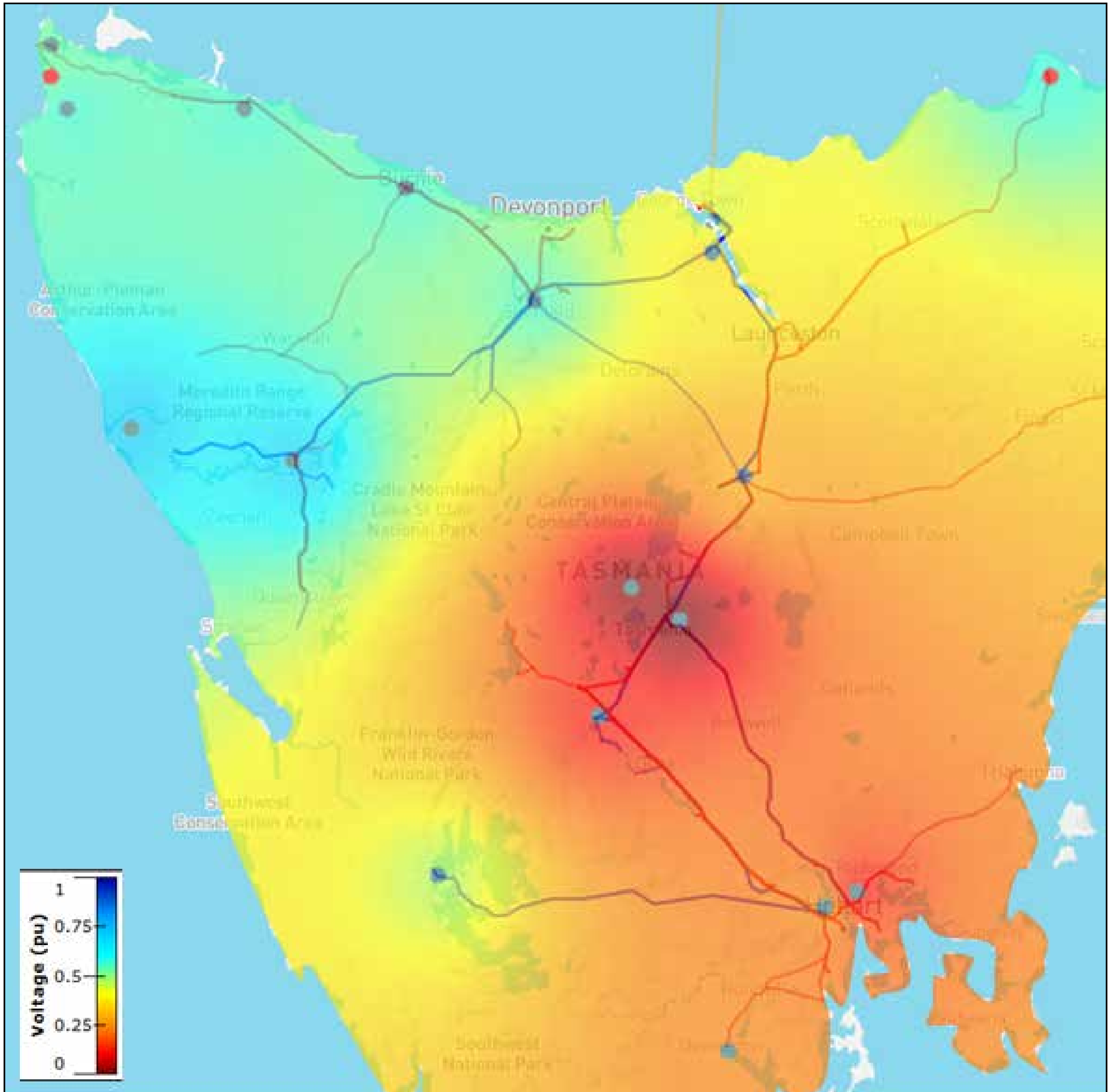
Voltage Dip Propagation for a 3 phase fault at DE 110 kV



Voltage Dip Propagation for a 3 phase fault at ST 110 kV



Voltage Dip Propagation for a 3 phase fault at WA 220 kV



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November 2017

POWER SYSTEM OPERATION WITH HIGH PENETRATION OF NONSYNCHRONOUS GENERATION: SOUTH AUSTRALIAN CASE STUDY

November 2017

PRESENTED BY BABAK BADRZADEH

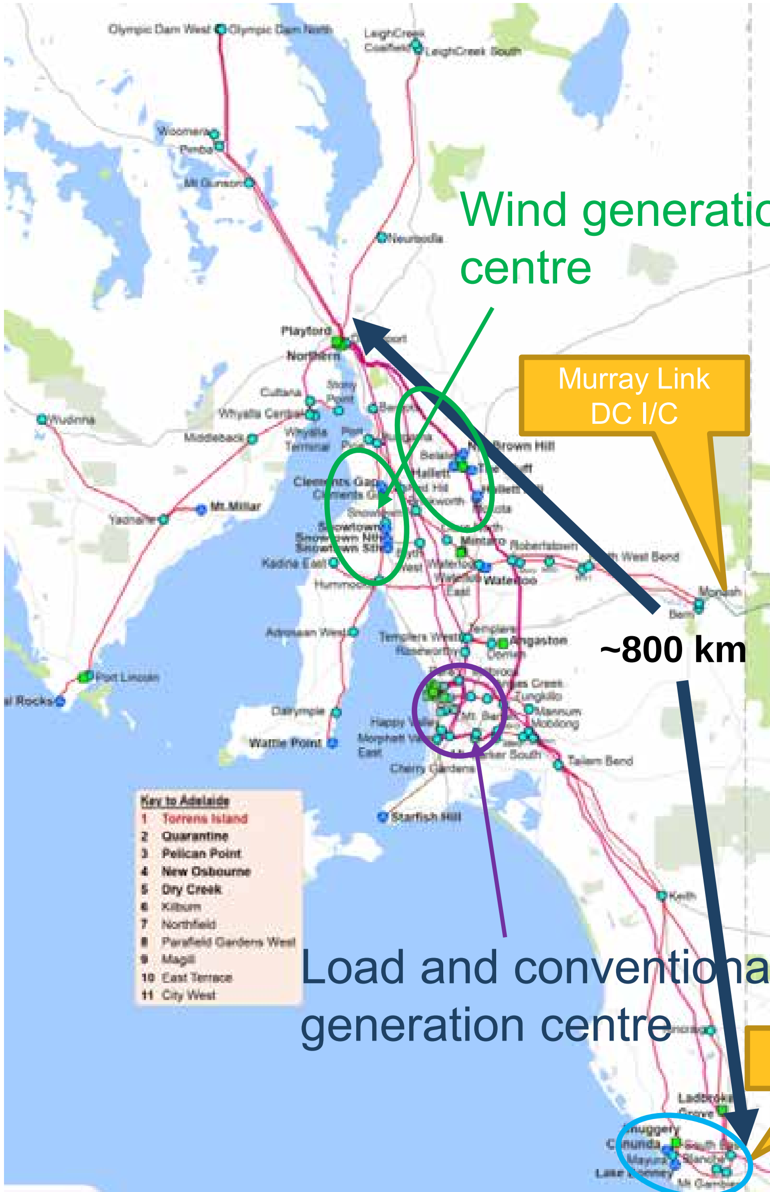
AEMO

AUSTRALIAN ENERGY MARKET OPERATOR

AGENDA SLIDE

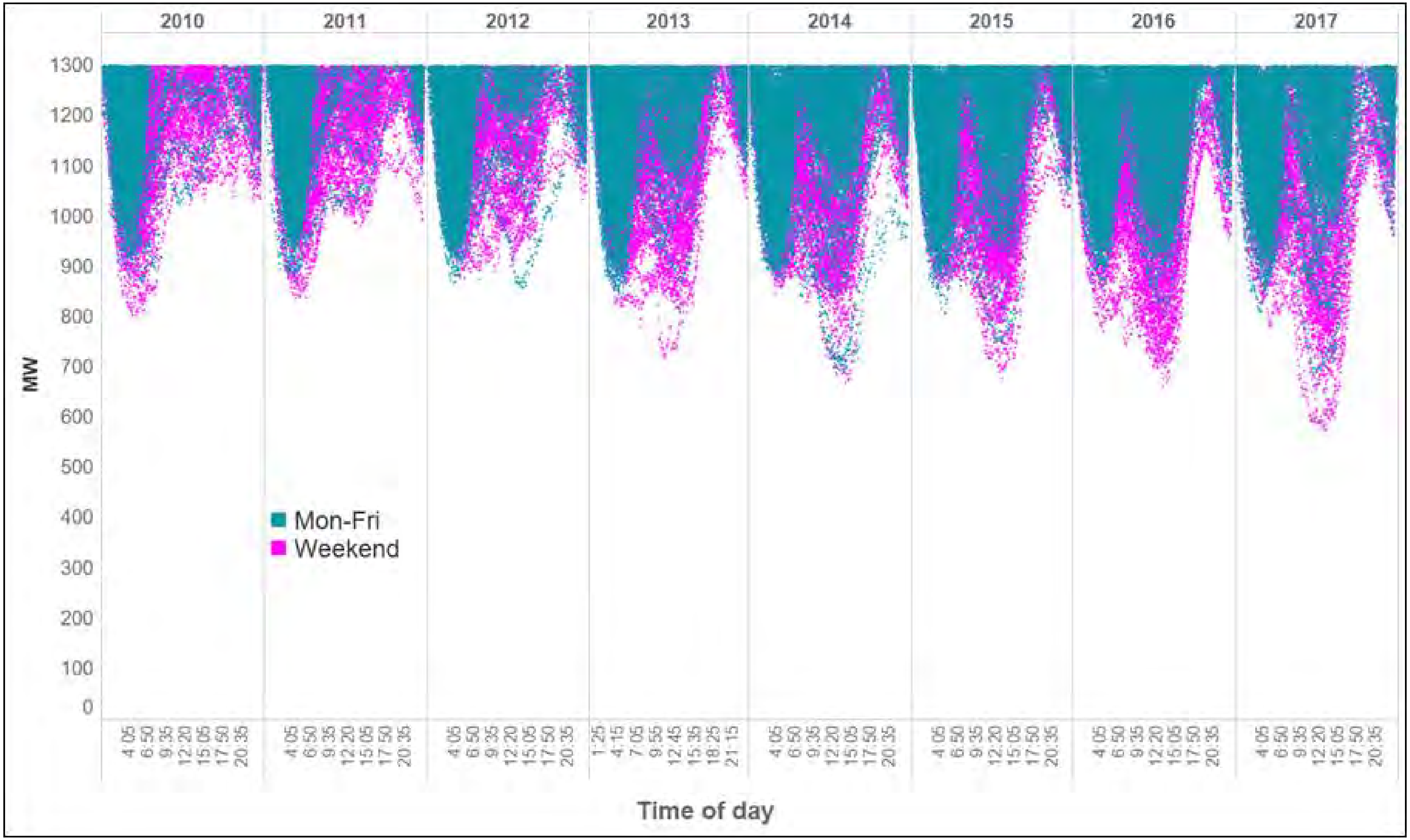
1. South Australian electrical system
2. Overview of system response during 28 September 2016 blackout event
3. SA system security challenges
4. Significance of modelling and simulation to develop system security solutions
5. Minimum combination of synchronous machines for system strength requirements
6. Pre-emptive load shedding
7. Technical performance requirements for generator connections

SOUTH AUSTRALIA



- Demand: 500−3400 MW
- Installed Wind: 1800 MW
- World's largest battery storage (100 MW) to connect in 4 weeks
- Gas fired synchronous generators primarily
- Historically operated with down to one synchronous generator only
- Interconnector capacity
  - Heywood : +500/- 600 MW (may be increased next year to up to +/- 650 MW)
  - Murraylink: +/- 220 MW
- ~800 MW of rooftop PV
- Maximum ~170% instantaneous renewable penetration to operational demand

DECLINE OF MINIMUM DEMAND

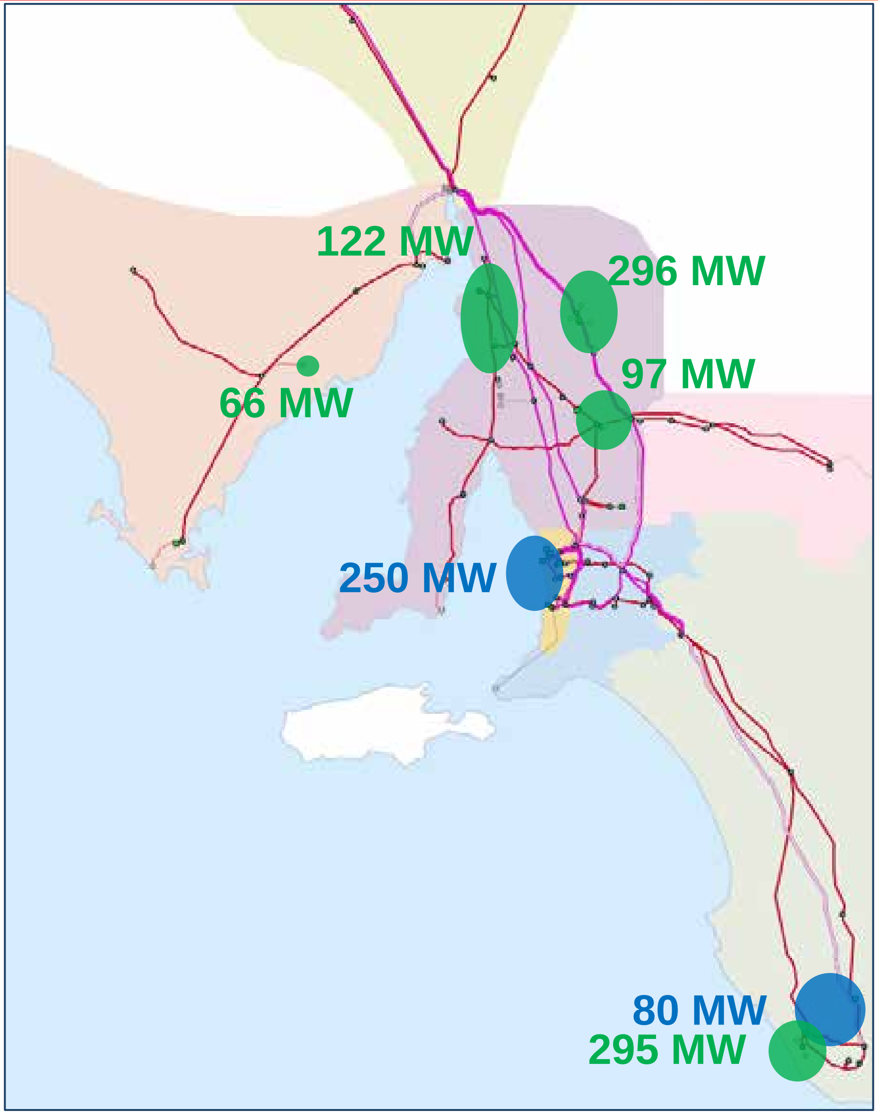


Minimum operational demand could be significantly lower than the native demand when rooftop PV output is high

OVERVIEW OF SYSTEM RESPONSE DURING 28 SEPTEMBER 2016 BLACKOUT EVENT

GENERATION MIX PRIOR TO THE EVENT

Synchronous Generation Distribution



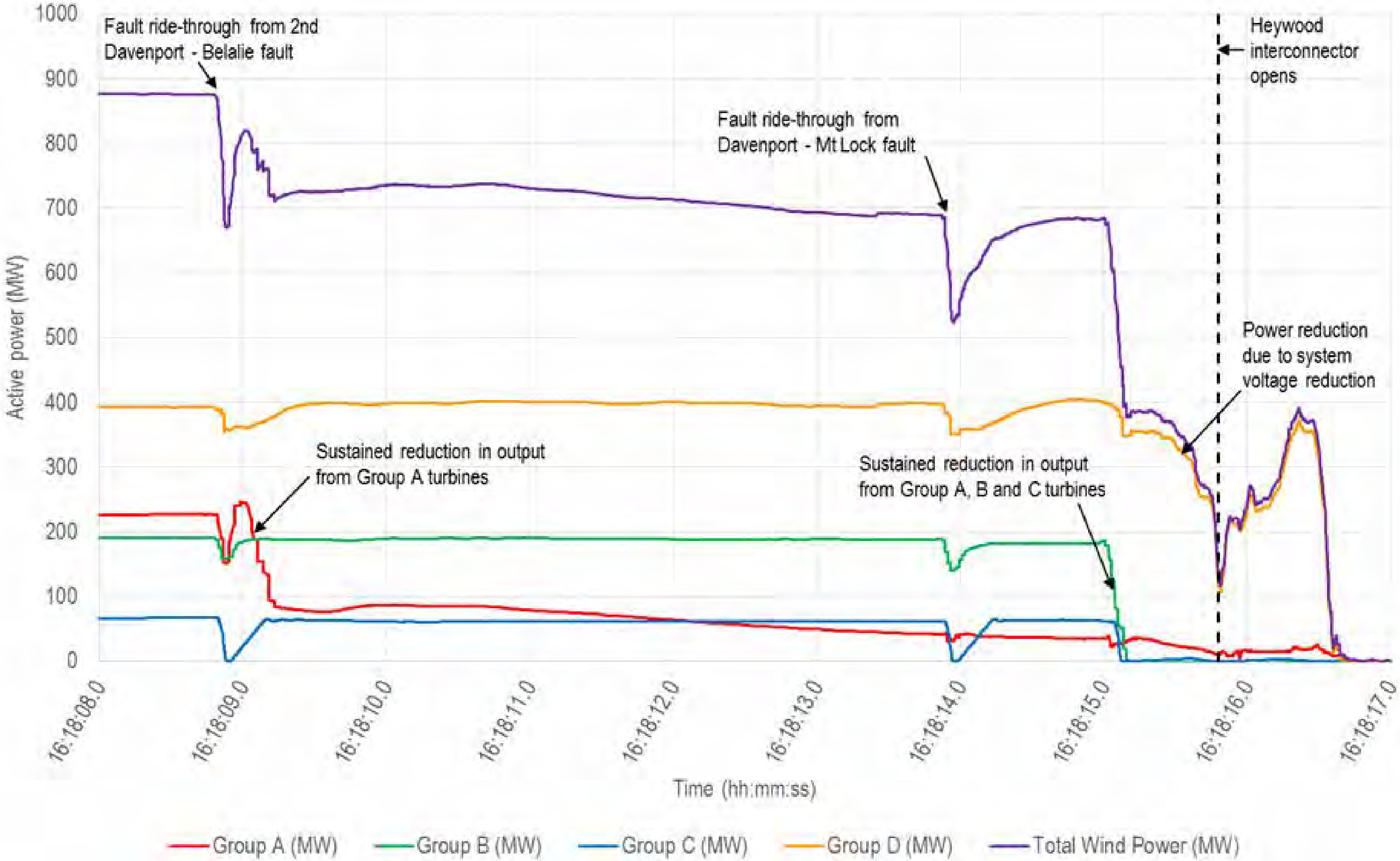
Wind Generation Distribution

The ratio of non-synchronous/synchronous generation is not considered excessive

VOLTAGE DISTURBANCES AT A SUBSTATION CLOSE TO WIND GENERATION CONCENTRATION

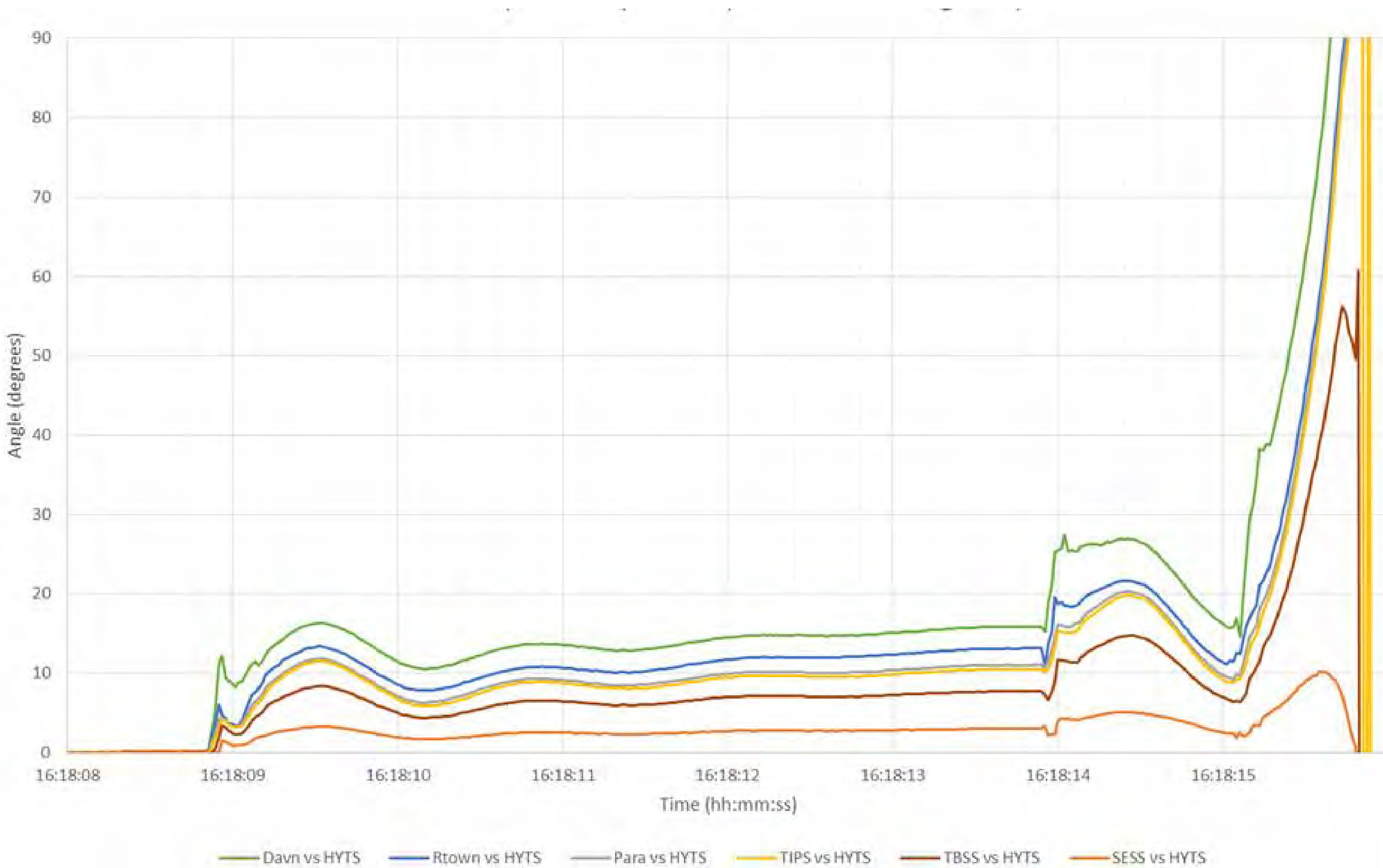
Short duration (less than 100 ms clearance), unbalanced (mostly LG) voltage disturbances well within LVRT withstand capability of wind turbines

WIND GENERATION FAULT RIDE-THROUGH RESPONSE



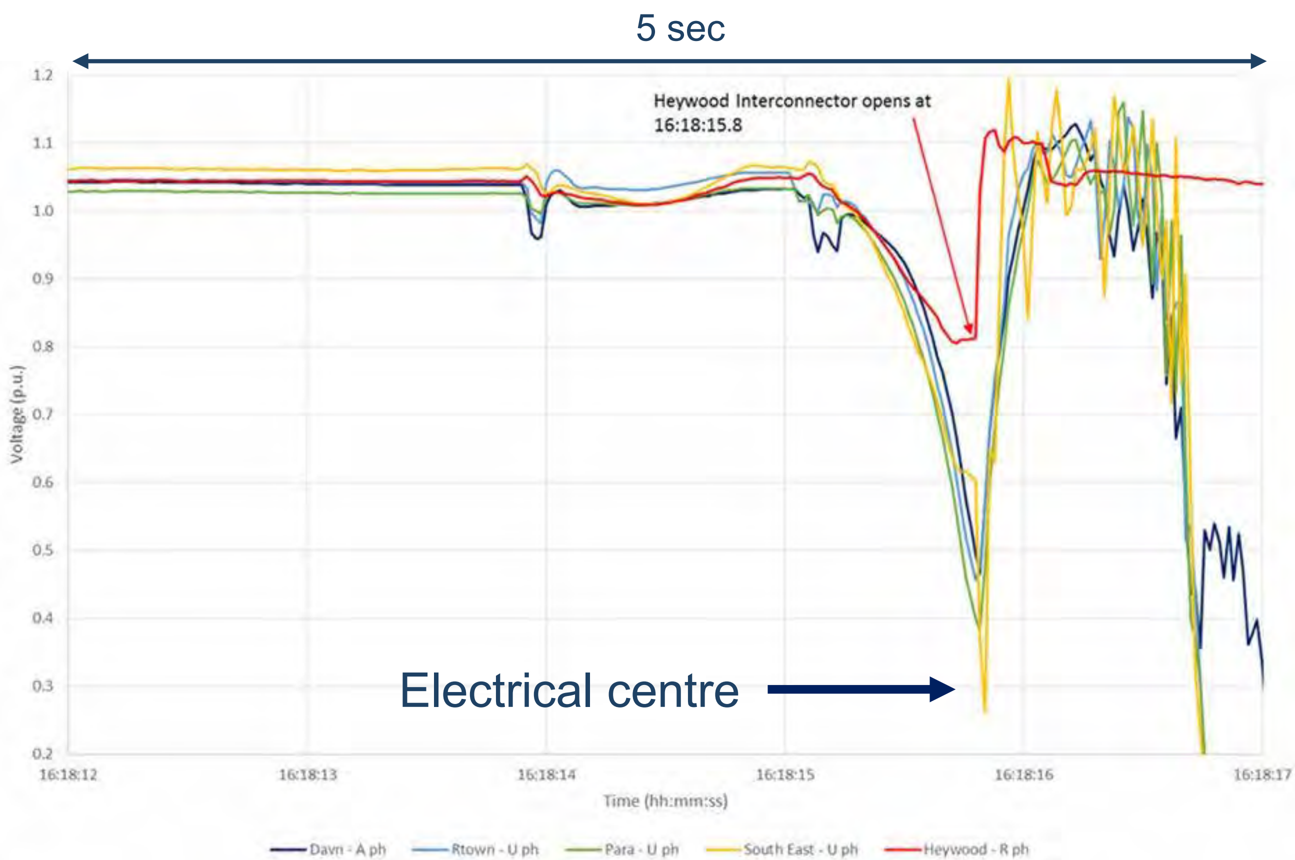
Wind turbine group	Multiple ride-through capability on 28 September 2016	Actions taken for improved ride-through capability
Group A1	2 within 2 minutes	6 within 2 minutes
Group A2	2 within 2 minutes	15–19 within 2 minutes
Group B	5 within 30 minutes (also 5 within 2 minutes)	Changed to 20 within 120 minutes (also 20 within 2 minutes)

VOLTAGE ANGLE DIFFERENCE BETWEEN VARIOUS SA NODES AND HEYWOOD SUBSTATION



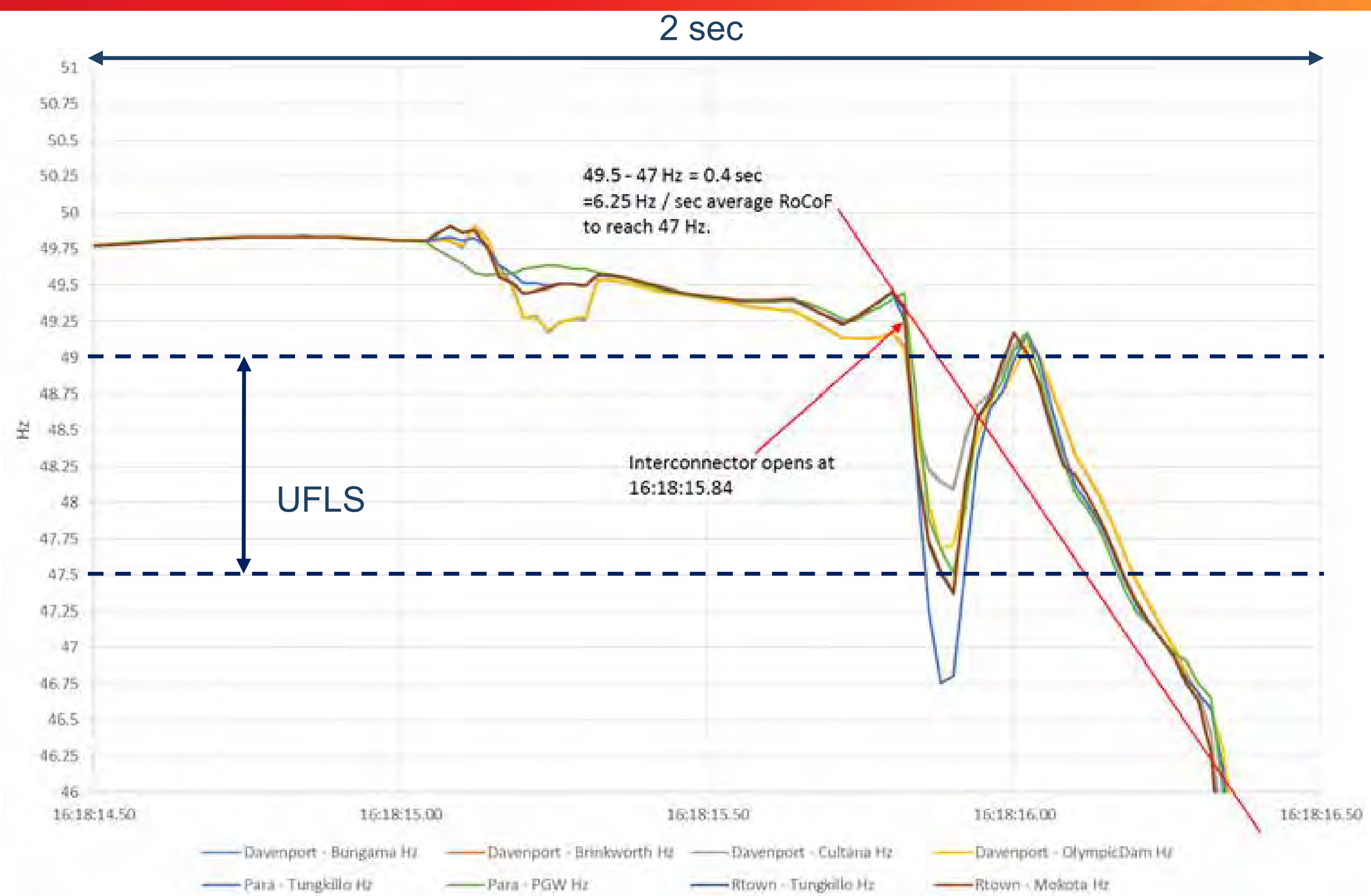
Relative phase angles started to diverge immediately after the sixth voltage disturbance due to loss of significant amount of active power resulting in loss of synchronism conditions.

SYSTEM VOLTAGE RESPONSE



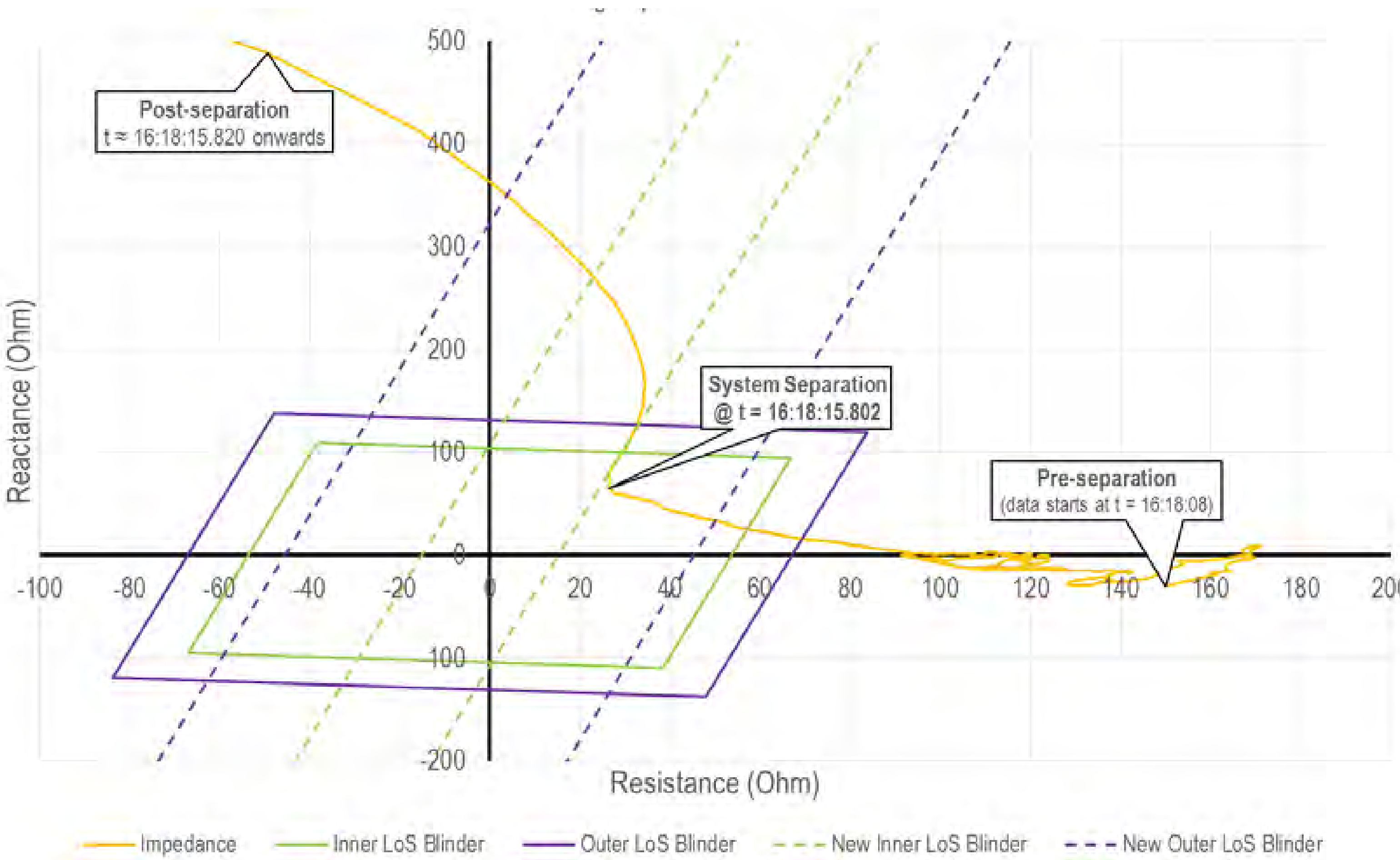
- System voltages started to decline globally until they collapse down to 0.2 pu within 600 ms
- Dynamic voltage collapse is a symptom of loss of synchronism conditions

SYSTEM FREQUENCY RESPONSE



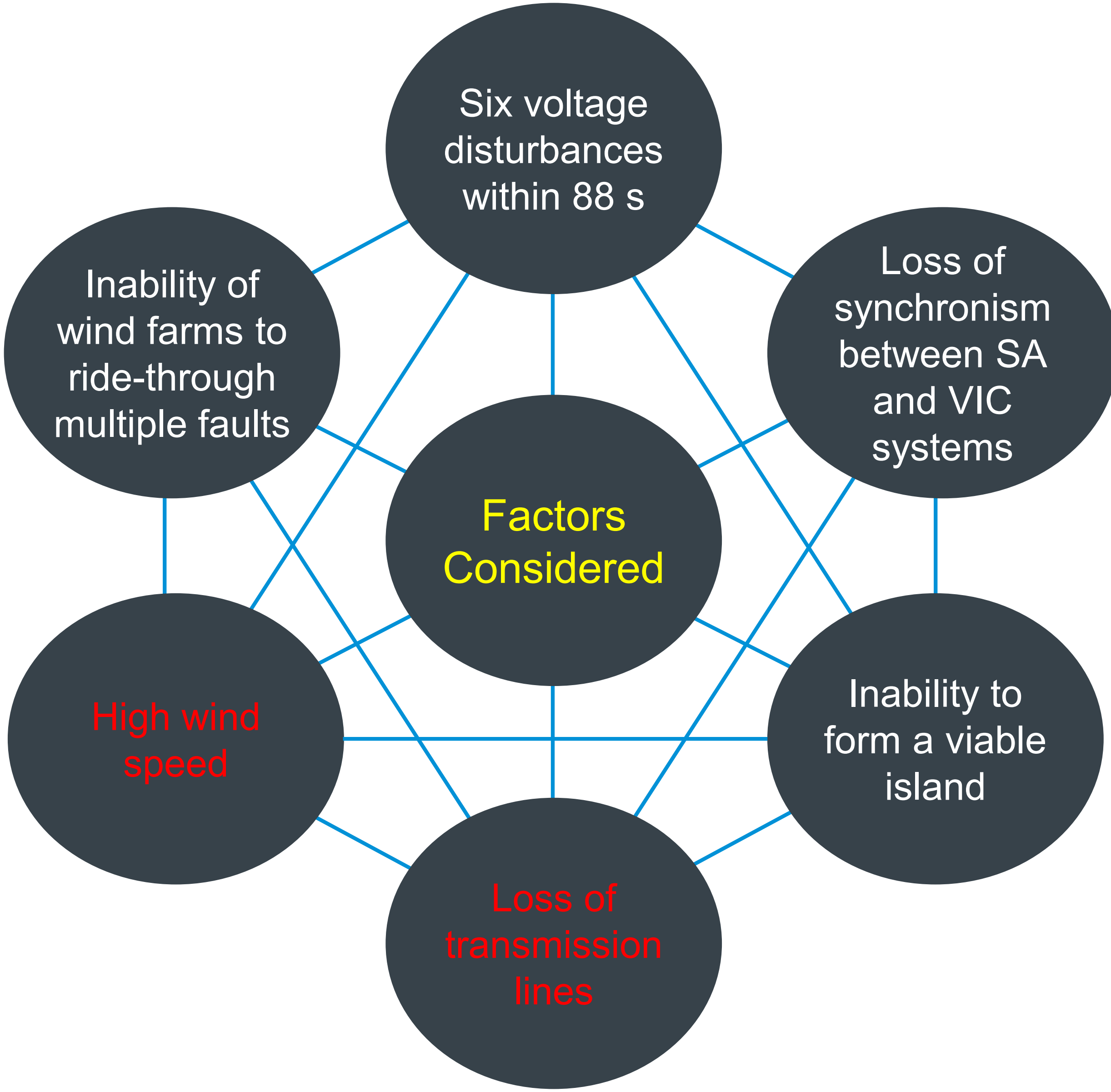
- Prior to system separation system frequency did not drop sufficiently to initiate UFLS or governor response (the latter would have been insignificant anyway).
- Post separation frequency collapsed very rapidly where UFLS did not have sufficient time to respond.

RESPONSE OF HEYWOOD INTERCONNECTOR LOSS OF SYNCHRONISM RELAY



Correct and intended operation of loss of synchronism relays which resulted in disconnection of SA power system from rest of the NEM

KEY CONTRIBUTORS TO THE BLACK SYSTEM



Legend
White: confirmed as contributing factors
Red: factors ruled out following investigations

SA SYSTEM SECURITY CHALLENGES

LEARNING FROM SYSTEM BLACK EVENT

Critical issues

- Pre-set protection settings on the number of voltage disturbances in quick succession.

Opportunities for improvement

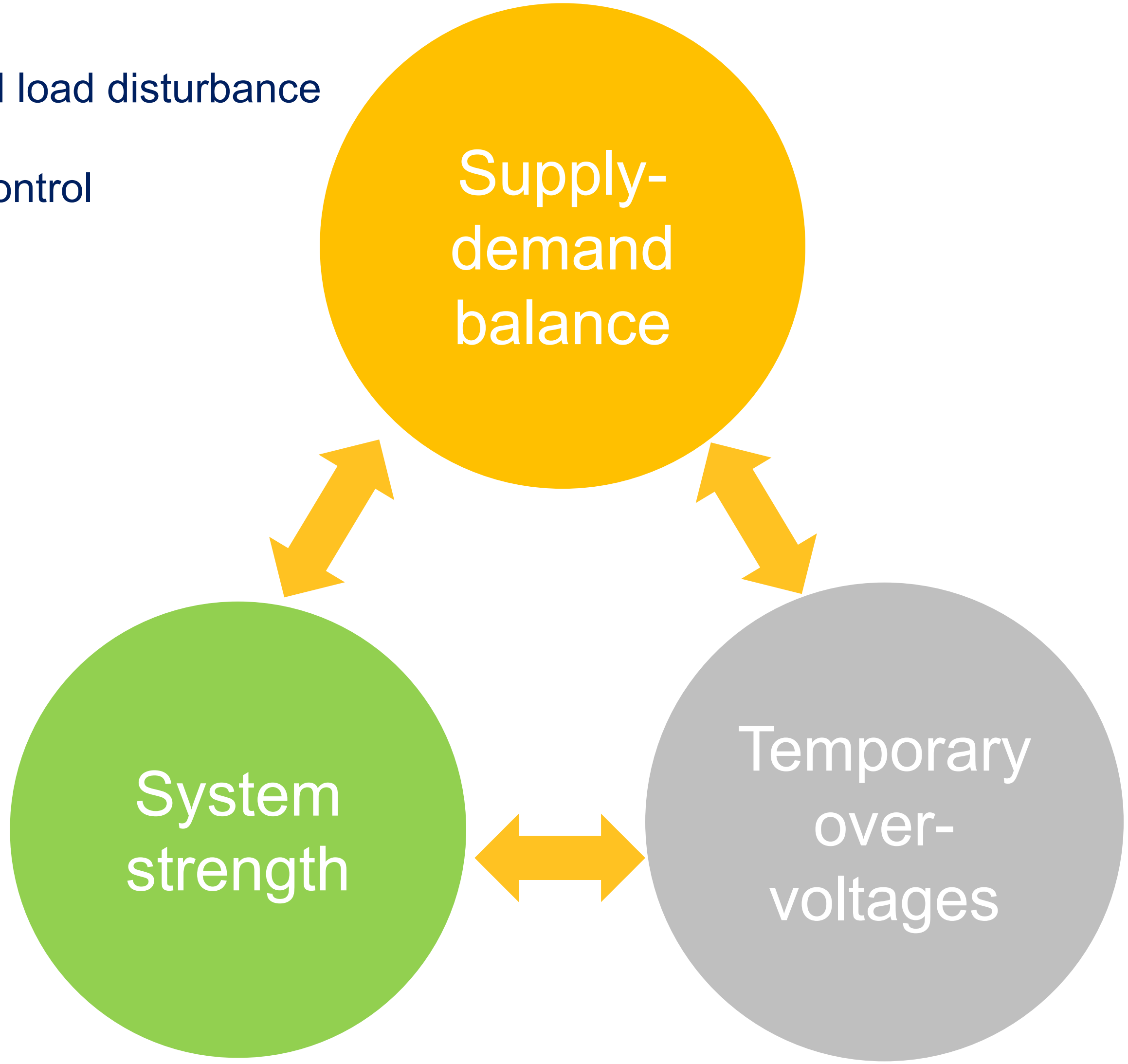
- Unexpected reactive power response of some wind farms during some of the voltage disturbances, i.e. no reactive current injection.
- Ability to shed loads before system separates, and while system frequency is still healthy.

Emerging issues not relevant to the actual event

- Transient power reduction of non-synchronous generation during a successful ride-through event.
- Over-voltage withstand capability of wind farms and synchronous generators.
- Management of adequate system strength accounting for the response of both generating systems and protection functions.
- Lack of observability/predictability/controllability of DER

SYSTEM SECURITY TRILEMA

- Generation and load disturbance ride-through
- Active power control
- Load shedding
- RoCoF



- Adequacy of synchronous machines and protection systems
- Withstand capability of non-synchronous generation

High-voltage disturbance ride-through

RISK MITIGATION METHODS TO MANAGE SA SYSTEM SECURITY

- Increased technical performance requirements on generating systems including DER.

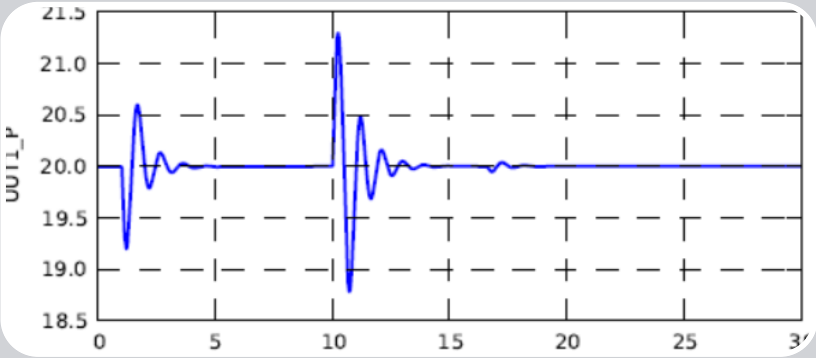
- The need for a minimum quantity of synchronous characteristics (currently in place operationally at all times).
  - Likely to be replaced by large-scale synchronous condensers in mid-term

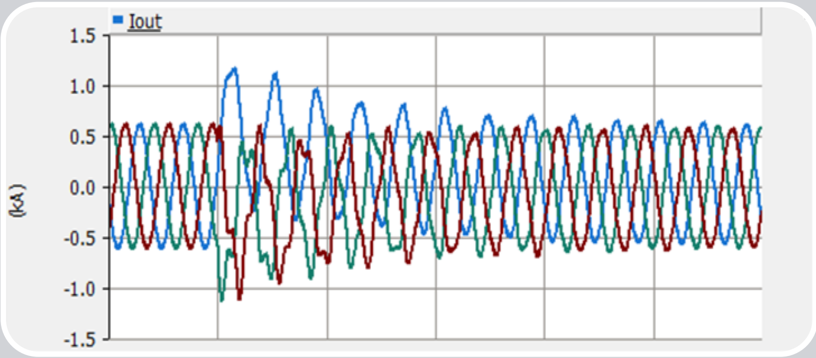
- Detailed modelling of both primary and secondary power system components with appropriate simulation tools.

- Consideration of both credible and non-credible events, and developing control and protection schemes to account for non-credible events:
  - E.g. pre-emptive load shedding before SA becomes islanded.

SIGNIFICANCE OF MODELLING AND SIMULATION TO DEVELOP SYSTEM SECURITY SOLUTIONS

RMS- AND EMT-TYPE MODELLING





PSS/E (RMS)

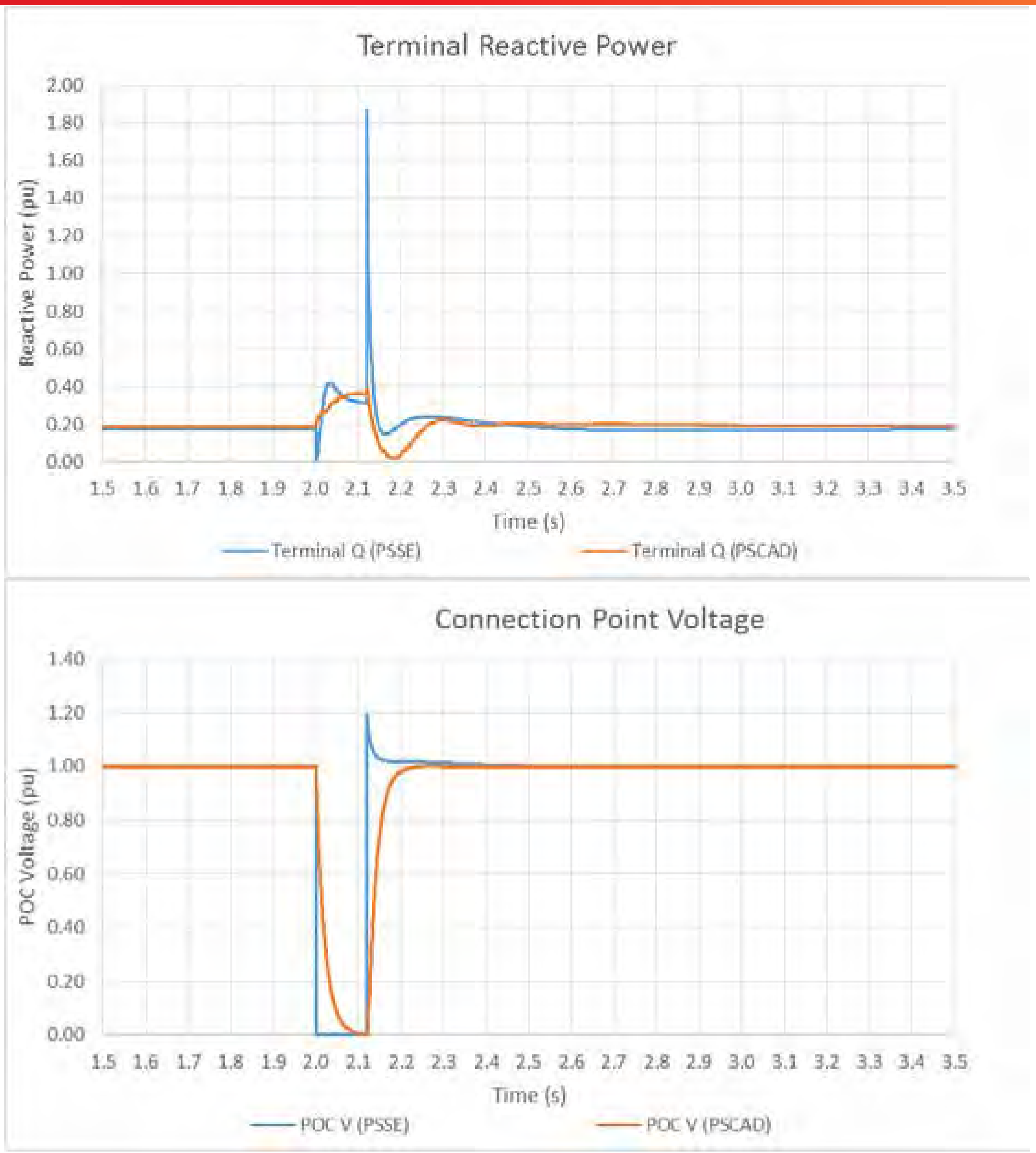
- Simplified representation of power electronic converter controls
- Fast speed of simulation
- Reasonable accuracy in conventional power systems
- Unstable in extreme conditions

PSCAD/EMTDC (EMT)

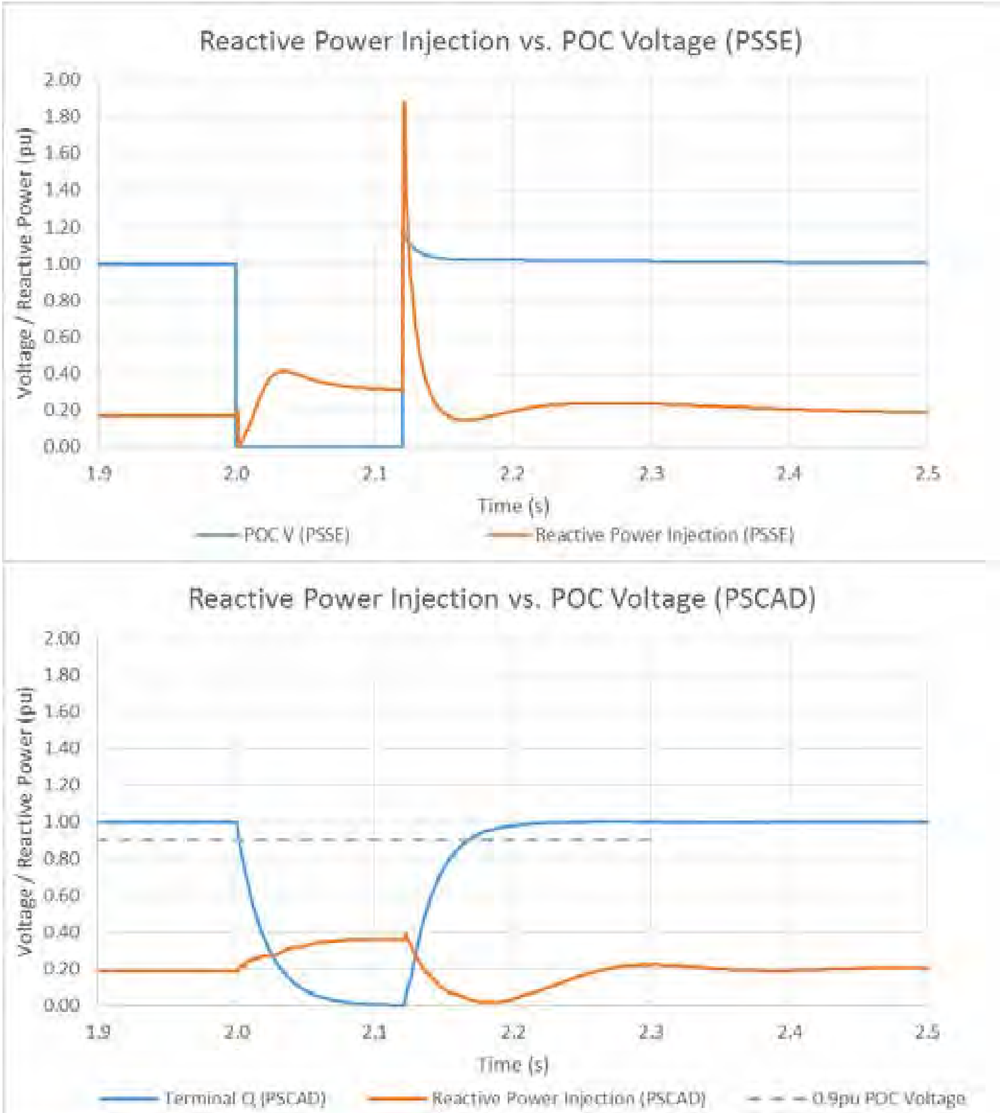
- Control systems identical to those actually used on-site
- Slow, however improvements are being made rapidly
- Can be made to provide the required accuracy for any power systems
- Generally stable for all conditions

Remember that three-phase RMS is still RMS

COMPARISON BETWEEN RMS- AND EMT-TYPE MODELS: CONNECTION POINT QUANTITIES FOR A SOLAR FARM WITH REASONABLE SCR

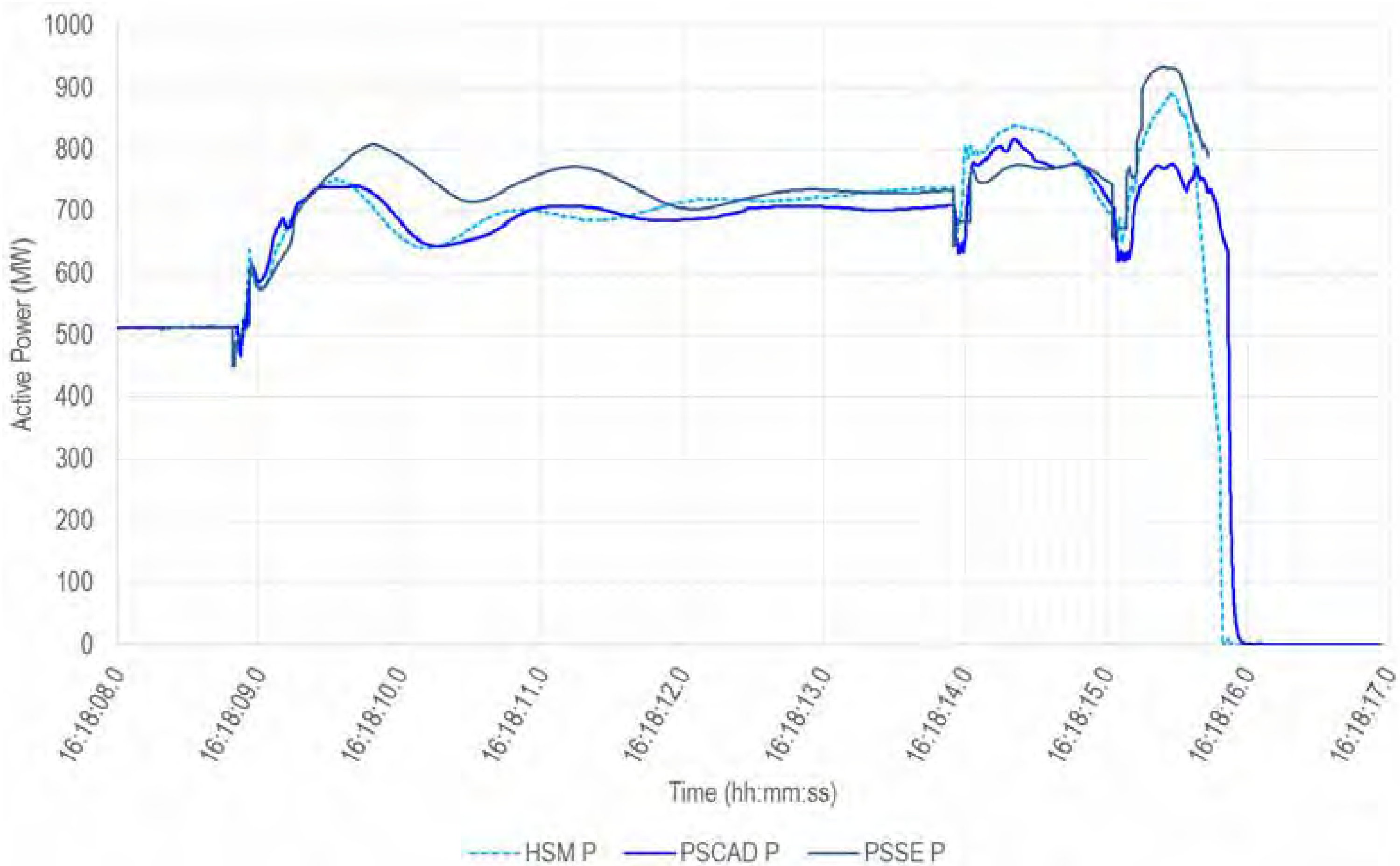


COMPARISON BETWEEN RMS- AND EMT-TYPE MODELS: REACTIVE CURRENT INJECTION



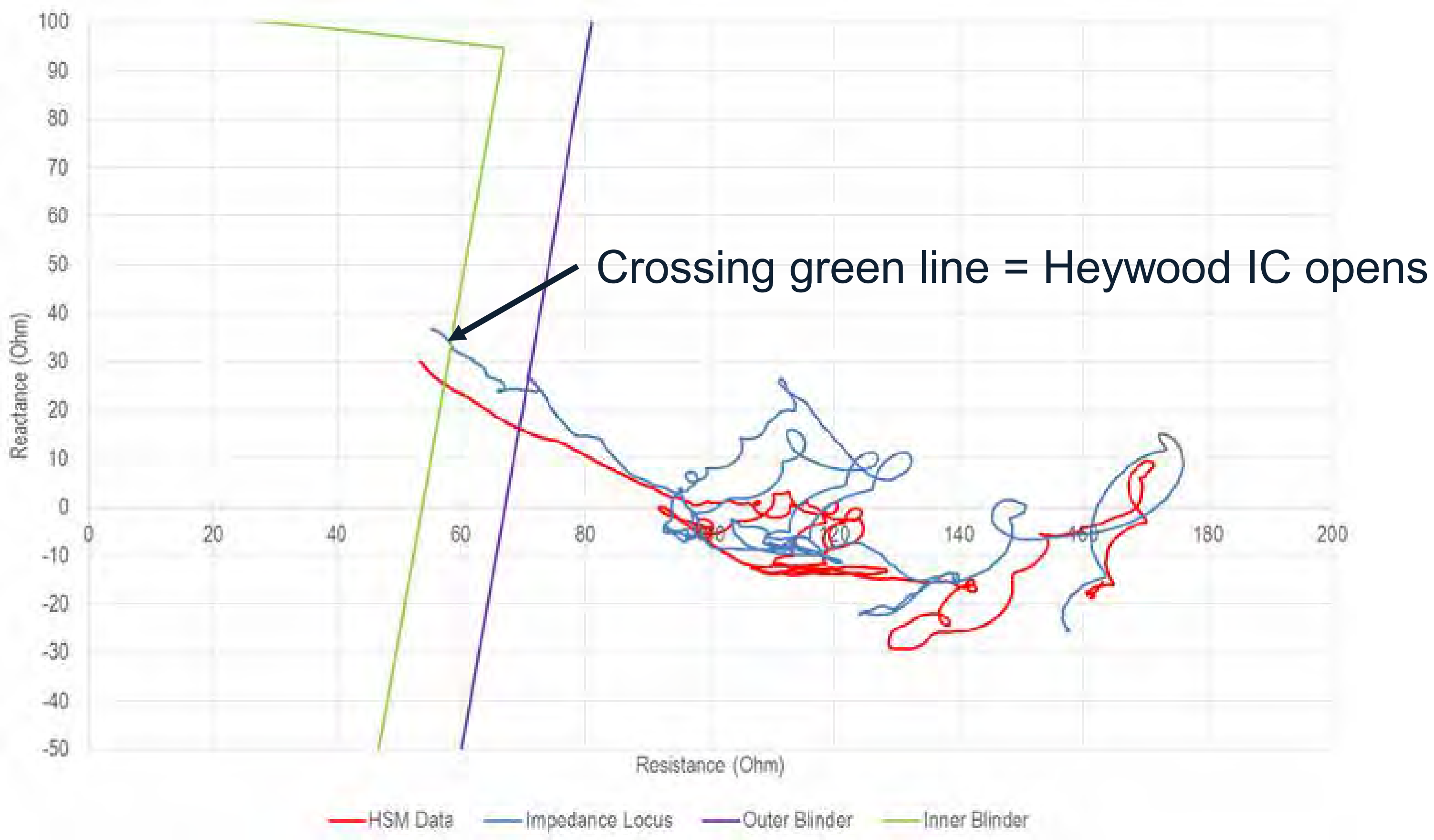
Faster and higher injection in the RMS-type model

HEYWOOD INTERCONNECTOR ACTIVE POWER FLOW DURING BLACK SYSTEM EVENT



PSCAD model replicates precisely the overall system response

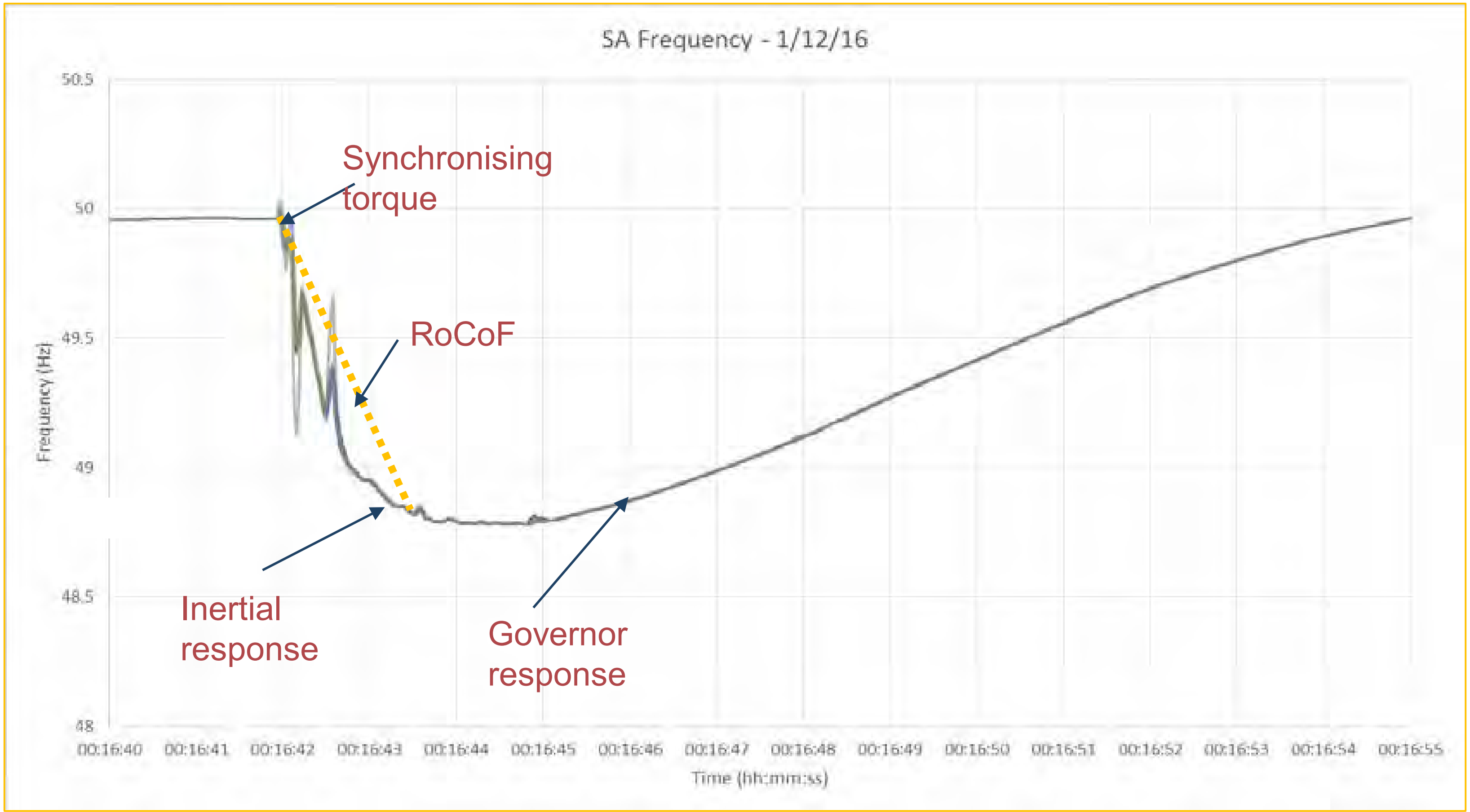
IMPEDANCE TRAJECTORY SEEN BY LOSS OF SYNCHRONISM PROTECTION DURING BLACK SYSTEM EVENT



Accurate replication of impedance trajectory seen by loss of synchronism relays

MINIMUM COMBINATION OF SYNCHRONOUS MACHINES FOR SYSTEM STRENGTH REQUIREMENTS

RELATION BETWEEN SYSTEM STRENGTH AND INERTIA



Power system studies should assess system strength/synchronising torque and system inertia/RoCoF collectively rather than in isolation

HOW LACK OF SYSTEM STRENGTH MANIFESTS ITSELF

Non Synchronous plant

- Need a minimum system strength to perform as designed and provide support to power system recovery following clearance of contingencies.
- Lack of system strength result in disconnection of non-synchronous plant, in particular in remote parts of the network.

Protection systems

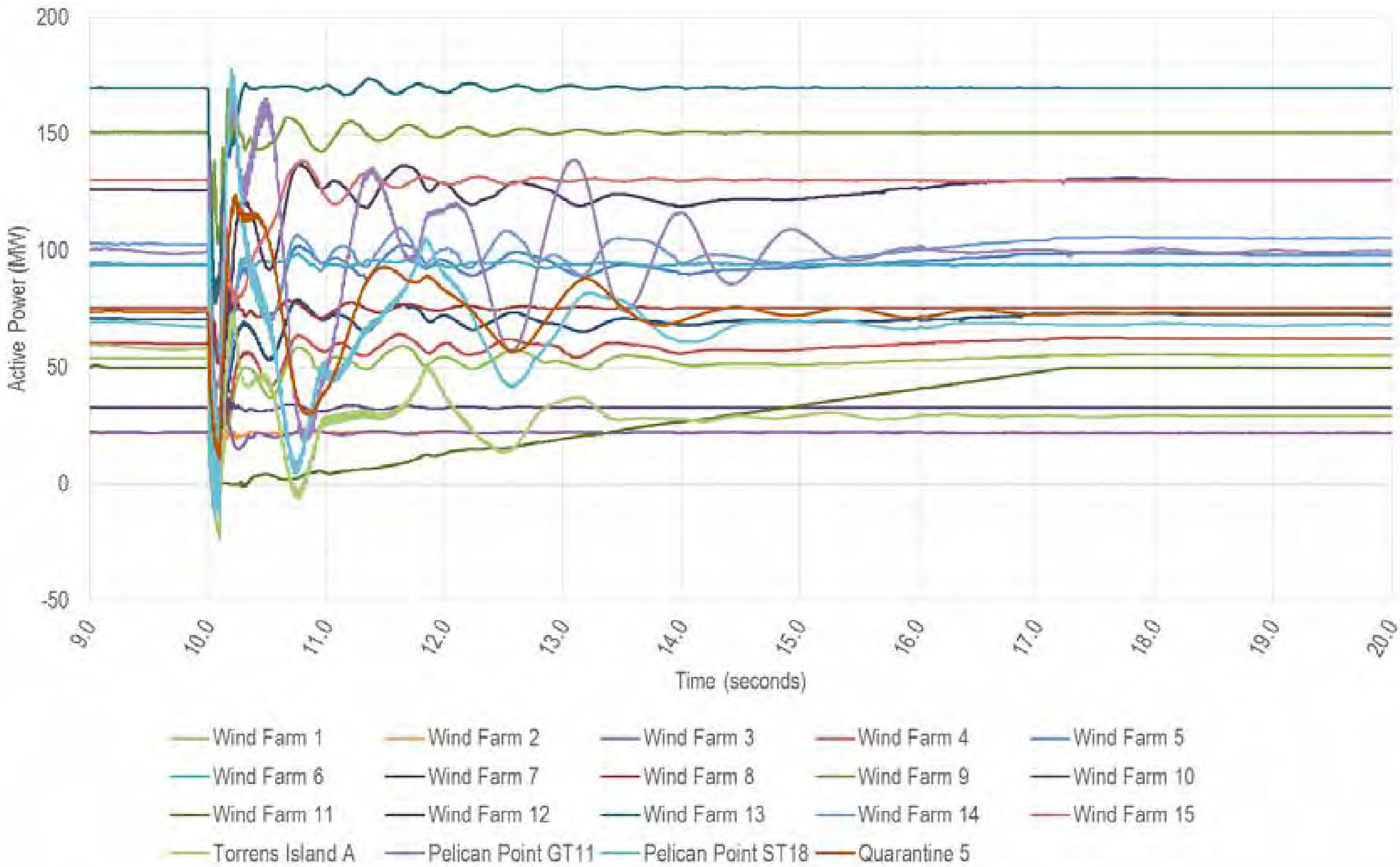
- Need a minimum fault level to operate where they should, and do not operate where they should not.
- Concerns due to declining system strength include cascaded tripping of transmission system elements, and public safety due to uncleared faults.

Synchronous plant

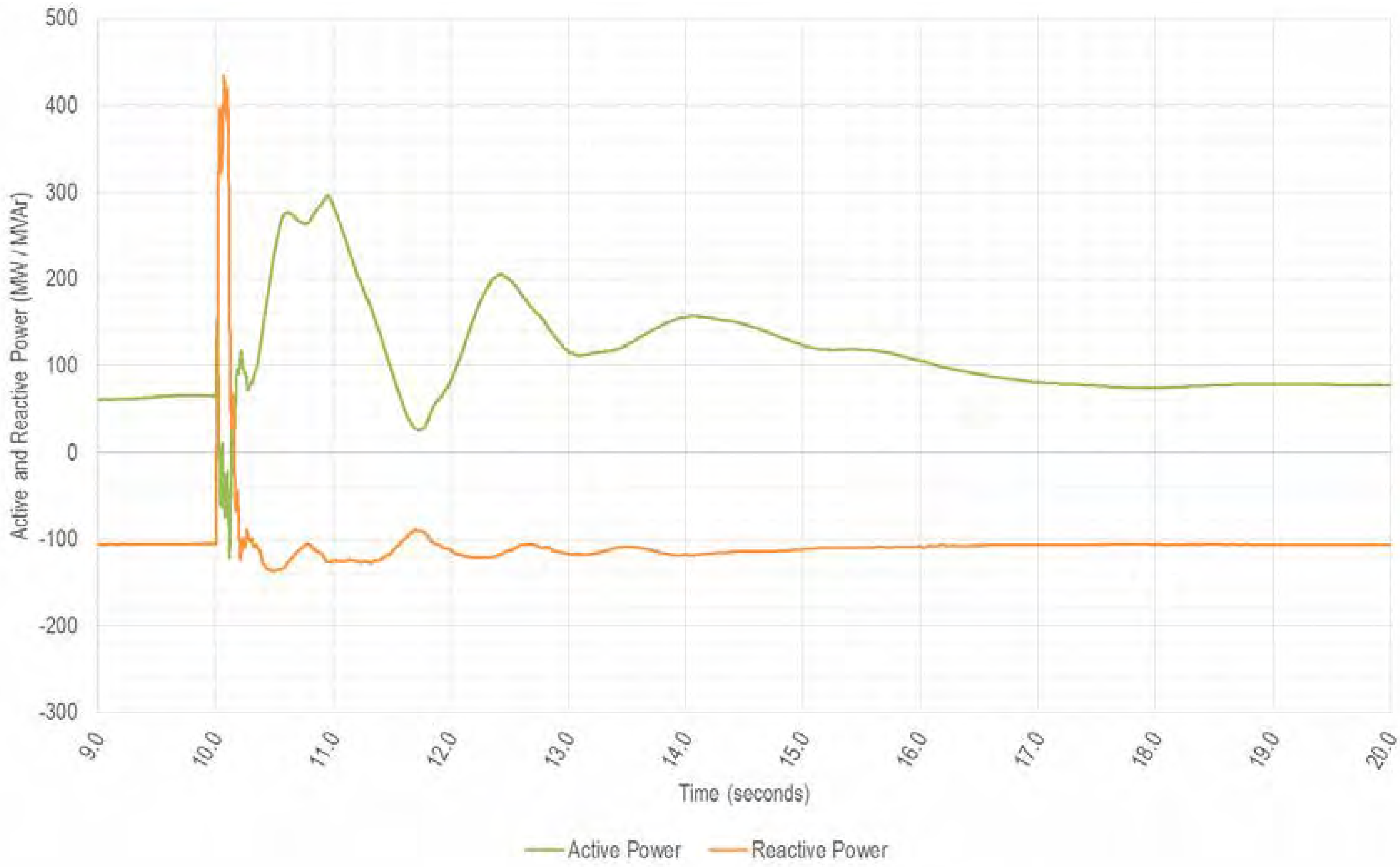
- Insufficient quantity of synchronous machines would result in their disconnection during credible contingencies due to operation of respective protection systems.

Stable operation of non-synchronous plant and protection systems is dependent on stable response and sufficient quantity of synchronous plant.

EXAMPLE RESULTS FROM PSCAD STUDIES: GENERATOR ACTIVE POWER



EXAMPLE RESULTS FROM PSCAD STUDIES: HEYWOOD INTERCONNECTOR FLOW

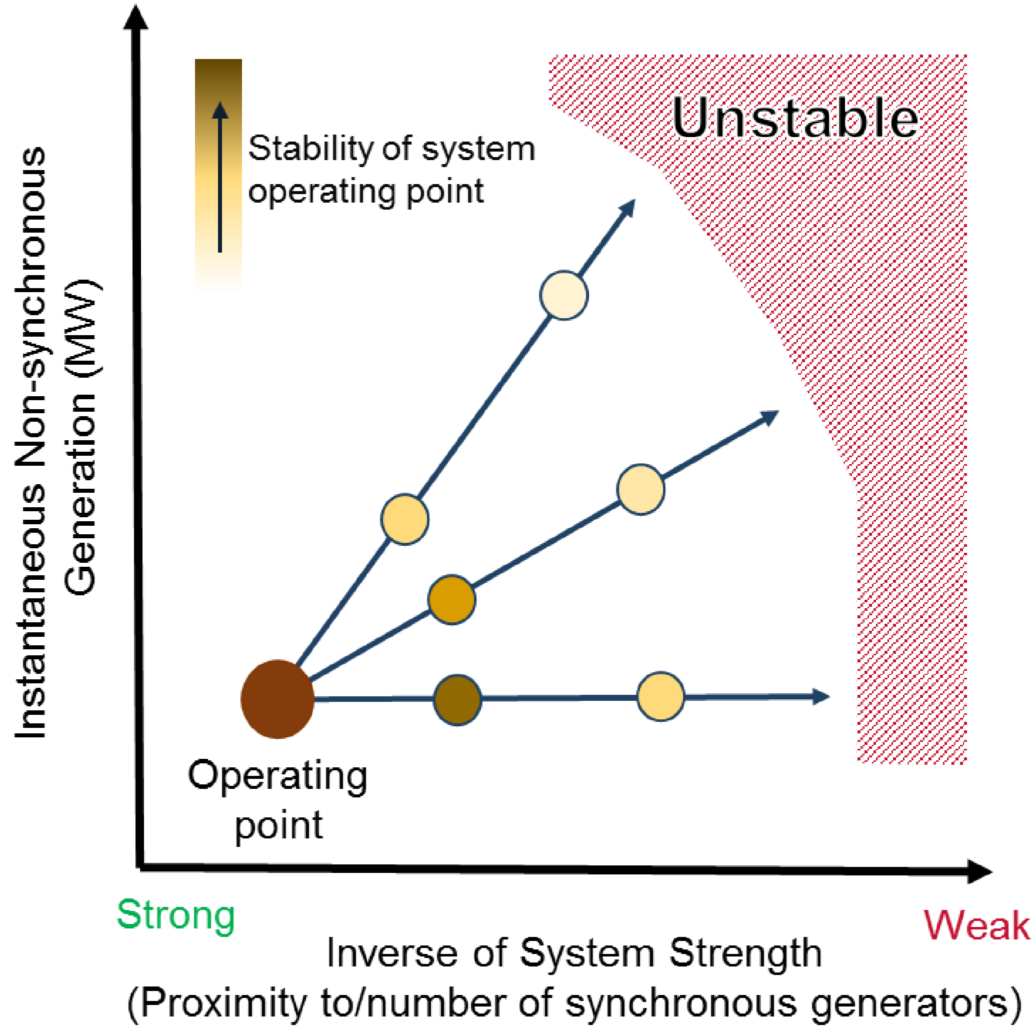


SUCCESS CRITERIA

- Non-synchronous generators remained online, except for those in electrically distant portions of the network
- All synchronous generators in the scenarios studies returned to steady-state conditions following fault clearance
- SA remained connected to the remainder of the NEM
- The transmission network voltages across the state returned to nominal range

FACTORS INFLUENCING SYSTEM STRENGTH

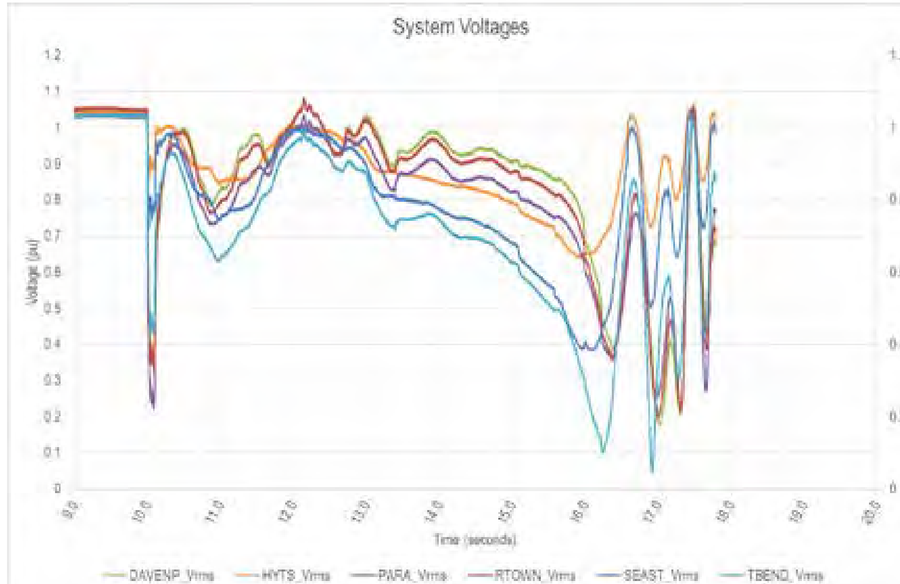
Current 1200/1700 MW wind generation constraint



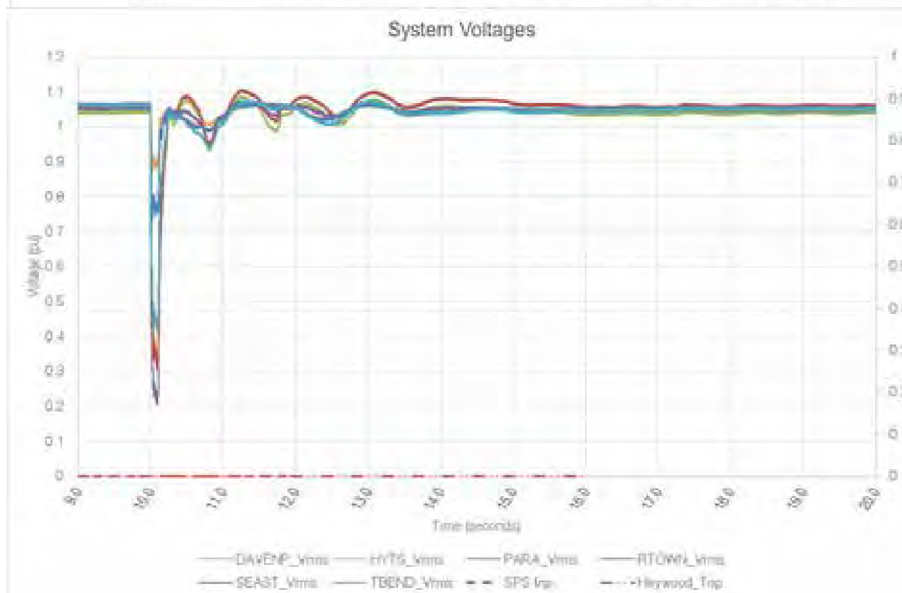
No constraints if all synchronous generators in one of the acceptable combinations are available/can be directed

PRE-EMPTIVE LOAD SHEDDING

- Should trigger load shed



- Should not trigger load shed



SCENARIOS / SYSTEM CONDITIONS

Non-credible loss of synchronous generation

Wind:1000MW

Sync Gen: ~450 MW

Demand: ~2100 MW

Contingency size:

250 MW

Associated with loss of three synchronous generators

(Simultaneously)

600 MW of Import

Expectation

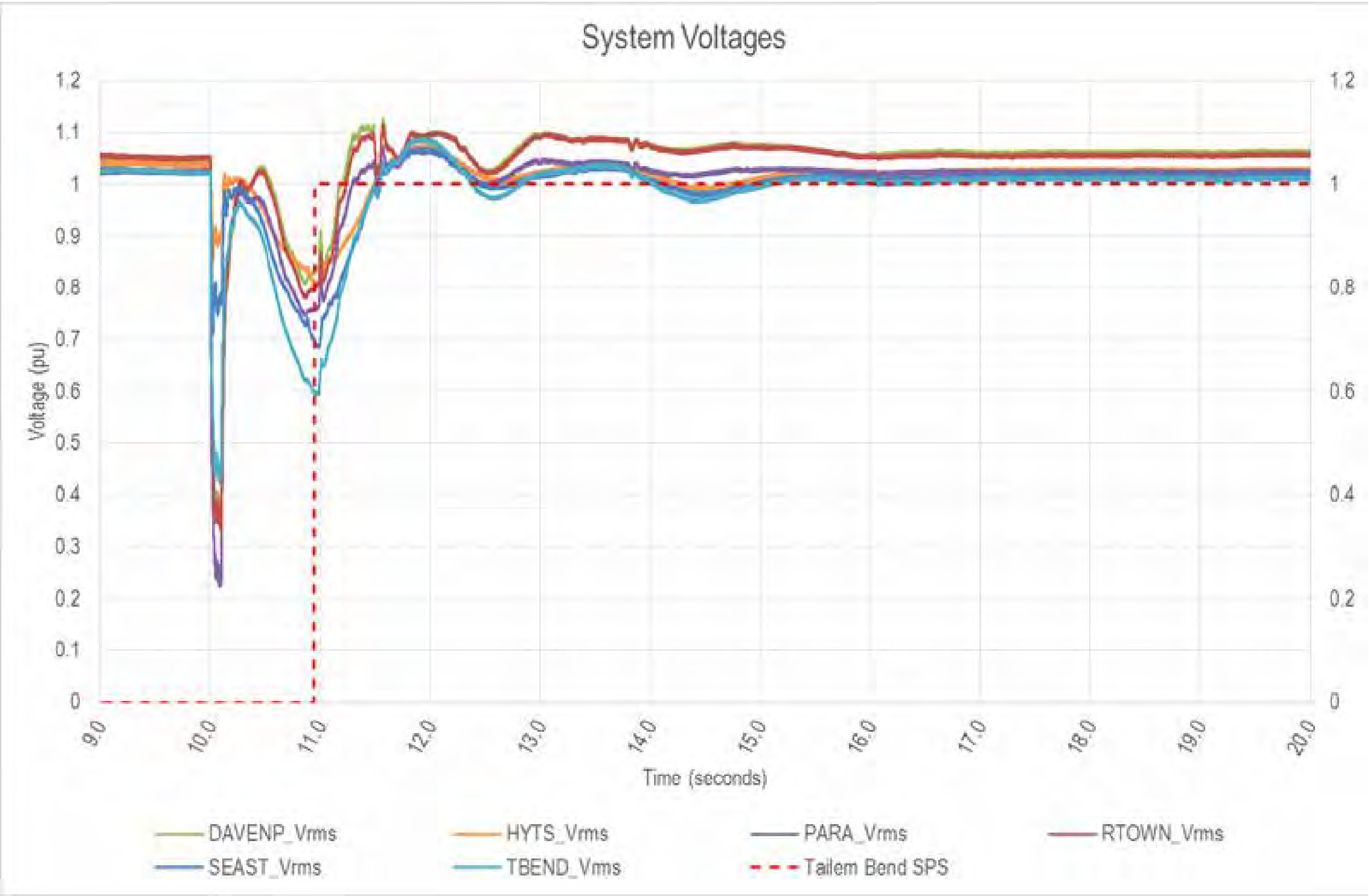
SPS Should Trigger

Simulation Outcome

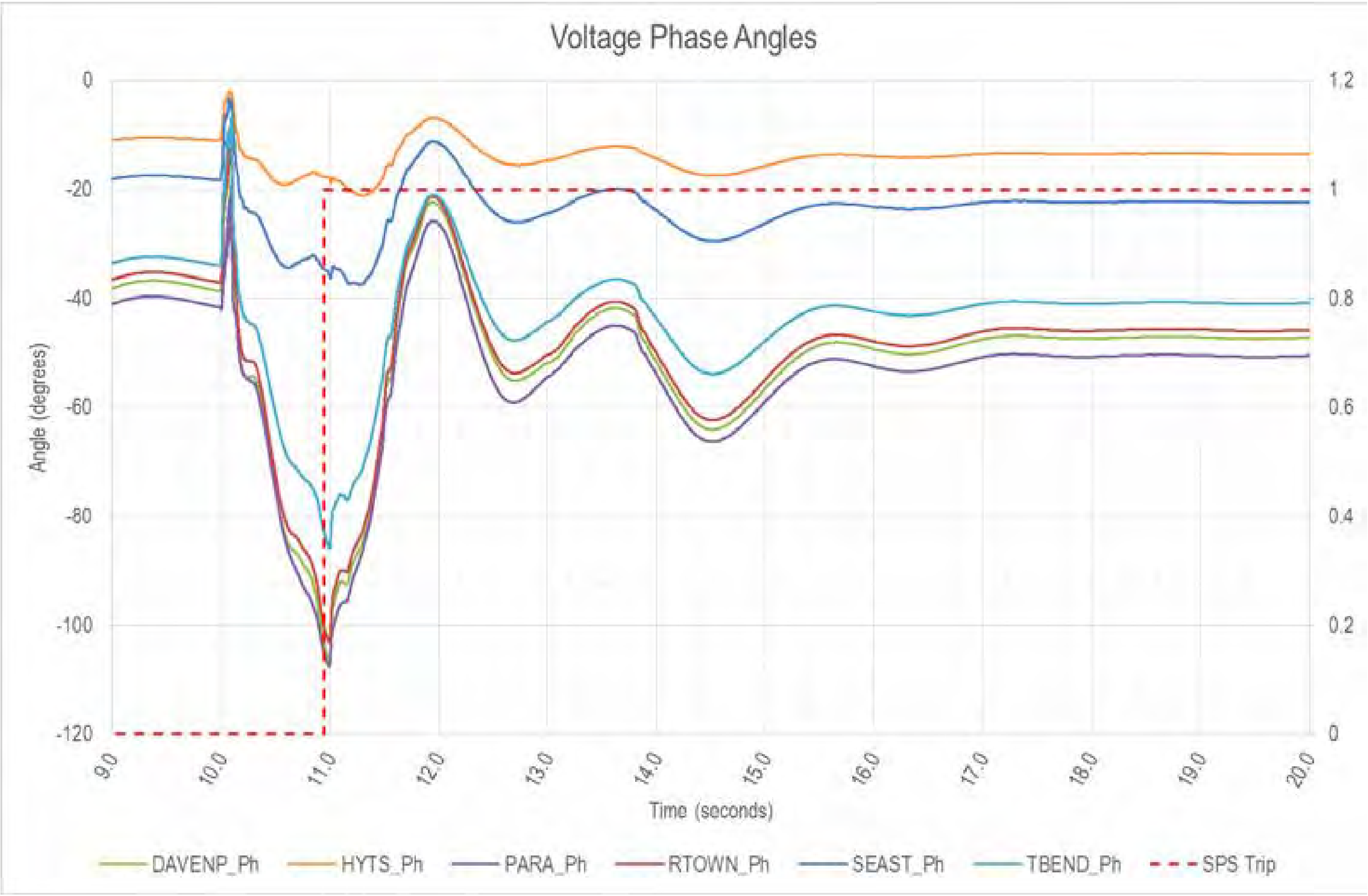
SPS DID trigger

- 250 MW of generation loss triggers SPS
- SPS stabilizes the SA system which would have otherwise been unstable

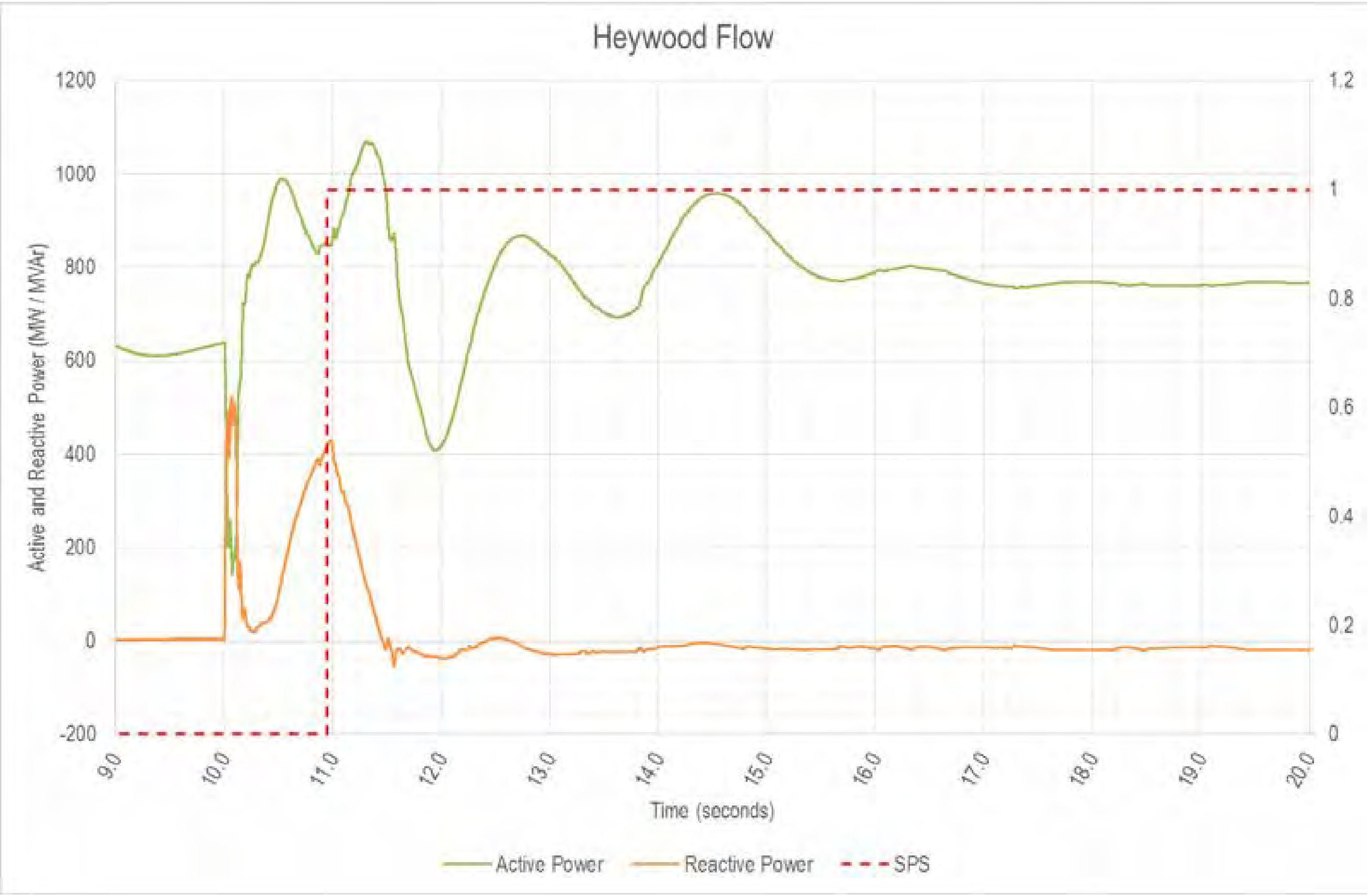
SYSTEM VOLTAGES FOR LOSS OF LARGE AMOUNT OF SYNCHRONOUS GENERATION



SYSTEM VOLTAGE PHASE ANGLES FOR LOSS OF LARGE AMOUNT OF SYNCHRONOUS GENERATION



HEYWOOD INTERCONNECTOR FLOW FOR LOSS OF LARGE AMOUNT OF SYNCHRONOUS GENERATION



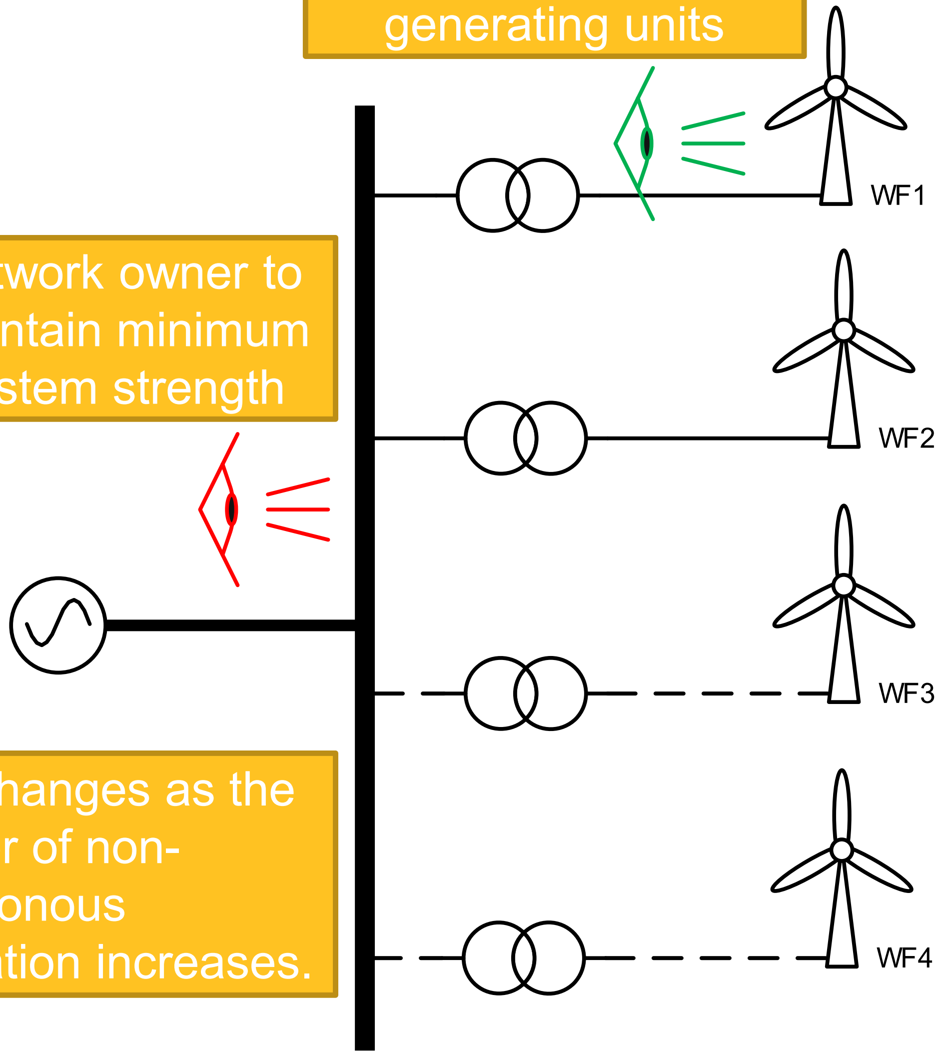
TECHNICAL PERFORMANCE REQUIREMENTS FOR GENERATOR CONNECTIONS

REQUIREMENT FOR GENERATING UNITS/SYSTEMS IN ISOLATION

Developers to use adequately designed generating units

- **Minimum SCR**
- **Minimum X/R**

Network owner to maintain minimum system strength



SCR changes as the number of non-synchronous generation increases.

Applies to all susceptible items of plant such as individual generating units, dynamic reactive power support plant, and storage interface units

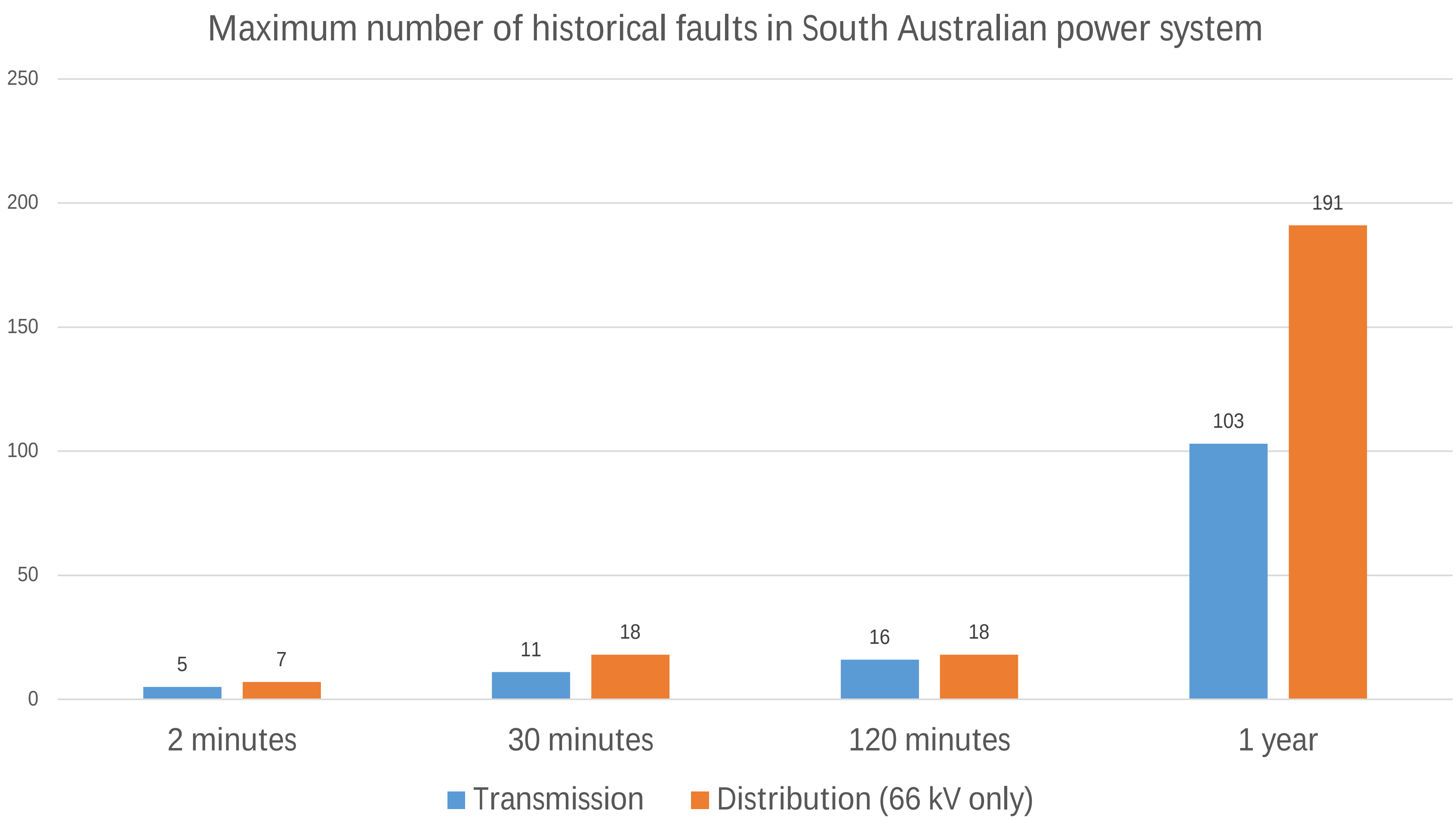
REQUIREMENT FOR GENERATING SYSTEMS AS PART OF THE WIDER POWER SYSTEM

- The aggregate impact and interaction between multiple concentrated non-synchronous generation should be studied with EMT-type models.

- *System strength impact assessment guidelines* is currently being developed, covering items such as:
  - Definition of *adverse system strength impact*
  - *System strength remediation scheme*

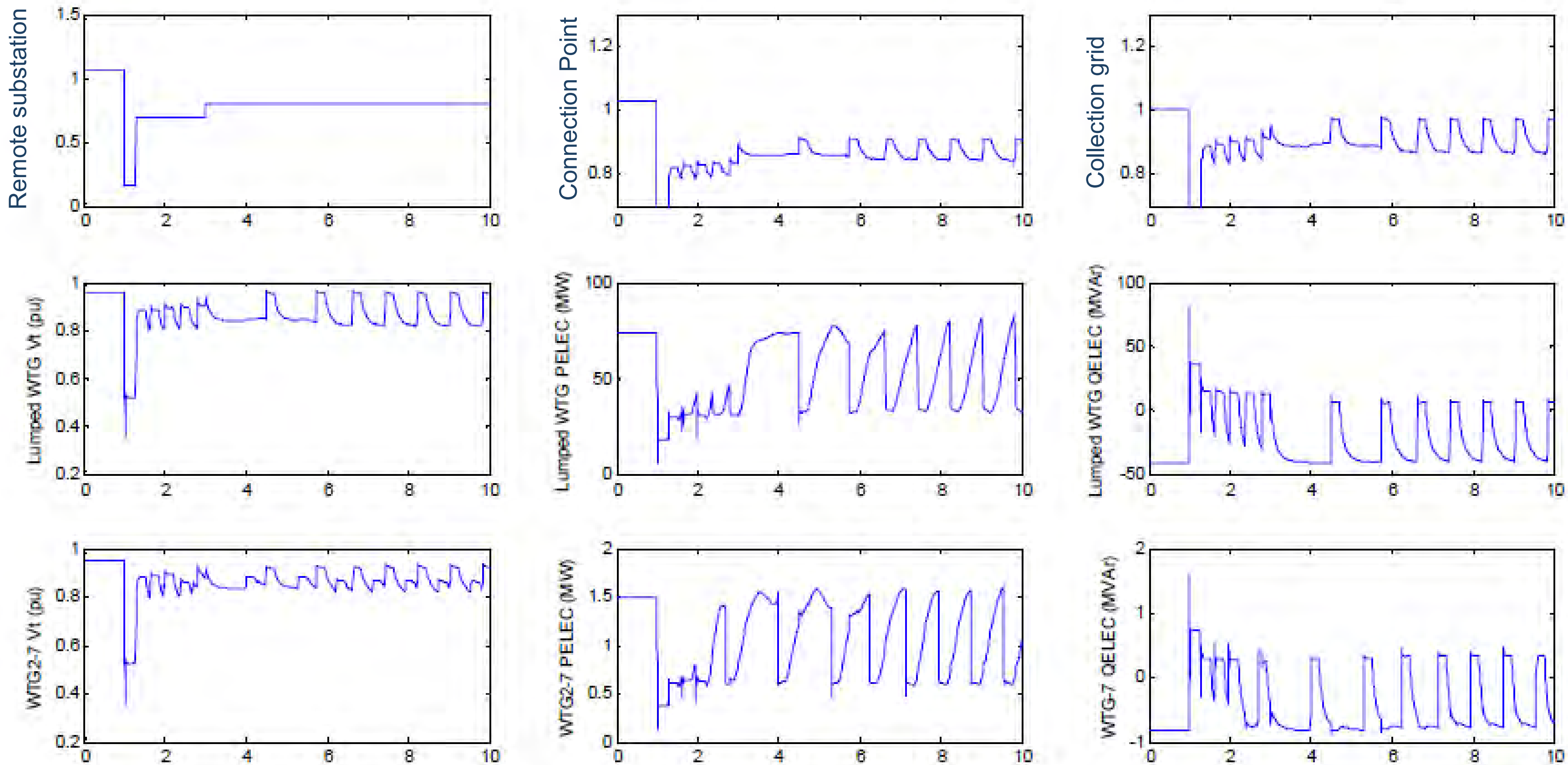
- This will be supplemented by a more comprehensive guideline that develops methodologies for assessing minimum system strength and inertia gaps on the overall system.

MAXIMUM NUMBER OF HISTORICAL FAULTS IN SOUTH AUSTRALIA



- Both transmission and distribution systems have been historically exposed to a large number of faults.
- Non-credible events had occurred in the past, and can happen again.

OTHER MECHANISMS CAUSING MULTIPLE VOLTAGE DISTURBANCES



LVRT control action especially in weaker parts of the network can be counted as multiple faults in quick succession by the wind turbine protection counter.

MULTIPLE LOW VOLTAGE DISTURBANCE RIDE-THROUGH

- Requirements on the number of faults would under-utilise the capability of generating units.

- Requirement for withstanding multiple voltage disturbances
  - Up to 15 voltage disturbances each resulting in up to 100% voltage drop at the connection point with the total disturbance duration limited to 1500 ms, and
  - A single worst-case long-duration shallow voltage disturbance, causing the voltage at the connection point to drop to 70- 80 percent of the normal voltage for a total duration of 2000 ms.

- The majority of wind turbine and solar inverter manufacturers meet the proposed requirements.
  - Generally no limitations on solar inverters other than UPS rating

DISCUSSION