Dynamics and Control of Renewable-Rich Power Systems: The Australian NEM Case

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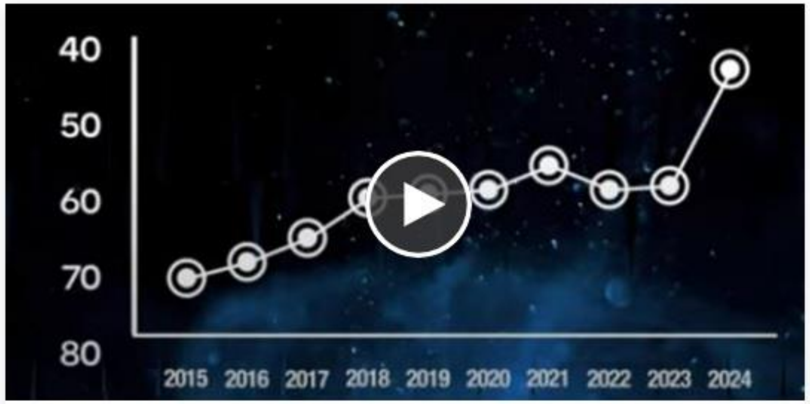
28th Energy Congress, Colombia

November 2023

Monash University (1/2)

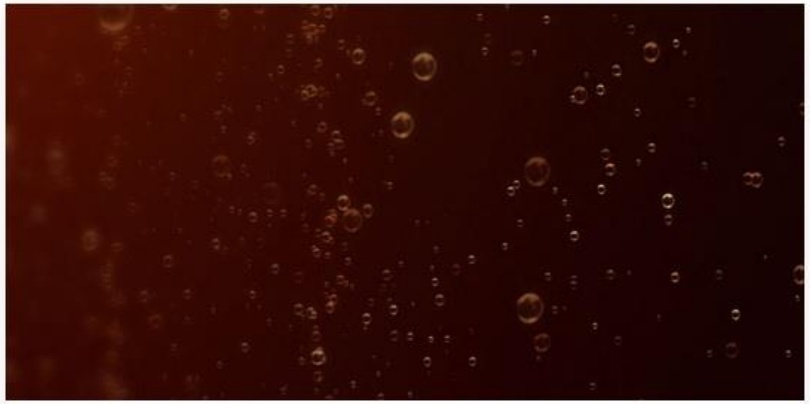
Monash University Overall Ranking

Overall world performance



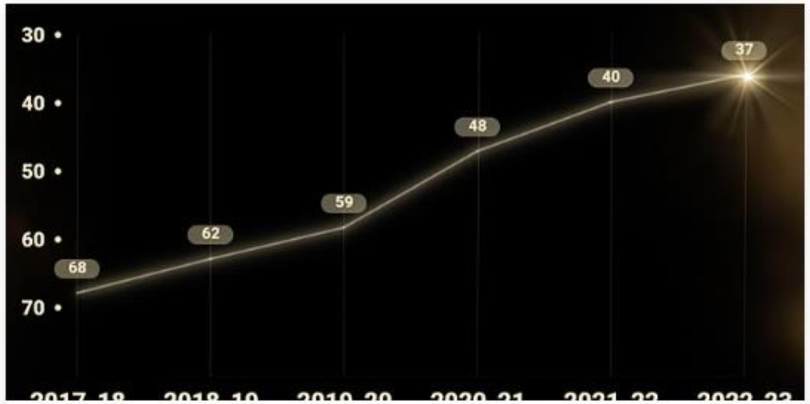
#42 IN THE WORLD

QS World University Rankings 2024



#54 IN THE WORLD

Times Higher Education (THE) World University Rankings 2024



#37 IN THE WORLD

US News and World Report 2022-23

Monash University (2/2)

Monash Engineering rankings

#1

Engineering

Ranked #1 in Australia for engineering, Times Higher Education (THE) World University Rankings 2023.

#39

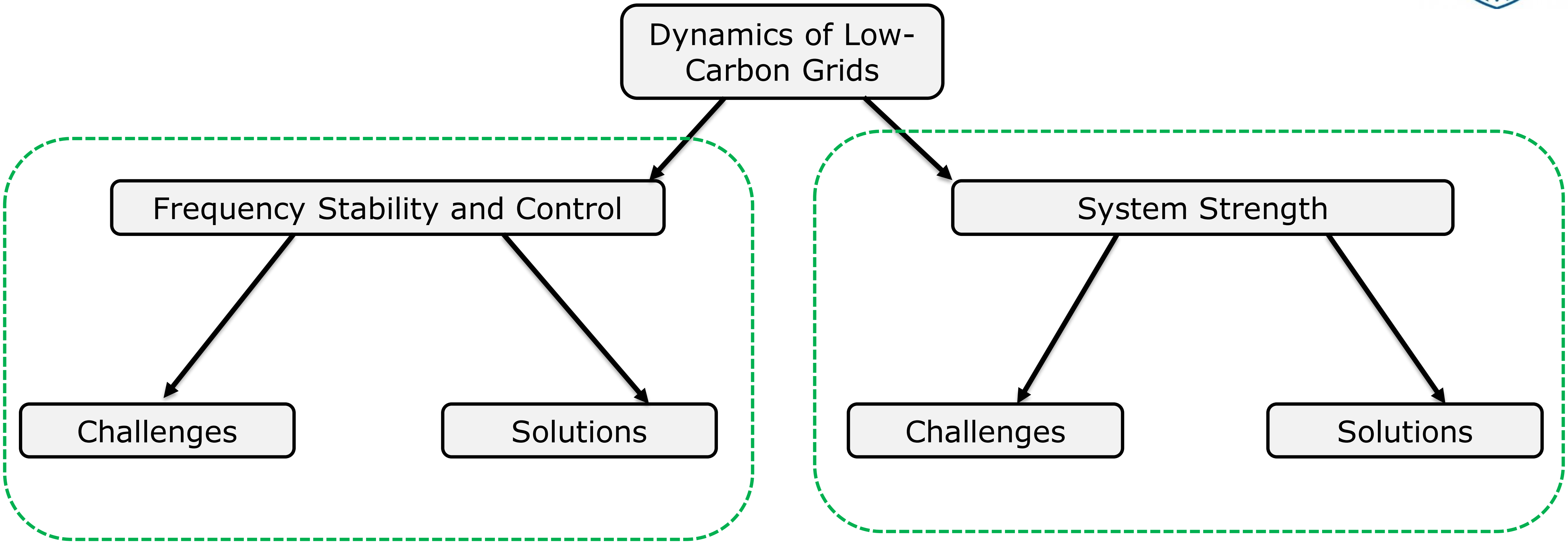
Engineering and Technology

Ranked #39 in the world for engineering and technology, QS World University Rankings by Subject 2022.

Go8 Members

Monash University is a member of Australia's prestigious Group of Eight universities.

Agenda



With More Focus on the Real-Life Australian Systems and Experiences

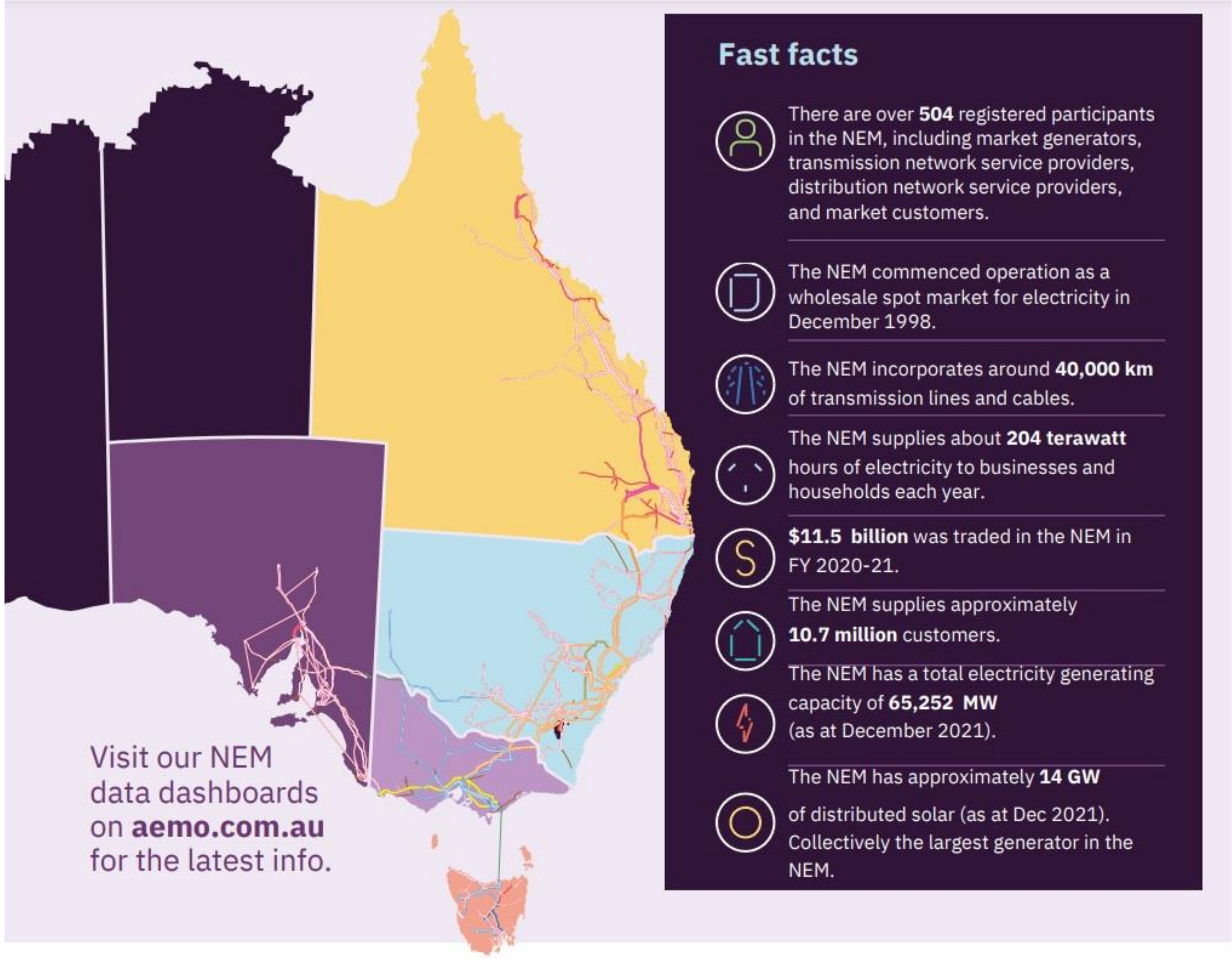
What is the NEM power system?

- NEM stands for **National Electricity Market**

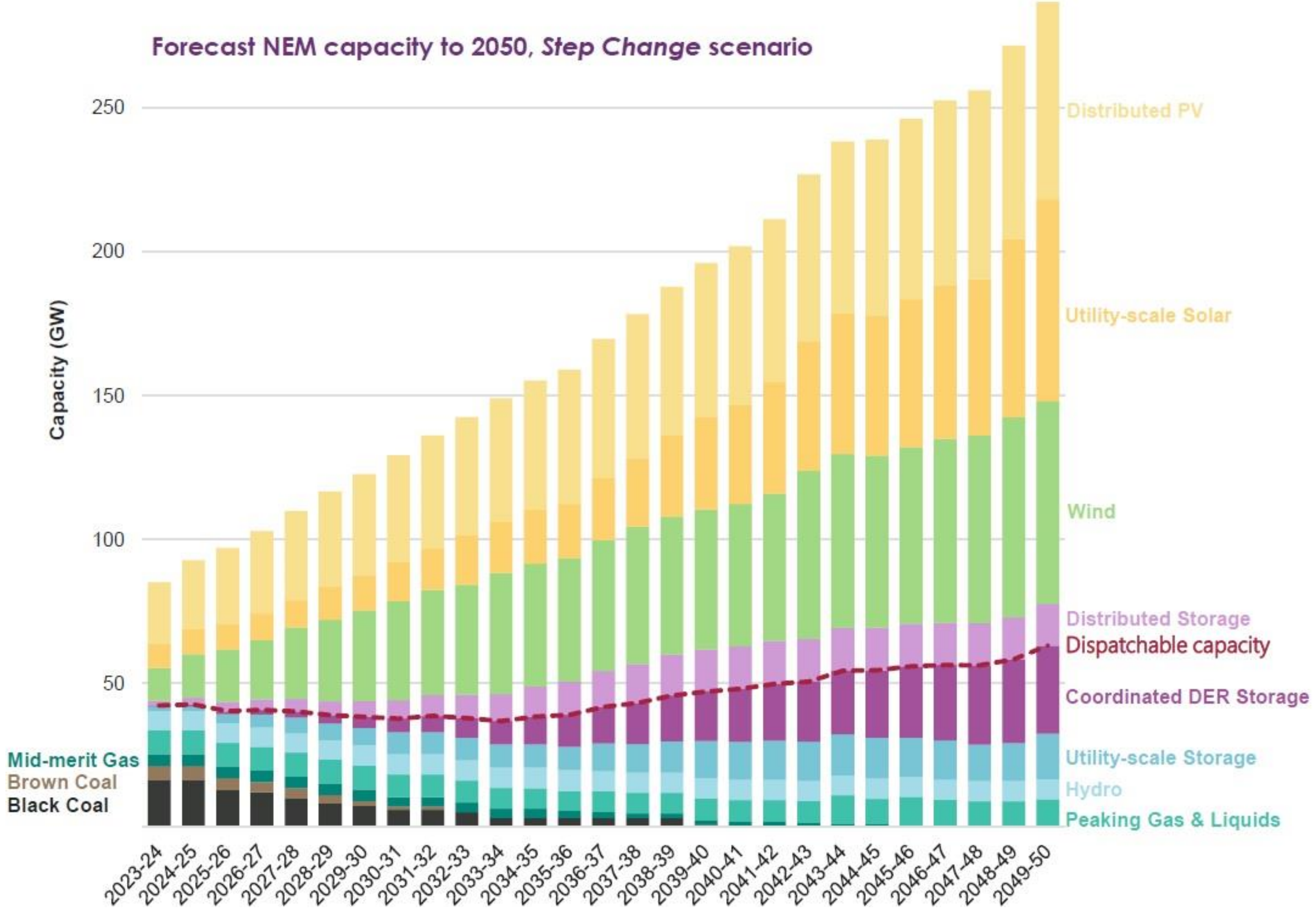
- The NEM power system relates to the transmission system in the **eastern part of Australia**

- Very **long** (40,000 km) **skinny** network!

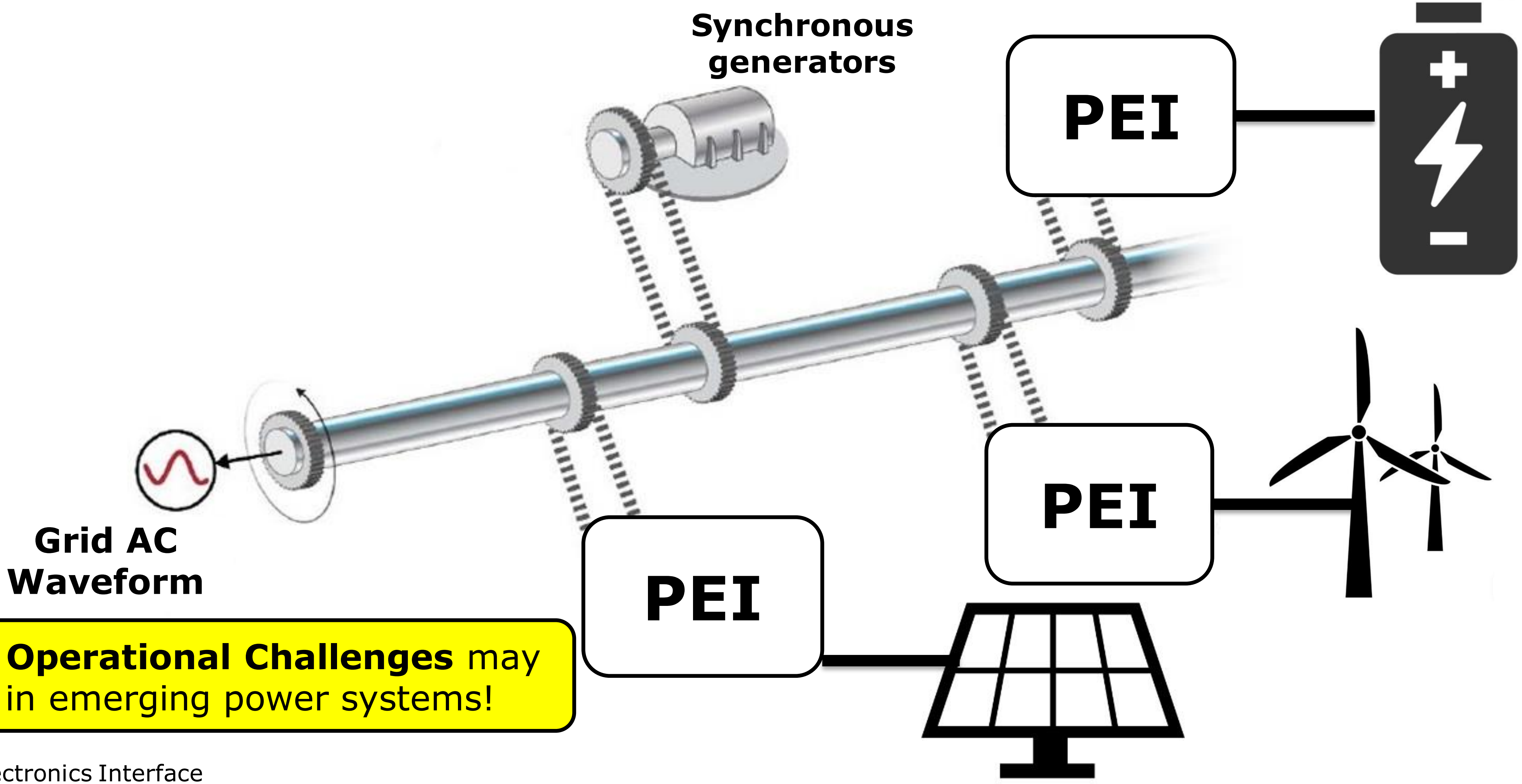
- **200 terawatt hours** of electricity **consumption** (Dec 2021)



Renewable Energy Target in Australia



Technological Revolution

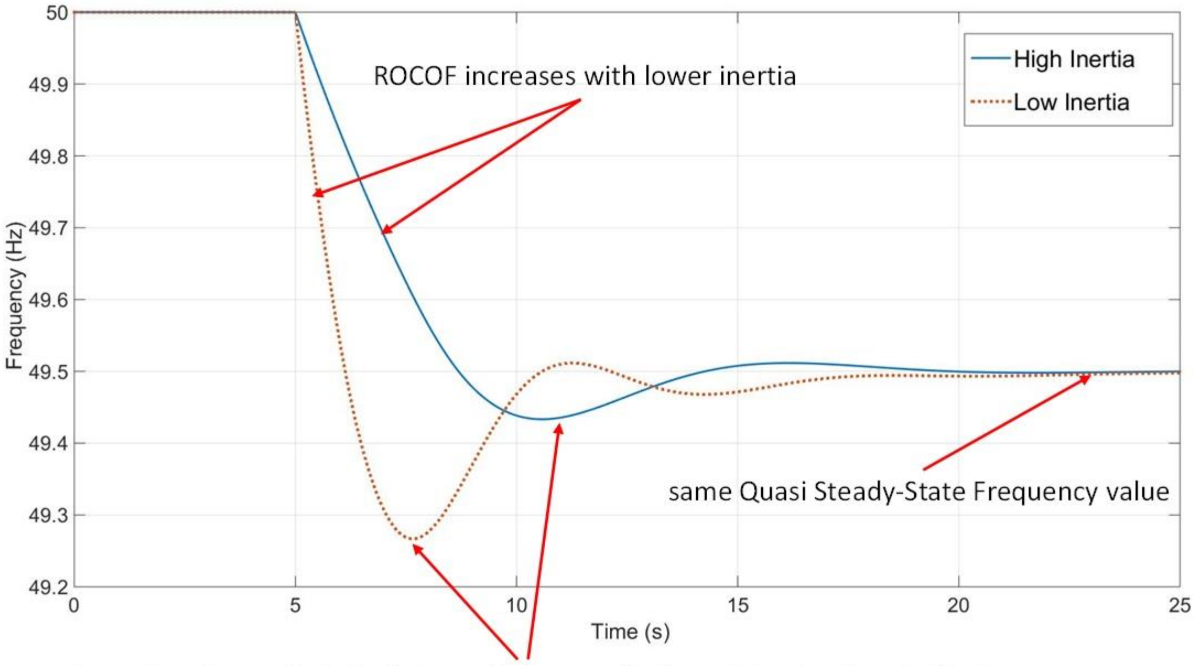


Several **Operational Challenges** may arise in emerging power systems!

PEI: Power Electronics Interface

Challenge: Frequency Stability Issues

- **Reduction in system inertia** may result in a higher chance of **frequency instability** in inverter-rich power systems



Low-inertia conditions → faster frequency dynamics

P. Mancarella *et al.*, "Power system security assessment of the future national electricity market", *Finkel Review*, Melbourne, June 2017.

Relationship between **system inertia** and **frequency dynamics**

$$\frac{d\Delta f}{dt} = \frac{f_s}{2E_s}(P_m - P_e) = \frac{f_s}{2E_s} \cdot \Delta P$$

$$RoCoF = \frac{\Delta P}{2 \times H_s}$$

Rate of change of frequency (RoCoF) following an **active power mismatch (ΔP)**

What is required to ensure frequency stability in low-inertia conditions?

Challenge: System Monitoring
ARENA Project

Australian Government
Australian Renewable Energy Agency

ARENA 10 YEARS

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Home > Projects > Reactive Technologies System Inertia Measurement Demonstration

Reactive Technologies System Inertia Measurement Demonstration

$1.43m
Funded by ARENA

$3.07m
Total project cost

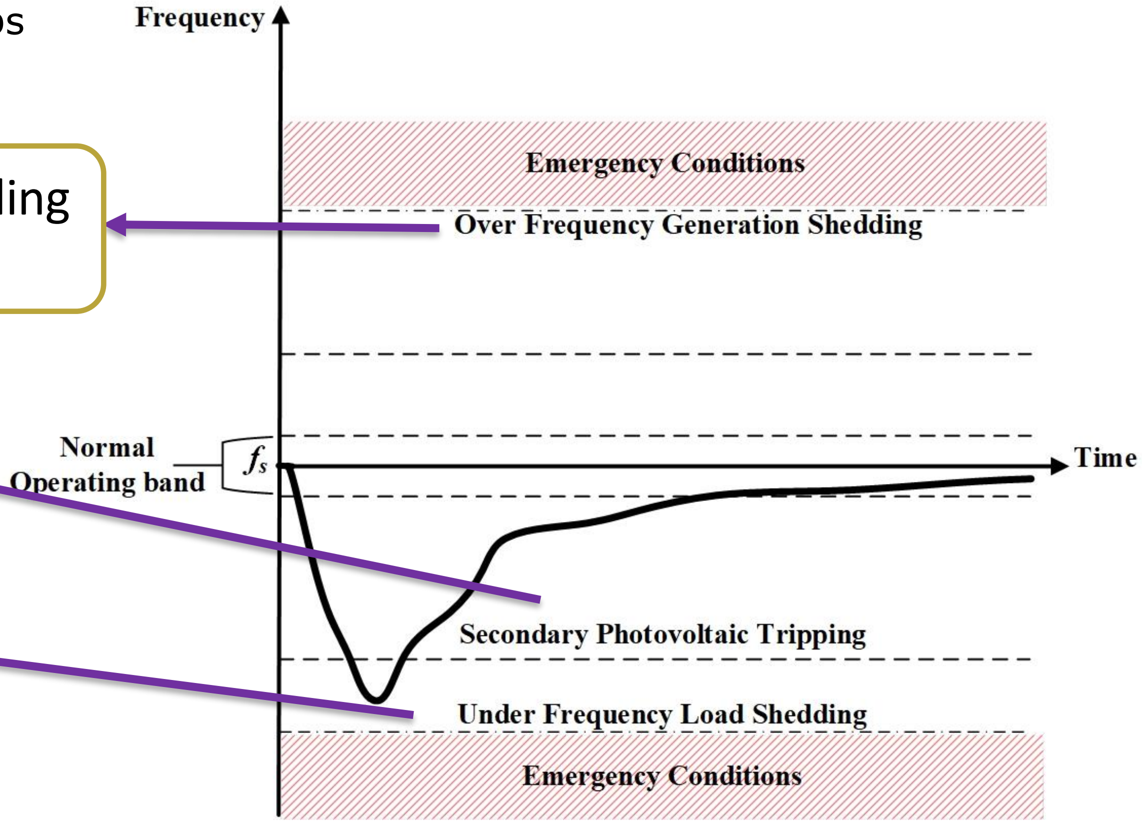
Challenge: System Fragility Issues

- There is a **higher chance of system fragility issues** in **low-inertia operating conditions**
- Possible **interactions** with **frequency-dependant protection schemes**
  - ✓ Generator trip, sympathetic renewable trip, load disconnection, interconnector trip, or the combinations of the mentioned trips

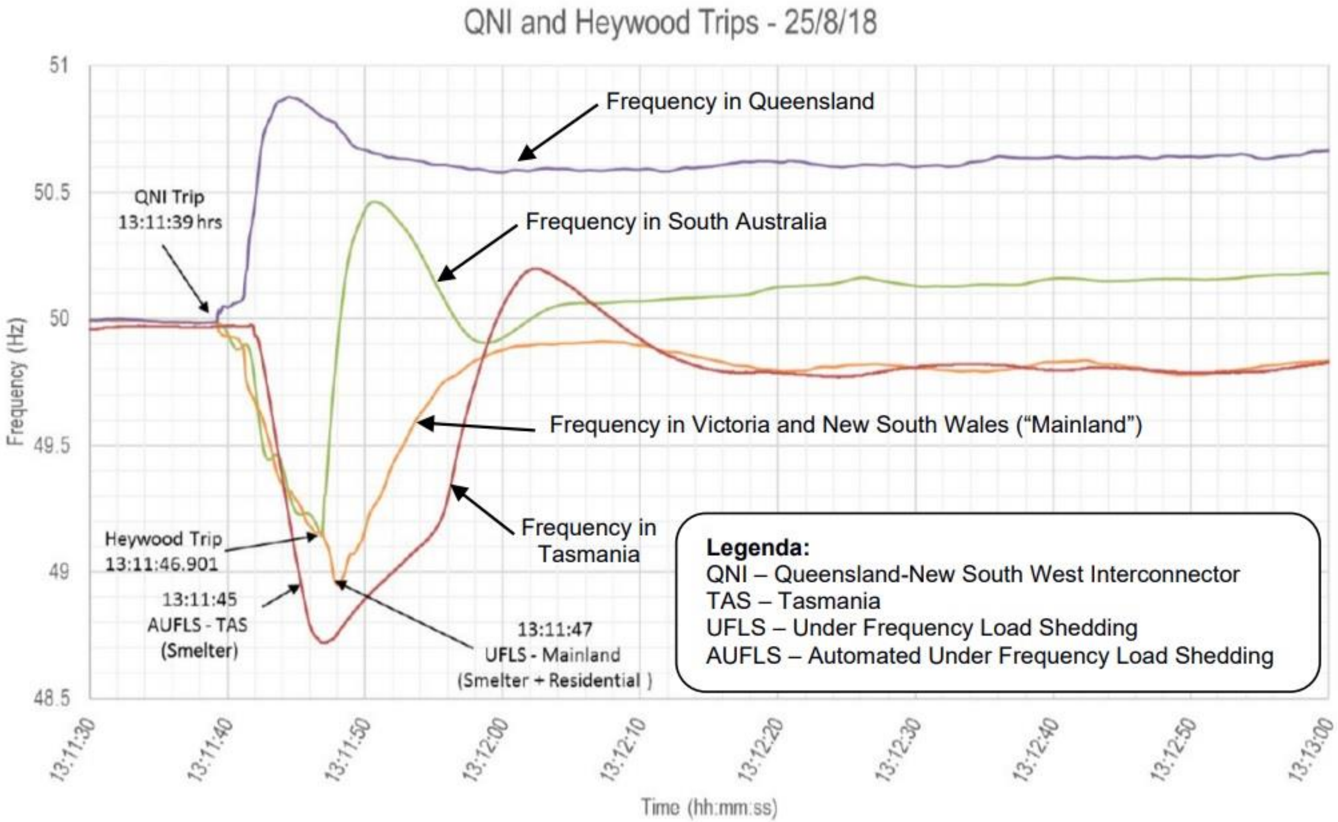
Over frequency generation shedding threshold in Australia: 51 Hz

Secondary PV tripping threshold in Australia: 49.5 Hz

Under frequency load shedding threshold in Australia: 49 Hz



Real-Life Example: The August 2018 Separation Event



Frequency Dynamics during the August event

System separation

Around 1 GW of load shedding

Around 200 MW of PV tripping

Source: AEMO

Challenge: Frequency Regulation Issues

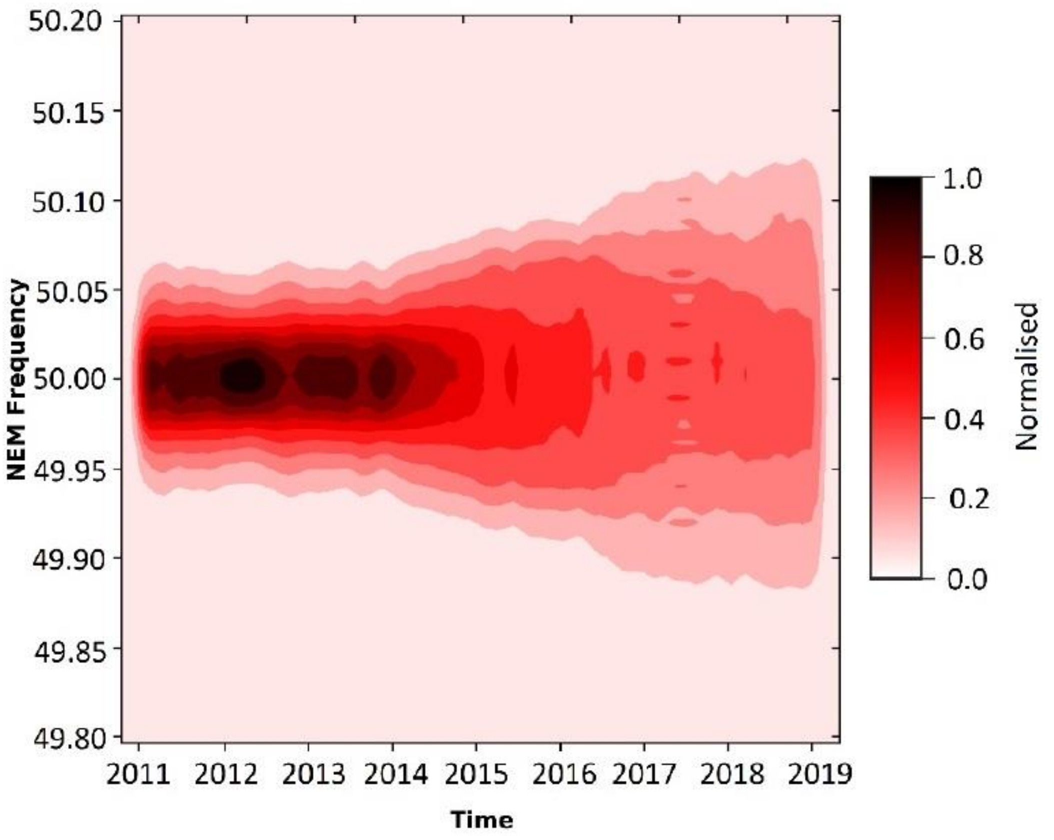
- **Renewable** energy resources are **stochastic in nature** with **inherent variability** and **uncertainty** in their **active power output**

Relationship between **system inertia** and **frequency dynamics**

$$\frac{d\Delta f}{dt} = \frac{f_s}{2E_s}(P_m - P_e) = \frac{f_s}{2E_s} \cdot \Delta P$$

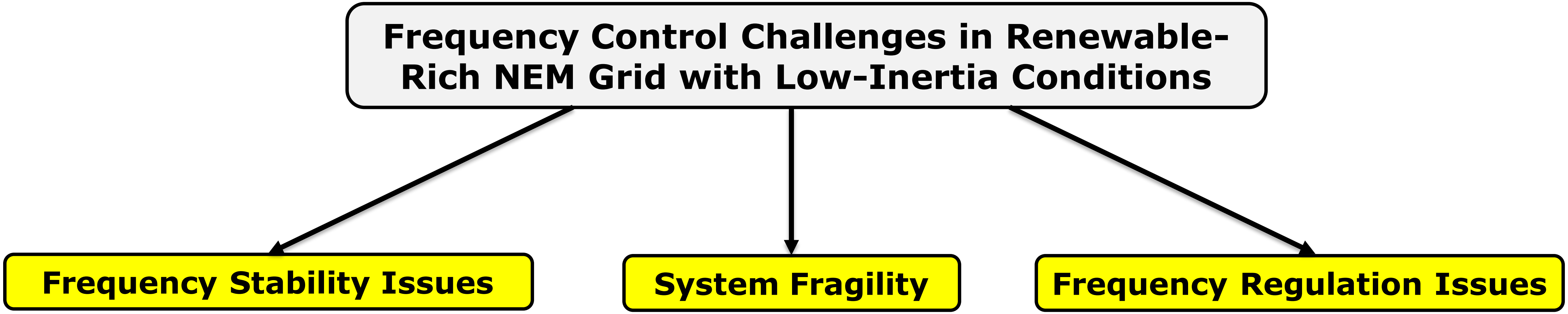
Higher chance of minor frequency excursions in emerging low-carbon power systems

What is required to ensure better performance in frequency regulation?



J. Bryant, R. ghanbari, M. Jalili, P. Sokolowski, L. Meegahapola, "Frequency control challenges in power systems with high renewable power generation: An Autralian perspective," RMIT University, 2019.

Quick Recap


Frequency Control Challenges in Renewable-Rich NEM Grid with Low-Inertia Conditions
Frequency Stability Issues
System Fragility
Frequency Regulation Issues

Potential Solutions for Frequency Control Management in Low-Carbon Grids

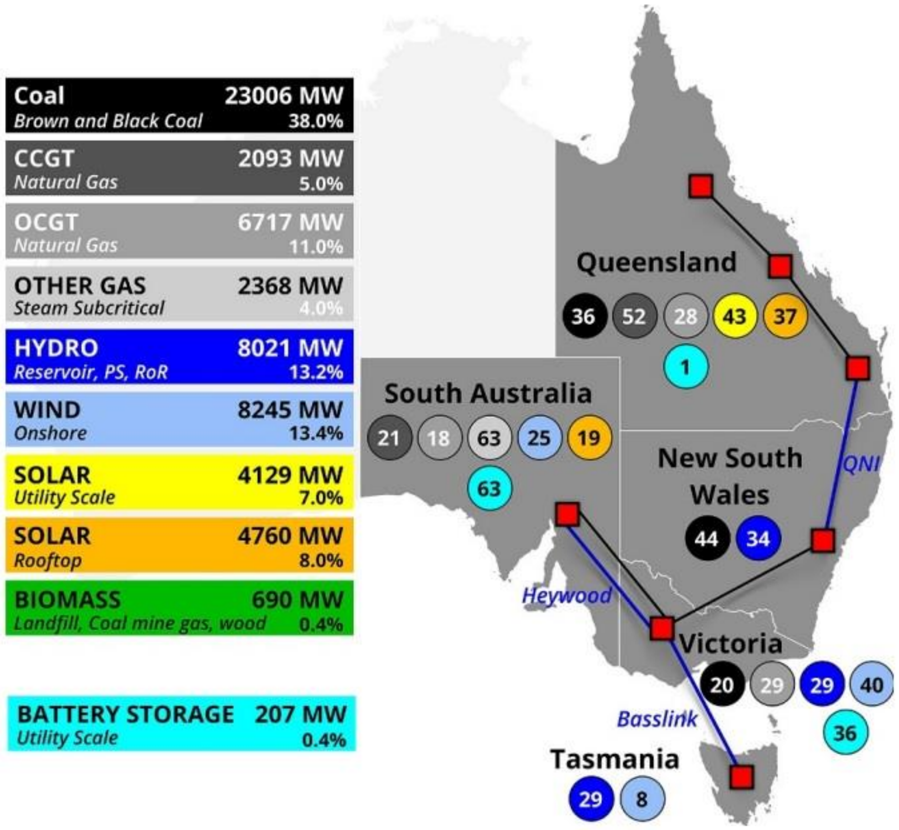
- There are several solutions to manage frequency control and the relevant fragility issues in low-carbon power systems including, but not limited to:

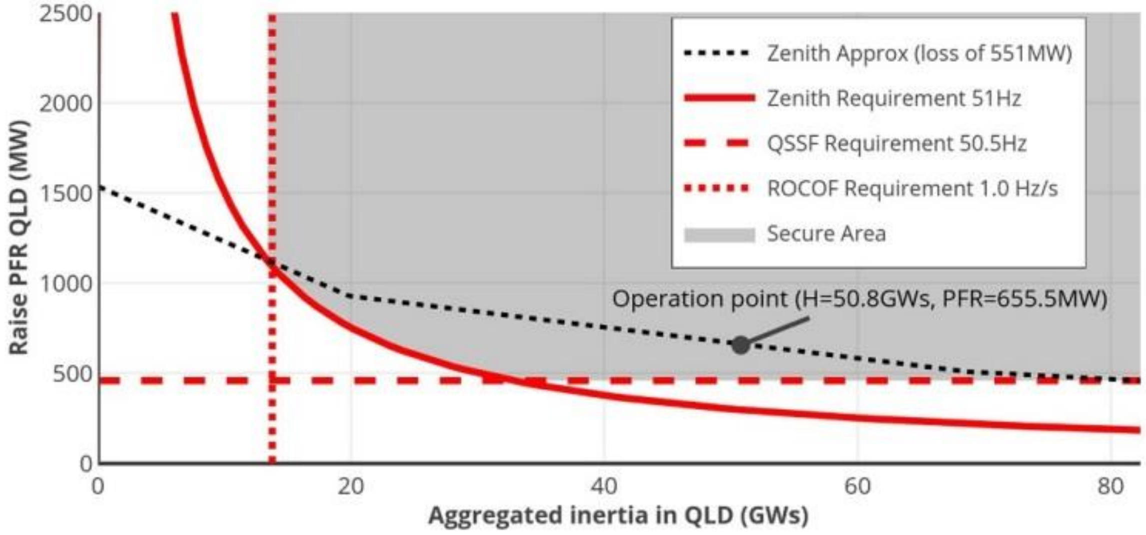
  ✓ Synchronous condenser installation (often coupled with flywheel)

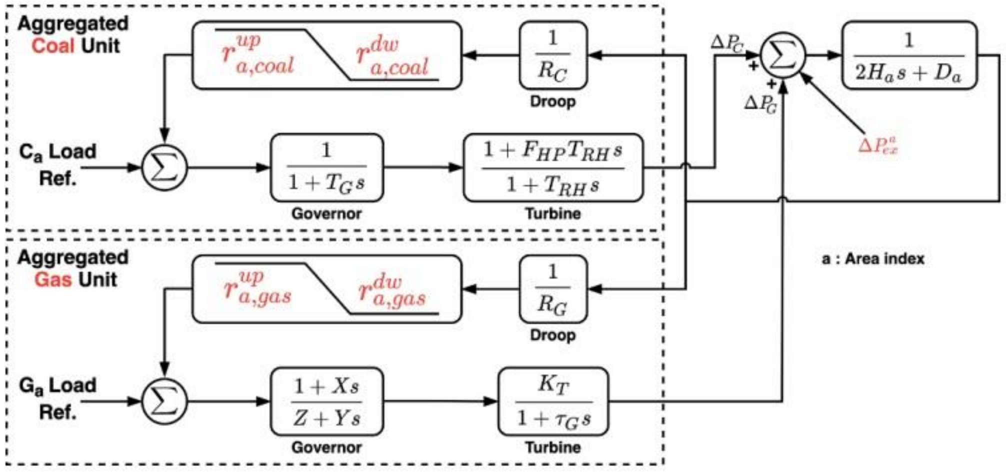
  ✓ Mandatory frequency response requirements

  ✓ **Frequency response constraints in security planning and unit commitment**

Example: Security-Constrained Unit Commitment







Dynamic model of the a-th area for separation event studies.

Sebastián Püschel-Løvengreen, Mehdi Ghazavi Dozein, Steven Low, Pierluigi Mancarella, "Separation event-constrained optimal power flow to enhance resilience in low-inertia power systems," Electric Power Systems Research, Volume 189, 2020,

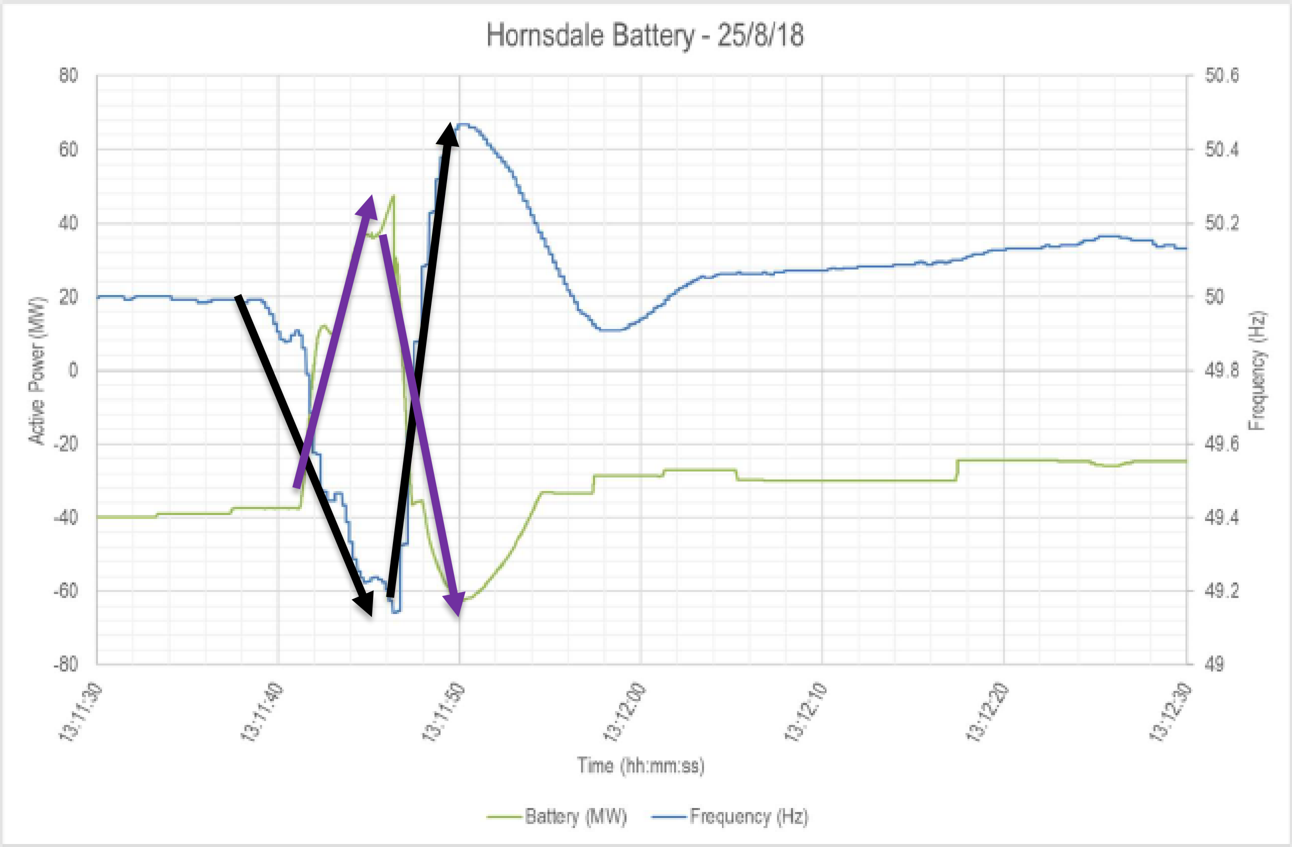
Potential Solutions for Frequency Control Management in Low-Carbon Grids

- There are several solutions to manage frequency control and the relevant fragility issues in renewable-rich power systems including, but not limited to:

  - ✓ Synchronous condenser installation (often coupled with flywheel)
  - ✓ Mandatory frequency response requirements
  - ✓ Frequency response constraints in system security planning
  - ✓ **Frequency stability support from inverter-based resources**
    - **Battery energy storage systems**

Fast Frequency Response (FFR) from Hornsdale Battery during the August 2018 Event

Great contribution to system frequency stability!

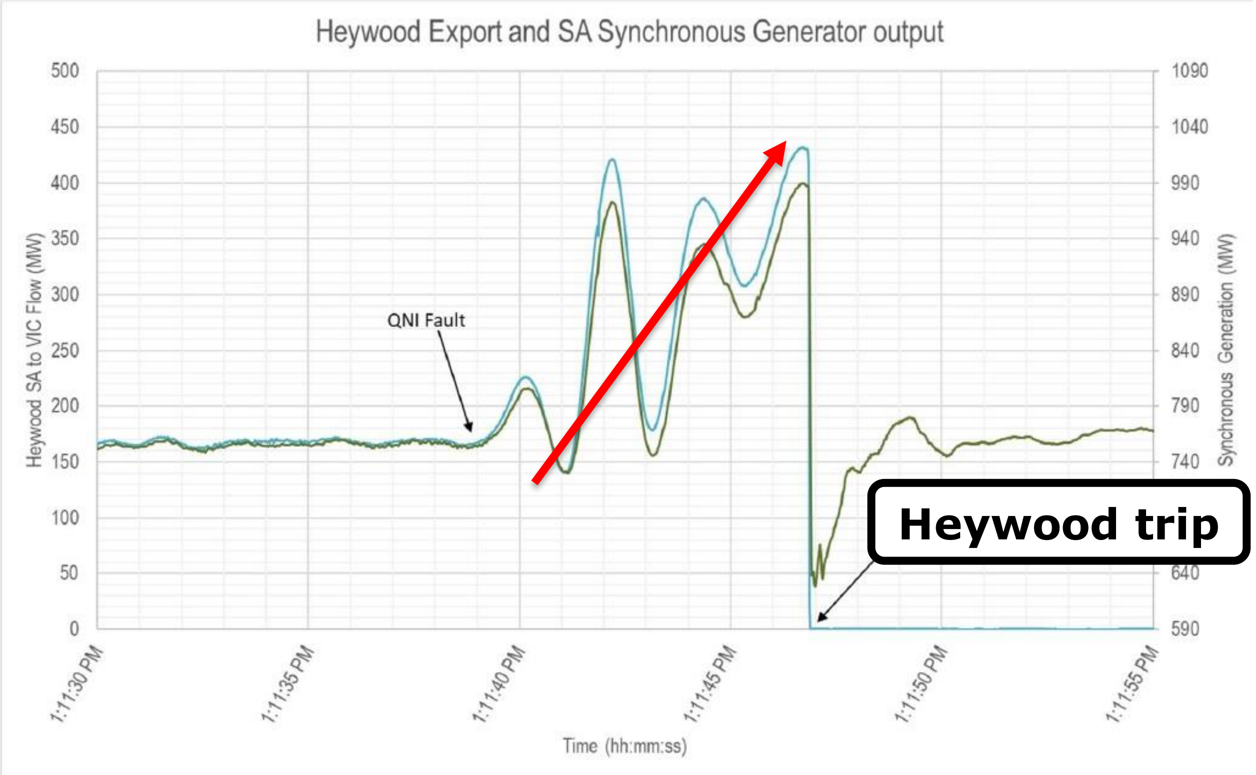


But there's a catch….

M. Ghazavi Dozein and P. Mancarella, "Frequency Response Capabilities of Utility-scale Battery Energy Storage Systems, with Application to the August 2018 Separation Event in Australia," *ICPES* 2019.

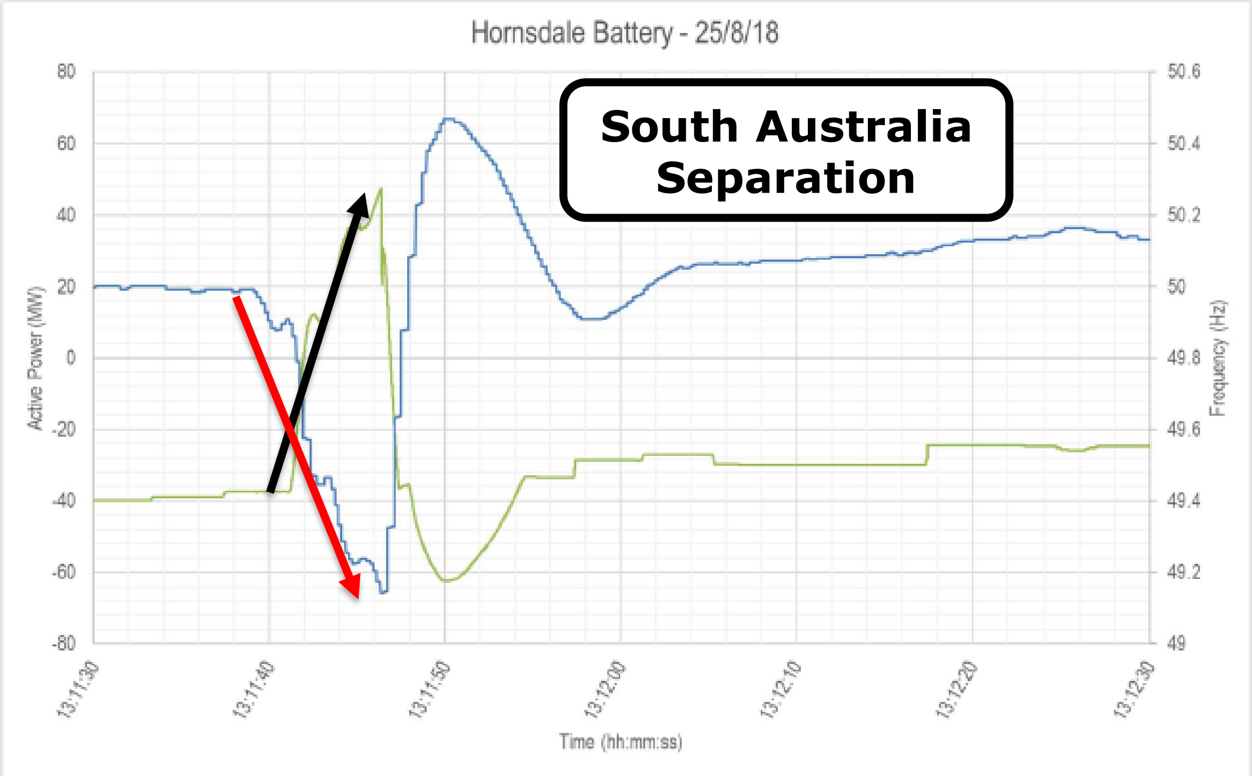
Battery FFR and System-Level Interactions

Negative contribution to system fragility!



Source: AEMO

Figure 41 SA transmission-connected battery response – short-term



Source: AEMO

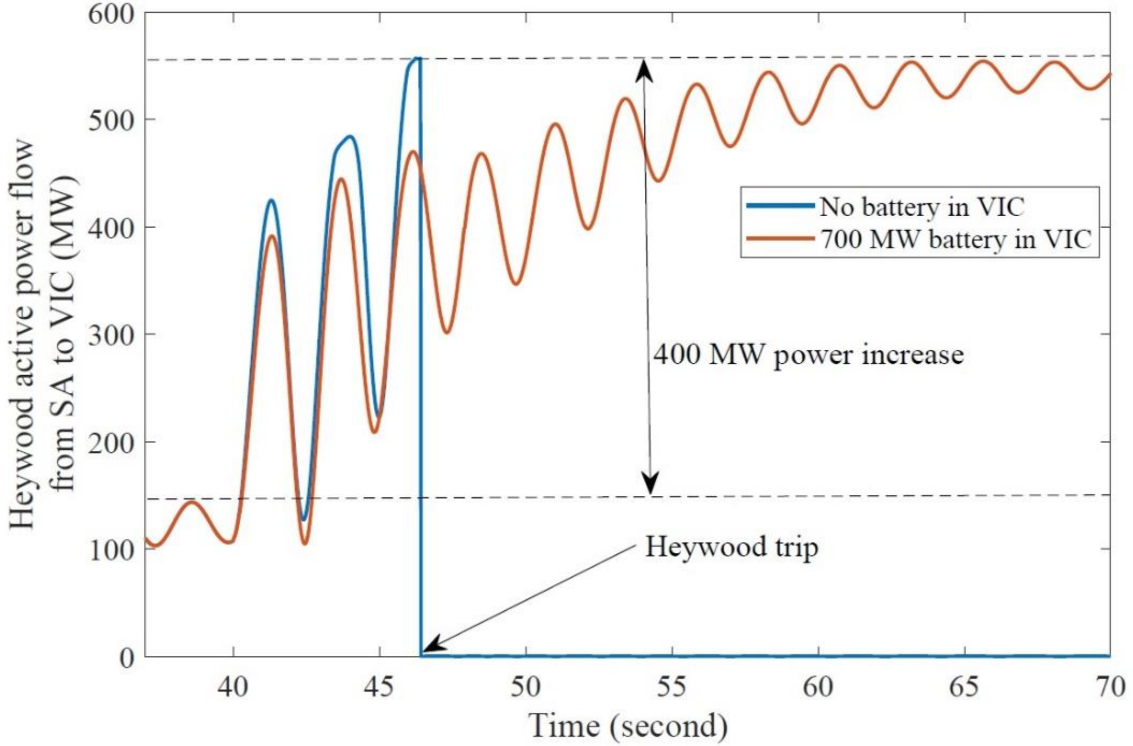
Interaction of battery FFR with interconnector protection

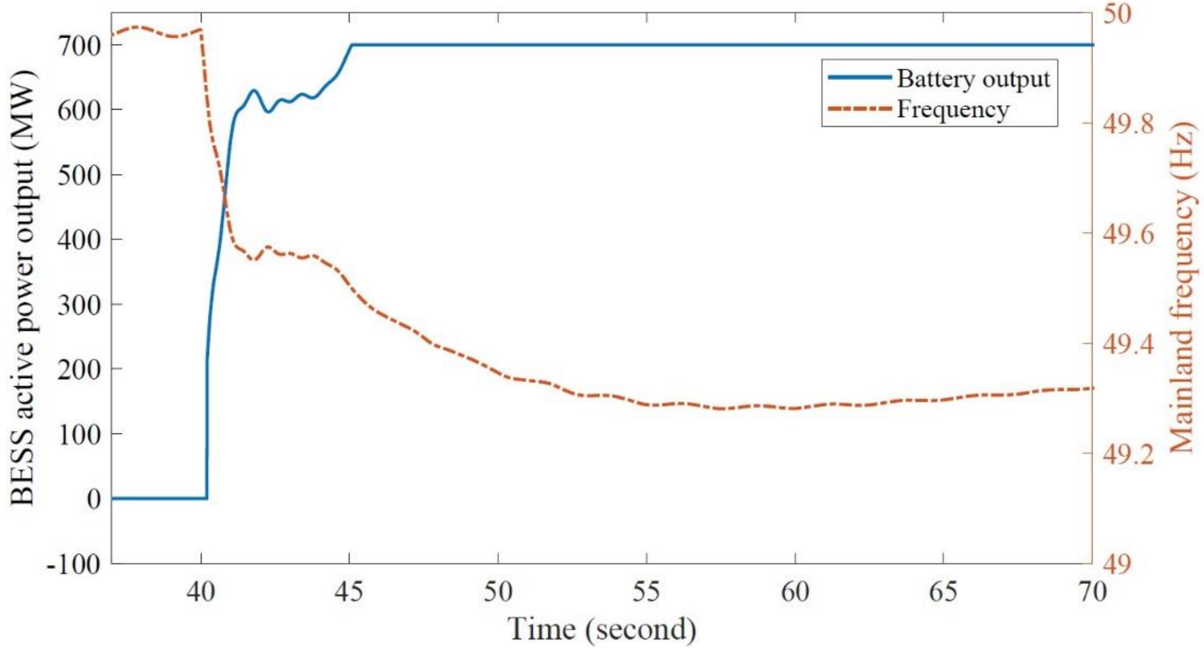
M. Ghazavi Dozein and P. Mancarella, "Possible Negative Interactions between Fast Frequency Response from Utility-scale Battery Storage and Interconnector Protection Schemes," AUPEC 2019.

Battery Contribution to Frequency Stability and Fragility

- Assuming a hypothetical 700 MW installed in Victoria during the August 2018 Separation Event

Heywood active power flow





Battery FFR and mainland frequency

Importance of FFR location

Importance of System-Level Understanding and Analysis

M. Ghazavi Dozein and P. Mancarella, "Possible Negative Interactions between Fast Frequency Response from Utility-scale Battery Storage and Interconnector Protection Schemes," AUPEC 2019.

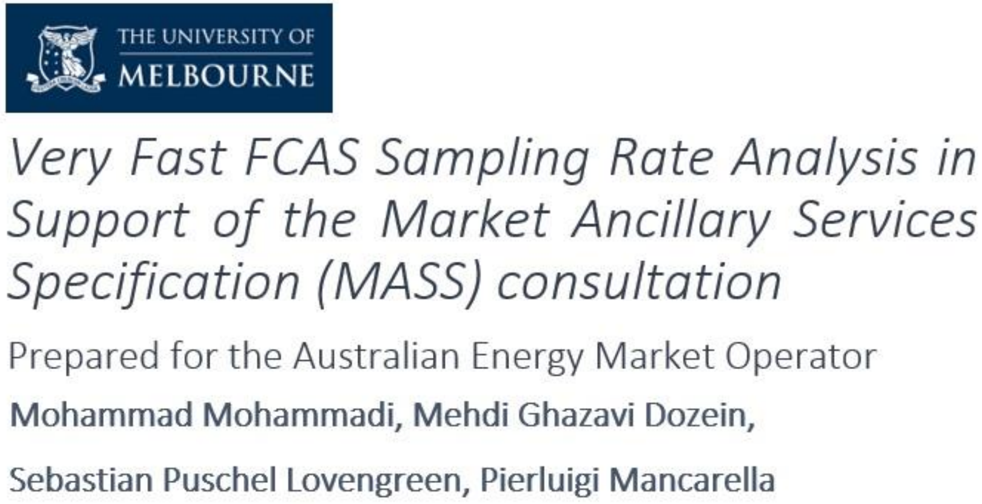
Final Points on Batteries

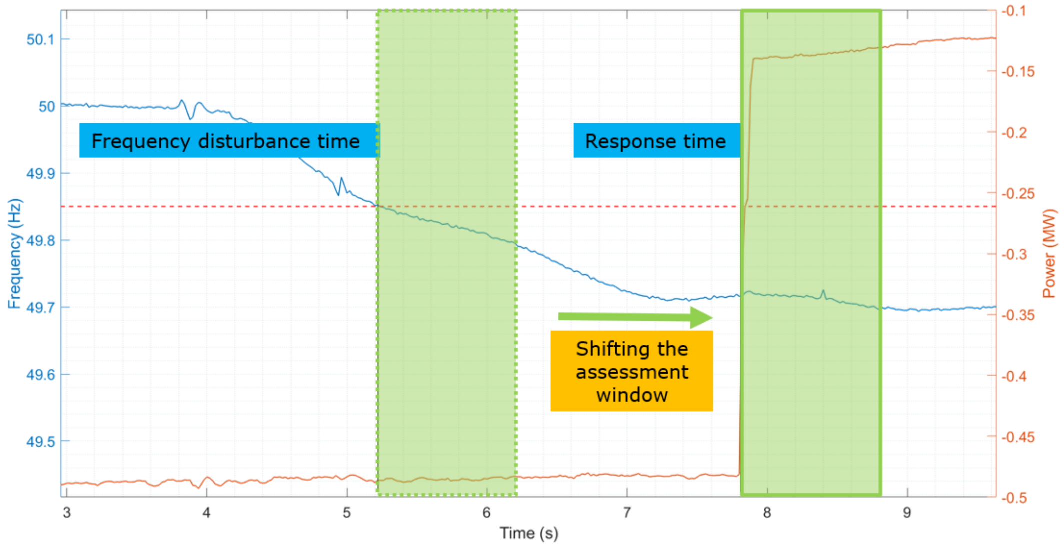
- Batteries can also be utilised for many other frequency support applications:
  - Frequency regulation
  - Virtual inertia response (if equipped with virtual synchronous machine (VSM) control)
  - ……
- There are certain system-level factors that may impact battery capabilities in frequency control support
  - We will discuss it later in this presentation!

How should we value the frequency stability support from batteries (or other fast responsive components?)

How should we incentivise the quality of response?

AEMO Project: Very Fast FCAS!





FCAS: Frequency Control Ancillary Services

For further information: https://aemo.com.au/en/consultations/current-and-closed-consultations/amendment-of-the-mass-very-fast-fcas

Potential Solutions for Frequency Control Management in Low-Carbon Grids

- There are several solutions to manage frequency control and the relevant fragility issues in renewable-rich power systems including, but not limited to:
  - ✓ Synchronous condenser installation (often coupled with flywheel)
  - ✓ Mandatory frequency response requirements
  - ✓ Frequency response constraints in system security planning
  - ✓ Frequency stability support from inverter-based resources
    - Battery energy storage systems
    - Hydrogen electrolysers!

Electrolyser vs Battery

Technology	System Support Service			
	Virtual inertia response	Fast frequency response	Primary frequency response	Frequency regulation response
Grid-following Alkaline Electrolyzer				
Grid-following PEM electrolyzer				
VSM PEM electrolyzer				
Grid-following battery storage				
VSM battery storage				

Frequency control from electrolysers **may reduce the need for frequency control-oriented battery installation**

M. Ghazavi Dozein, A. Jalali and P. Mancarella, "Fast Frequency Response From Utility-Scale Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2021.

M. Ghazavi Dozein, A. M. De Corato, and P. Mancarella, "Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers," *IEEE Transactions on Power Systems,* 2022.

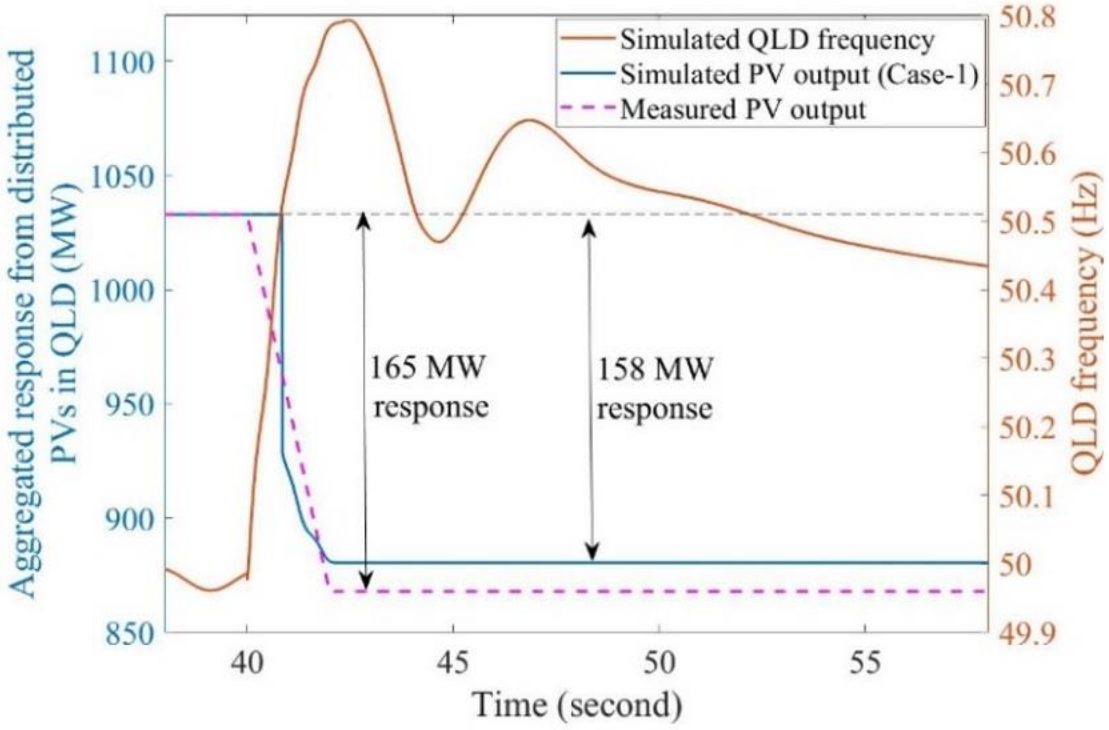
S. D. Tavakoli, M. Ghazavi Dozein, *et al*., "Grid-Forming Services From Hydrogen Electrolyzers," in *IEEE Transactions on Sustainable Energy*, 2023.

The darker colour indicates a better performance in system dynamic support delivery

Potential Solutions for Frequency Control Management in Low-Carbon Grids

- There are several solutions to manage frequency control and the relevant fragility issues in renewable-rich power systems including, but not limited to:
  - ✓ Synchronous condenser installation (often coupled with flywheel)
  - ✓ Mandatory frequency response requirements
  - ✓ Frequency response constraints in system security planning
  - ✓ Frequency stability support from inverter-based resources
    - Battery energy storage systems
    - Hydrogen electrolyzers!
    - **Distributed energy resources, including photovoltaics**

Project with AusNet



THE UNIVERSITY OF MELBOURNE

AusNet services

Frequency Control Ancillary Services in Low Inertia Power Systems: DER Opportunities

Mehdi Ghazavi Dozein, Ahvand Jalali, Amin Mahdizadeh, Gilles Chaspierre, Pierluigi Mancarella

Keep this project in mind, we will talk about this project later!

Potential Solutions for Frequency Control Management in Low-Carbon Grids

- There are several solutions to manage frequency control and the relevant fragility issues in renewable-rich power systems including, but not limited to:

  - ✓ Synchronous condenser installation (often coupled with flywheel)
  - ✓ Mandatory frequency response requirements
  - ✓ Frequency response constraints in system security planning
  - ✓ Frequency stability support from inverter-based resources
    - Battery energy storage systems
    - Hydrogen electrolyzers!
    - Distributed energy resources, including photovoltaics
    - **And many more .....**

There are technology solutions, but.....

Back to the Principles of Power System Dynamics

Power system variables and various stability types are influenced by certain controls and physical characteristics!

What are these physical characteristics????

Inertia→ already talked about it

System strength????

What is system strength???

System Strength

Recognized as an
American National Standard (ANSI)

IEEE Std 1204-1997(R2003)

IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities

Sponsor
Transmission and Distribution Committee of the IEEE Power Engineering Society

Approved 26 June 1997
Reaffirmed 10 December 2003
IEEE Standards Board

Connection of wind farms to weak AC networks

Working Group B4.62

December 2016

cigré

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Integrating Inverter-Based Resources into Low Short Circuit Strength Systems
Reliability Guideline

December 2017

System Operability Framework 2016

UK electricity transmission

nationalgrid

Australian Energy Market Commission

AEMC

DISCUSSION PAPER

INVESTIGATION INTO SYSTEM STRENGTH FRAMEWORKS IN THE NEM

26 MARCH 2020

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

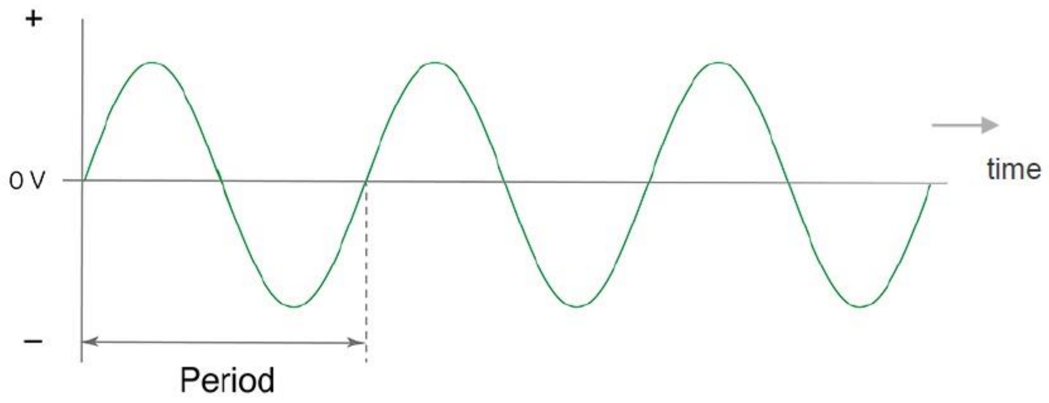
System Strength

March 2020

System strength in the NEM explained

System Strength Definition

- System strength indicates the system ability to maintain **voltage waveform stability**
  - ✓ Voltage magnitude
  - ✓ Voltage angle
  - ✓ Waveform shape



- Consolidating different views and definitions

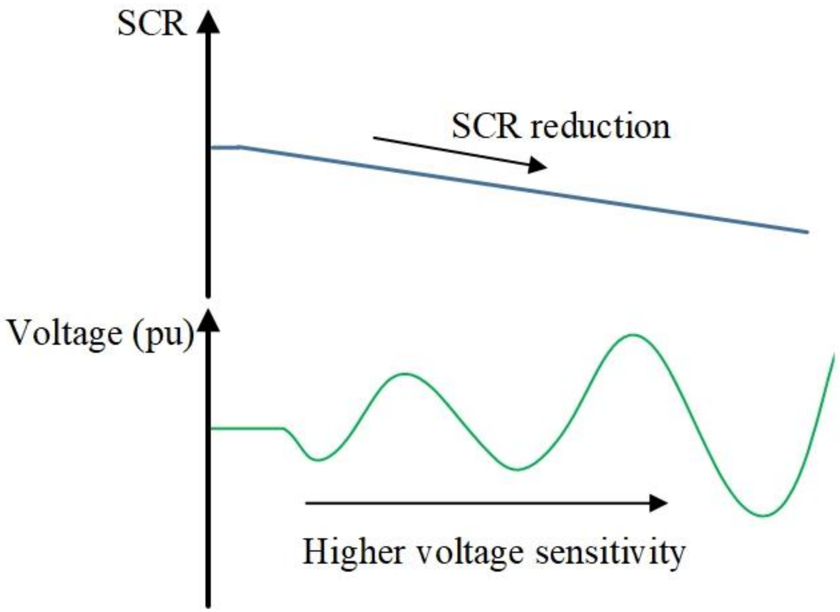
> ***System strength*** *relates to the* ***sensitivity of voltage magnitude, phase angle, and its waveform*** *at any given connection with respect to* ***the change in system active/reactive loading*** *in every possible operating condition*

M. Ghazavi Dozein, "*System Dynamics of Low-Carbon Grids: Fundamentals, Challenges, and Mitigation Solutions*," PhD Thesis, University of Melbourne, 2021.

System Strength Qualitative Metrics

- System strength has traditionally been assessed via fault level related metrics
- The simplest quantitative metric is short circuit ratio

$$SCR = \frac{S_{SCMVA}}{P_{MWR}}$$



Strong grid → higher SCR values

Weak grids → lower SCR values

- Other assessment metrics have also been used in industry including operating short circuit ratio, weighted short circuit ratio, composite SCR, site-dependent metrics, etc

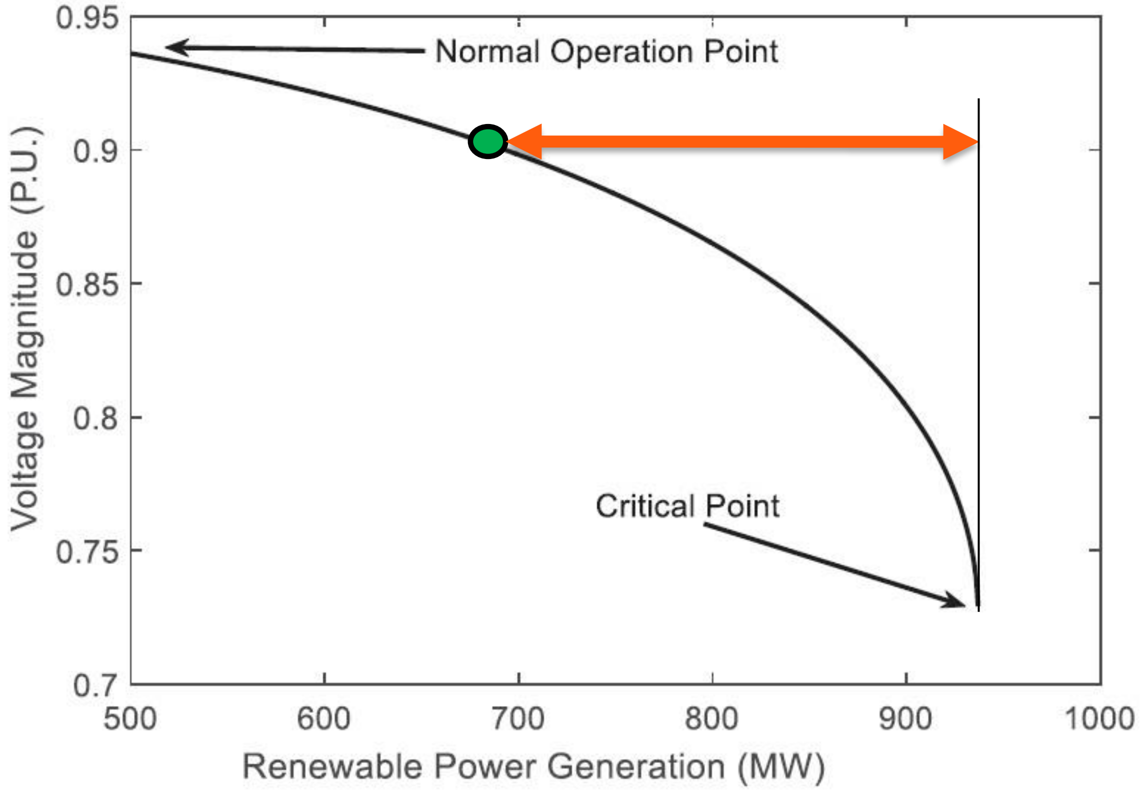
M. Ghazavi Dozein, P. Mancarella, T.K. Saha, R. Yan, “System strength and weak grids: fundamentals, challenges, and mitigation strategies”, AUPEC 2018.

Operational Challenges in Weak Grids
Voltage Stability Issue and Power Transfer Limit

- There is a relationship between system strength, voltage stability, and power transfer limit at a given location

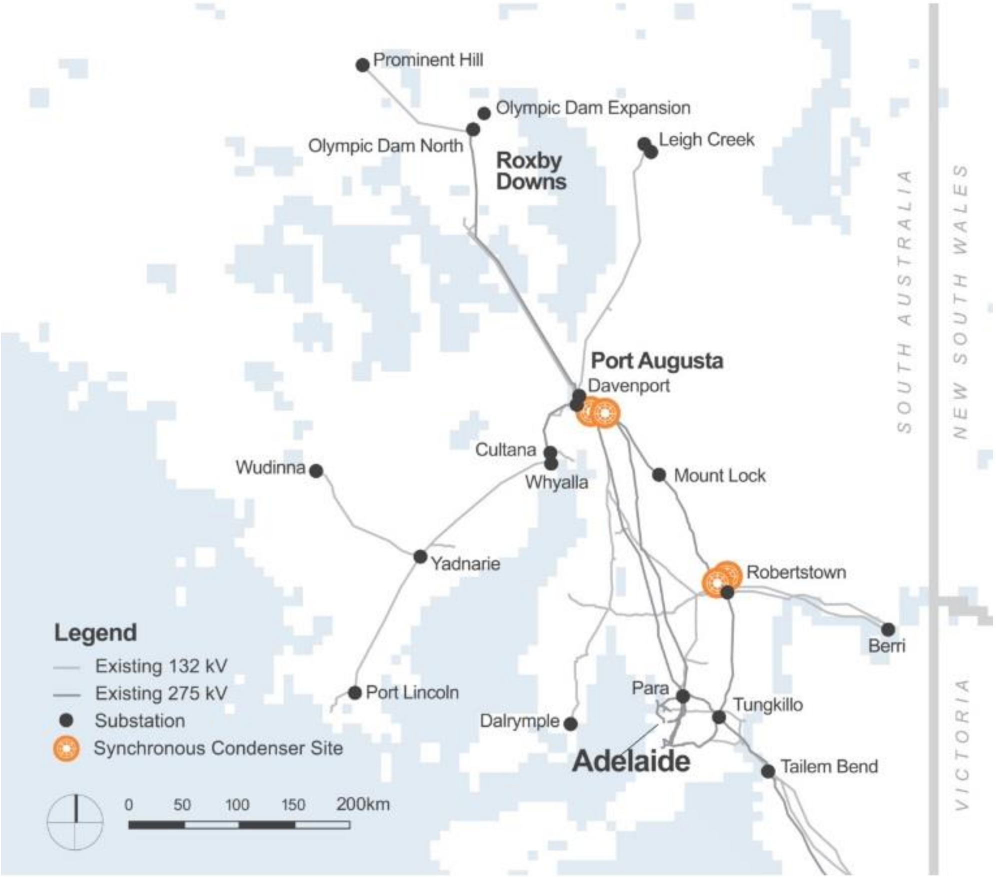
The SCR value reflects on how far a connection point is from its voltage critical point!

Sufficient fault level needs to be in place to achieve certain power injection into the system

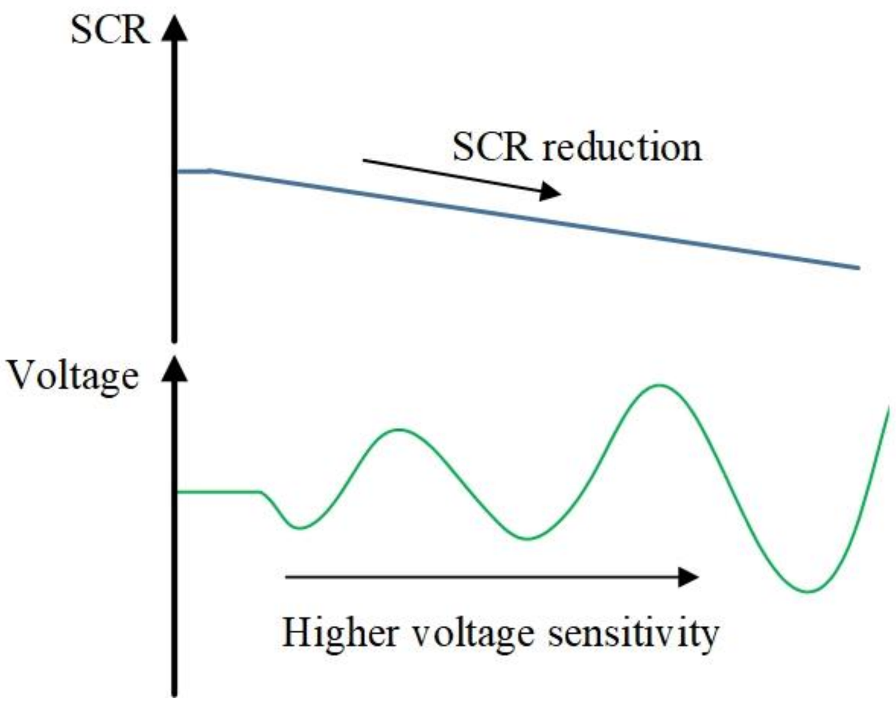


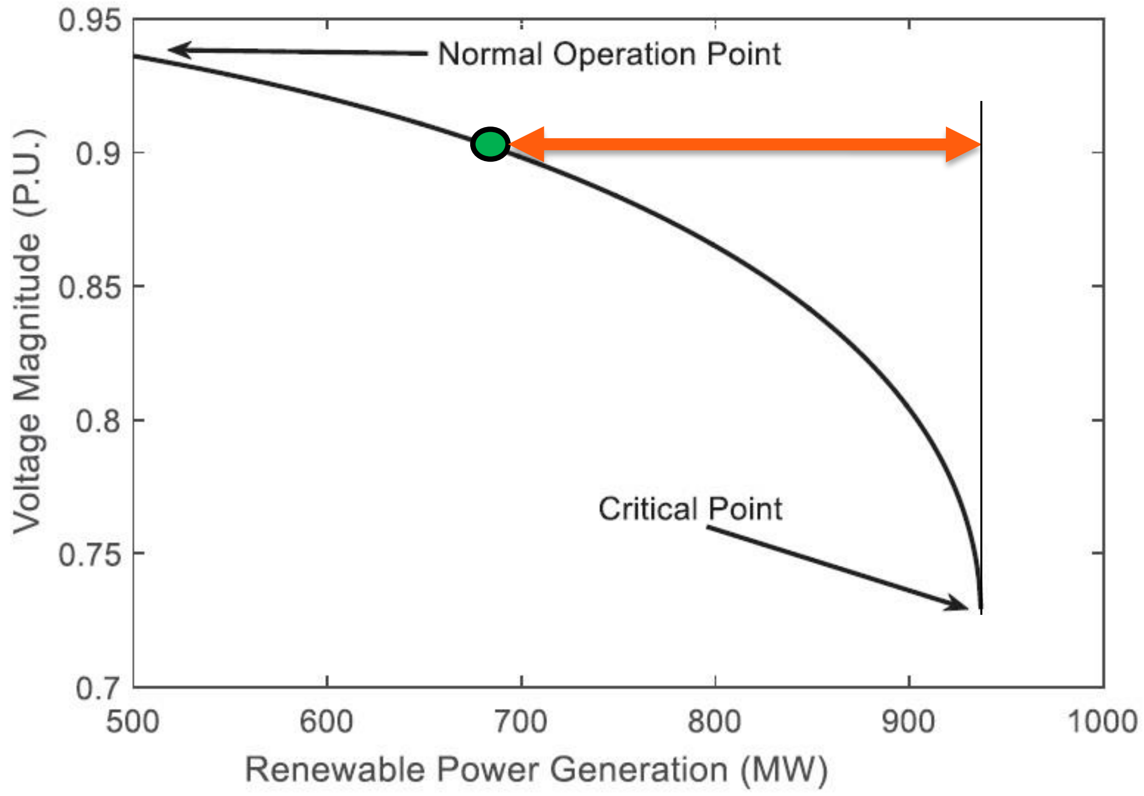
Potential Solution: Synchronous Condenser Installation

- Synchronous condenser installation in South Australia



Need for Voltage Support in Weak Grids!

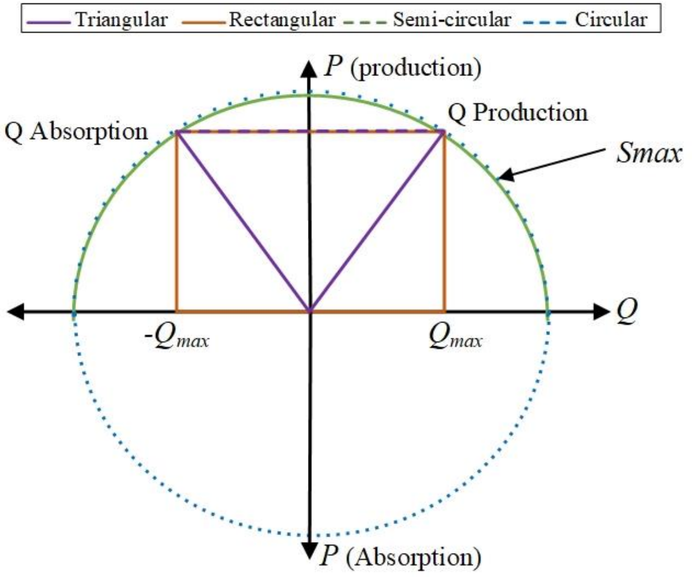


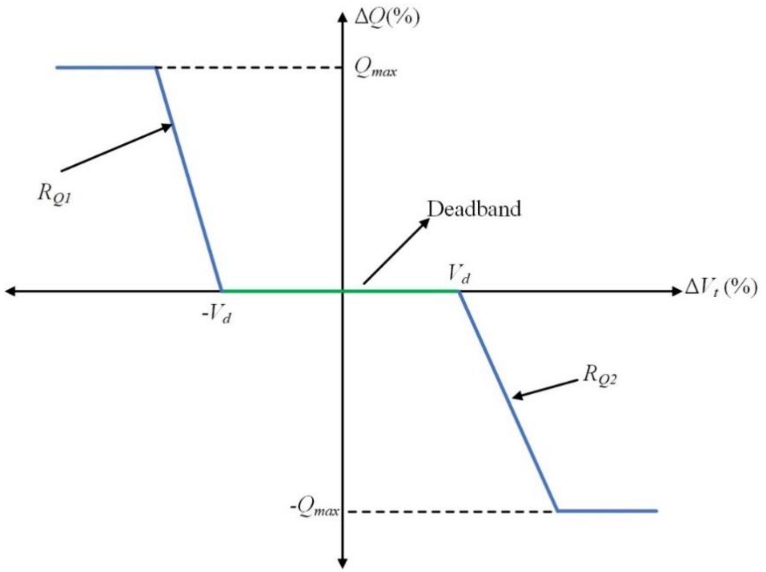


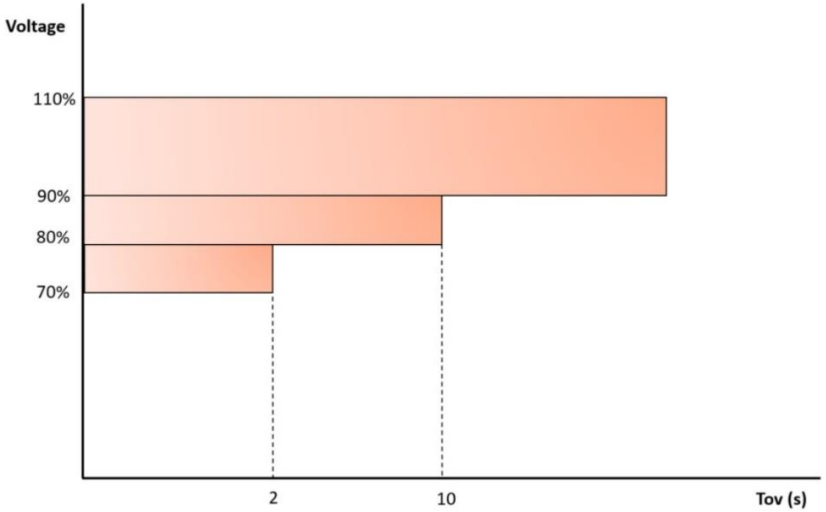
Can IBRs help with voltage control and reactive power support????

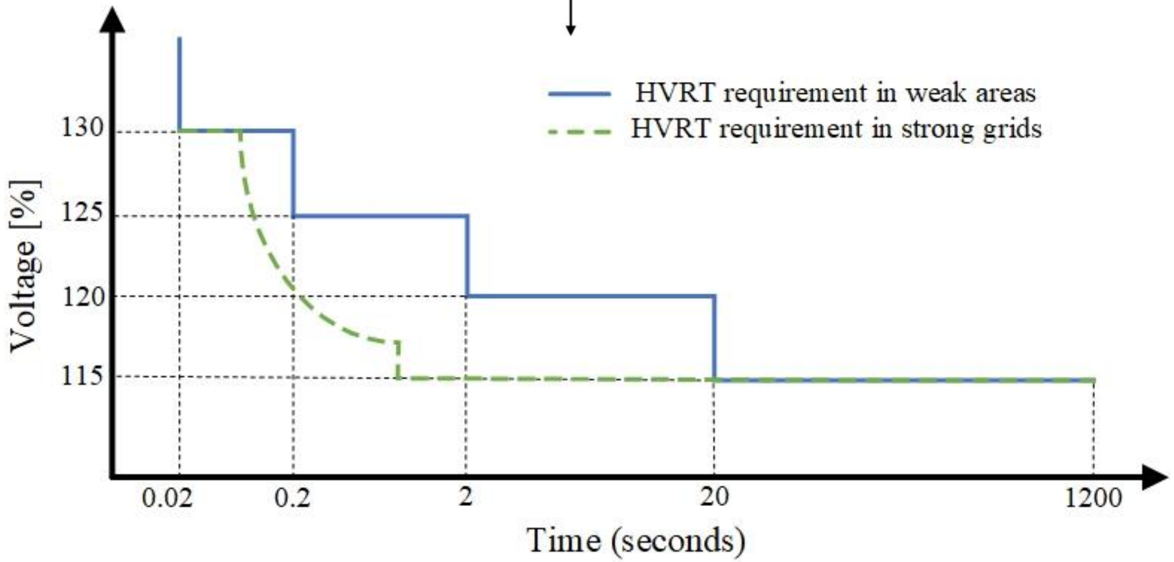
IBR: Inverter-Based Resources

IBR Capability/Requirement in/for Voltage Support







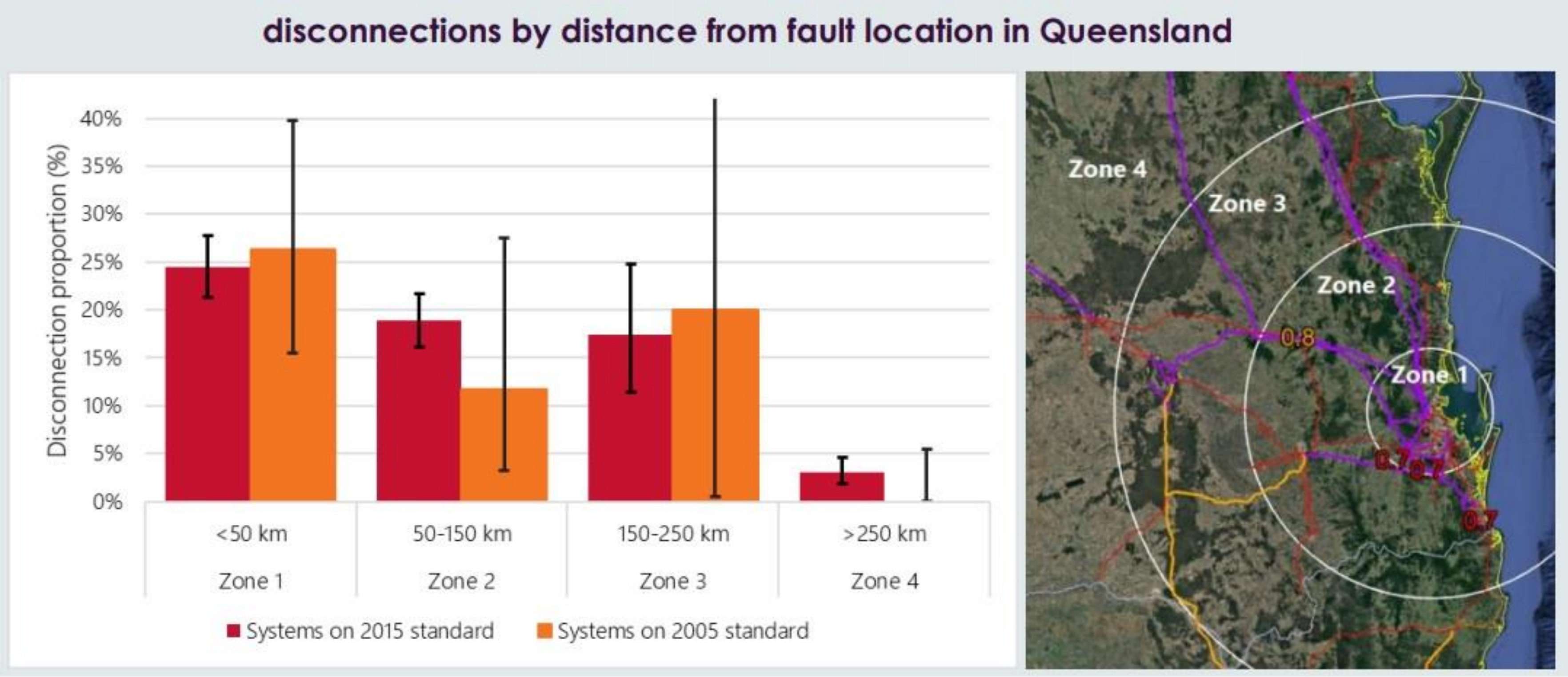


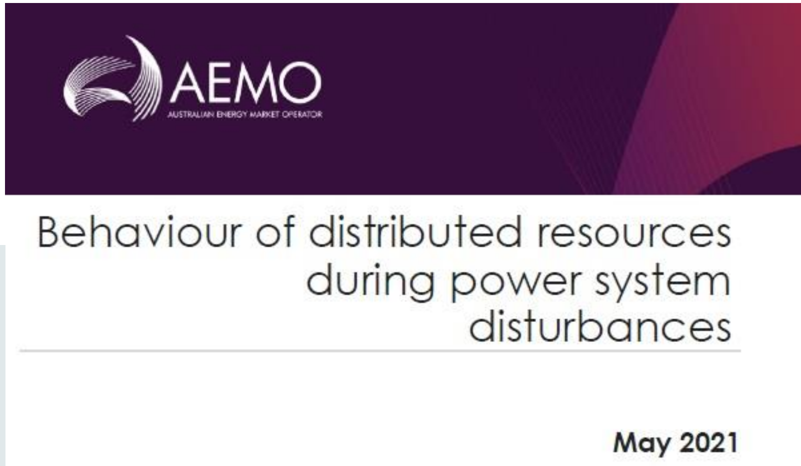
M. Ghazavi Dozein, "*System Dynamics of Low-Carbon Grids: Fundamentals, Challenges, and Mitigation Solutions*," PhD Thesis, University of Melbourne, 2021.

Real-life Example of Sympathetic IBR Tripping

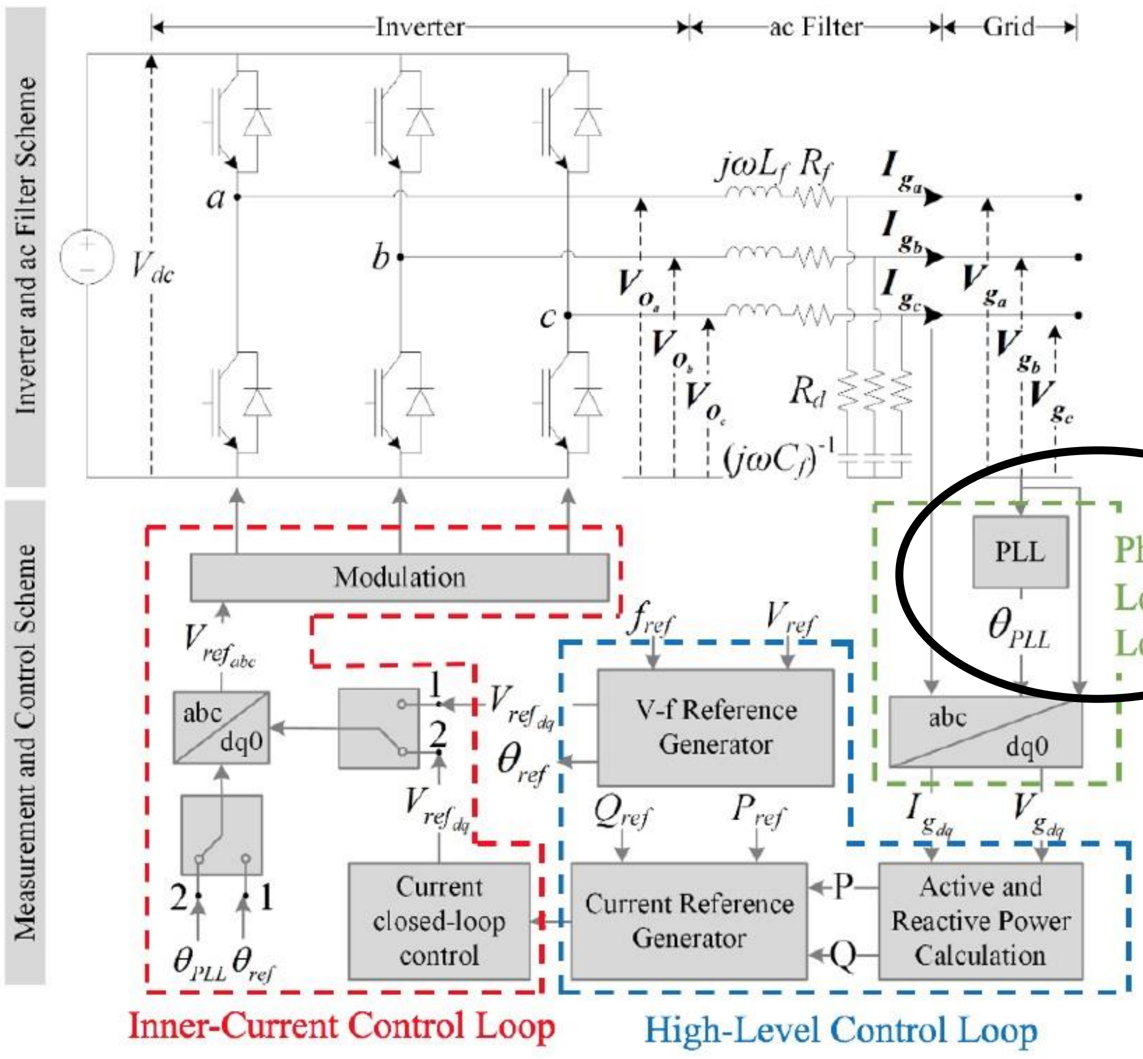
- Example: The November 2019 event in Queensland

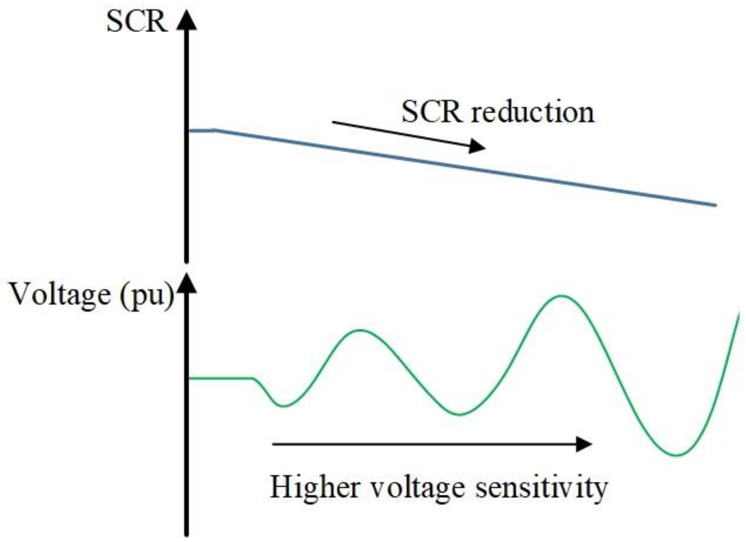
180 MW- 310 MW PV disconnection following the fault





Operational Challenges/Solutions in Weak Grids
Inverter-driven Instability Issues



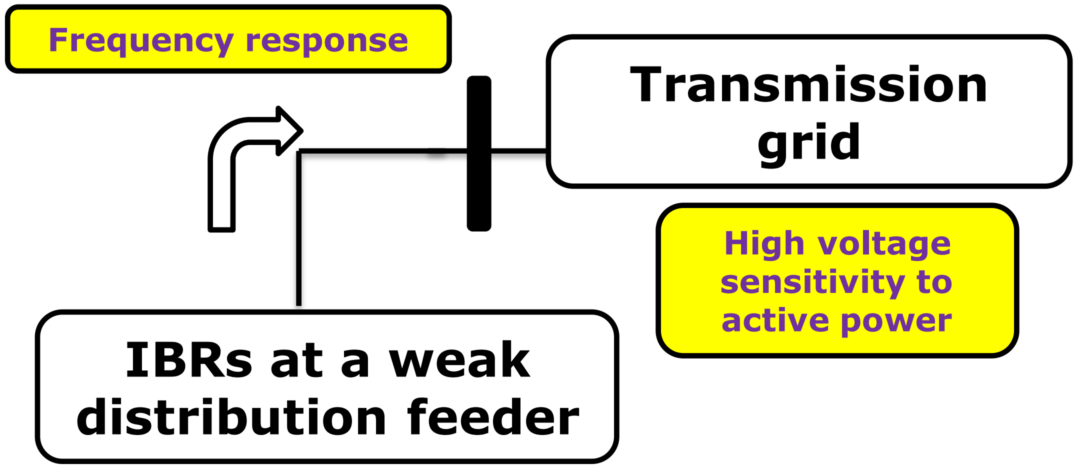


Solution: Advanced Inverter Control!

IEEE Power System Dynamic Performance Committee, "Task force on stability definitions and characterization of dynamic behaviour in systems with high penetration of power electronic interfaced technologies," Tech. Rep., May 2020.

Operational Challenges in Weak Grids
Interactions in System Support Services

- The delivery of one system stability service to meet a specific system need may **negatively impact** another system need, e.g.,
  - ✓ System stability service: frequency control response
  - ✓ System need #1: frequency stability
  - ✓ System need #2: voltage control



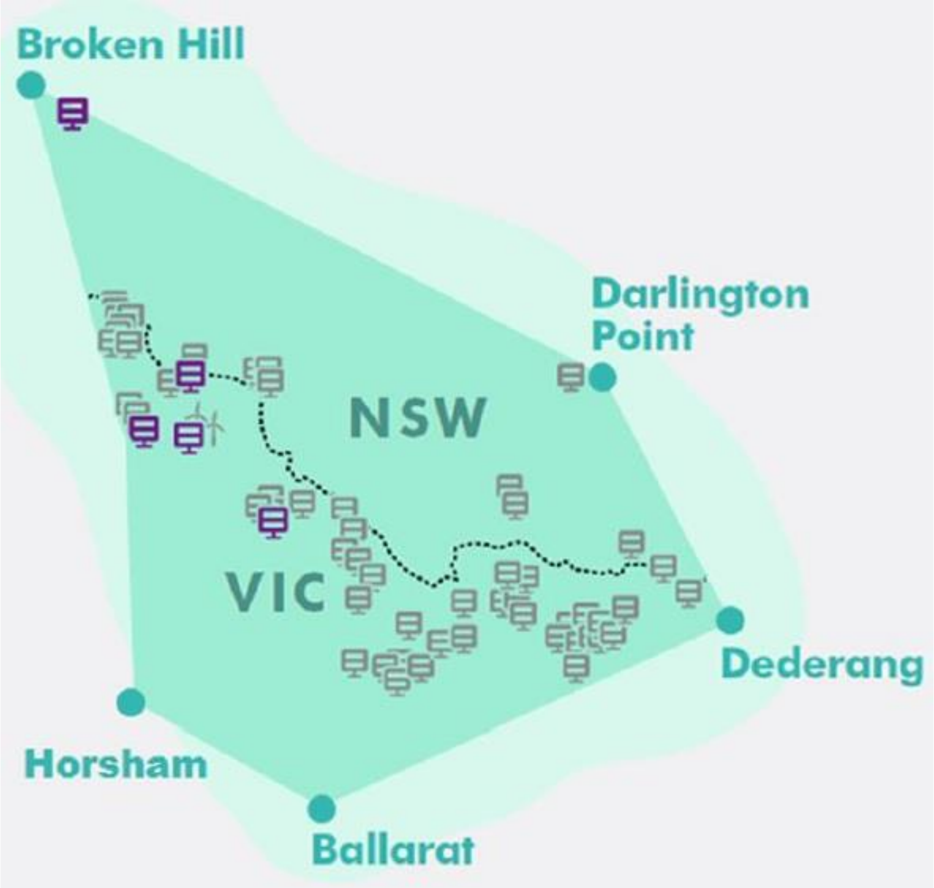
- This is something that **market does not consider**!
- This is **not** an inverter-driven issue!
- System physical characteristics and operating point may lead to such interactions!

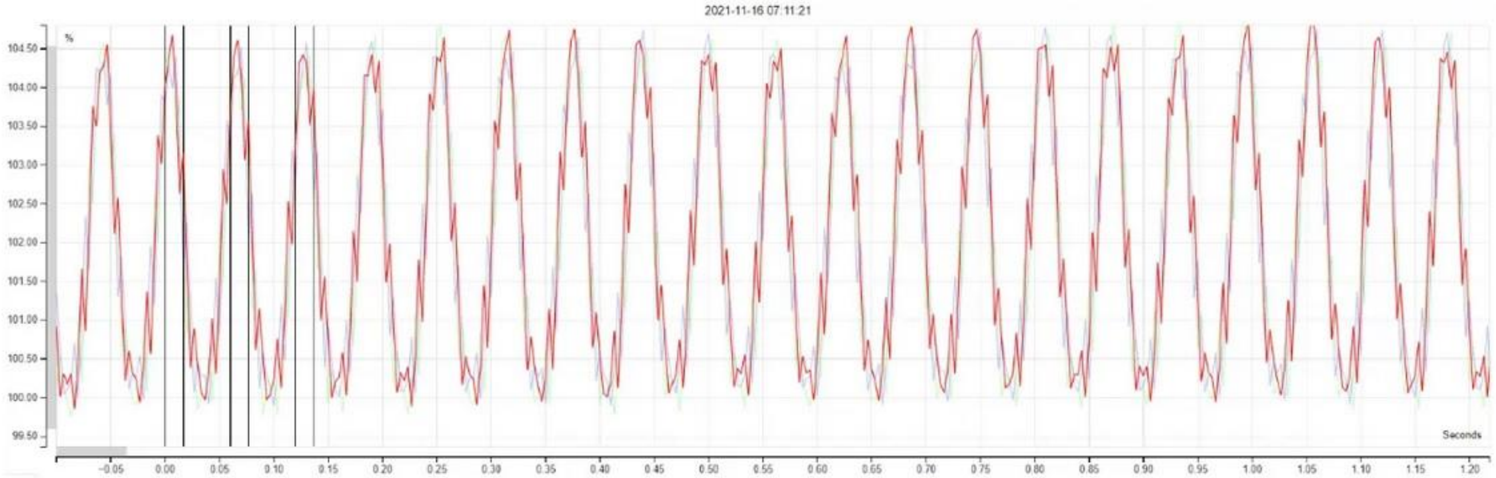
M. Ghazavi Dozein, B. C. Pal and P. Mancarella, "Dynamics of Inverter-Based Resources in Weak Distribution Grids," in *IEEE Transactions on Power Systems*, 2022.

Operational Challenges in Weak Grids
Small-signal Oscillating Phenomena

- Weak systems are prone to small-signal oscillating phenomena due to several reasons
  - ✓ Cross IBR interactions and instabilities
  - ✓ Poor PLL performance and implementation
  - ✓ Poor IBR current control tunning
  - ✓ Weak grid characteristics (high impedances, low fault level, low SCR)
  - ✓ High IBR penetrations
  - ✓ …..

Real-life Example: West Murray Region



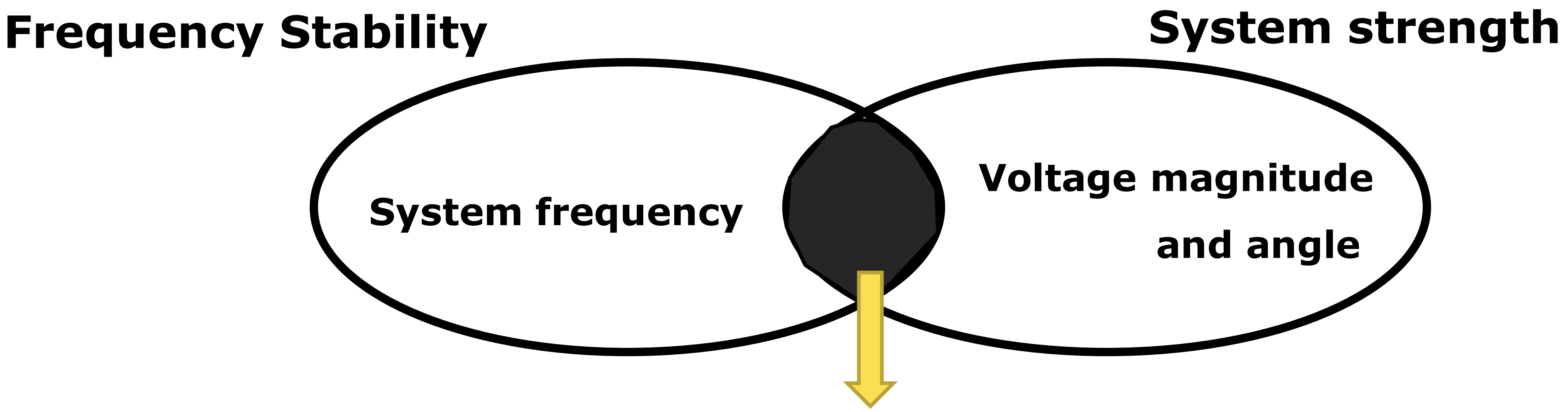


AEMO, “West Murray”, AEMO Website, Nov 2021.

Solution: 50% renewable generation constraint was issued by AEMO + IBR disconnections

Zone of Overlap

System strength and Frequency stability



IBR control instability

Small-signal instability

Cascading events

Other operational issues in weak grids

- There are other challenges in the operation of weak grids:
  - ✓ Power quality issues
  - ✓ System protection issues
  - ✓ System monitoring issues
  - ✓ etc

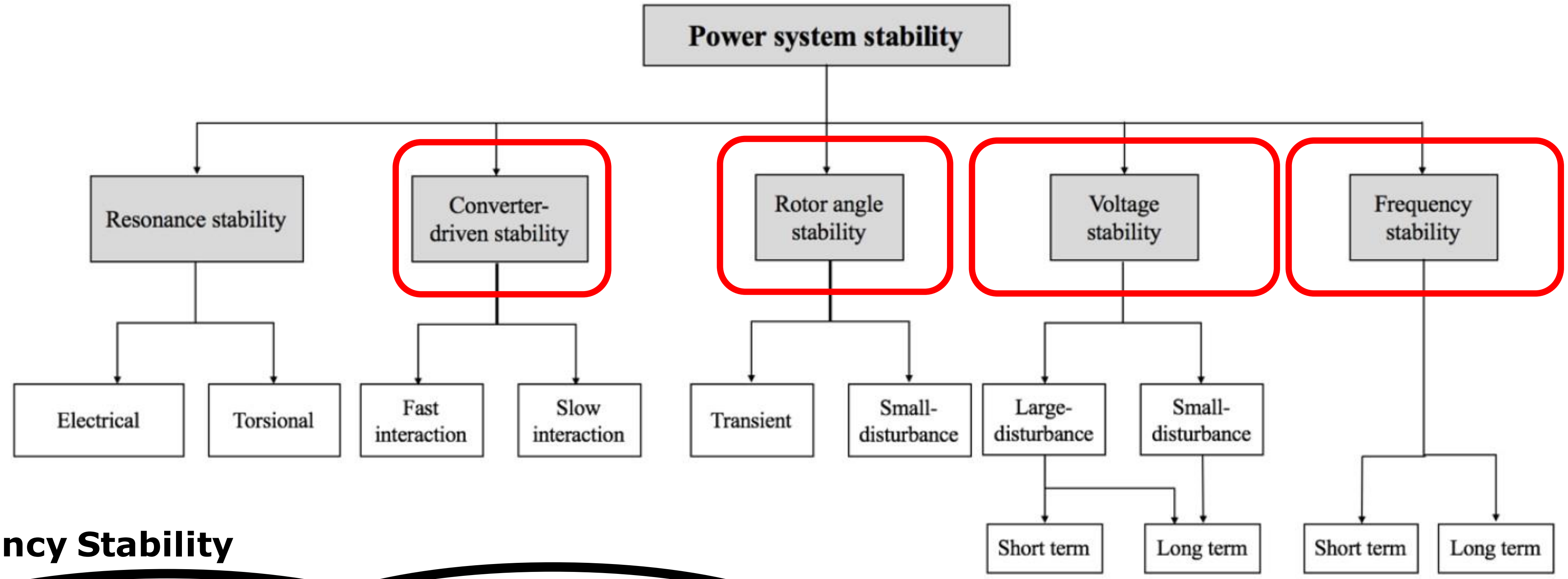
Project with Reactive Technology

THE UNIVERSITY OF MELBOURNE

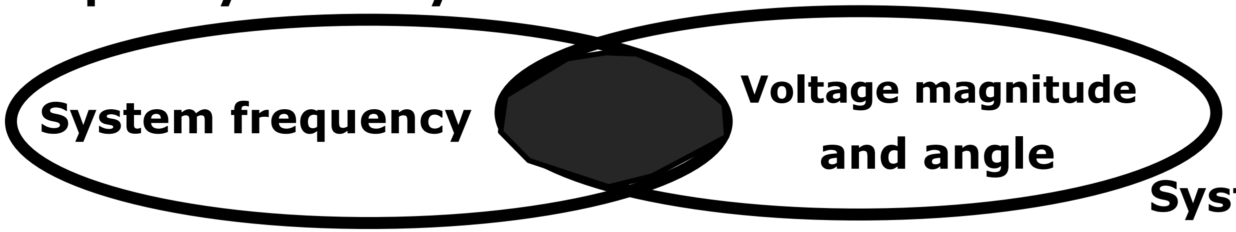
reactive technologies

System Strength: A Techno-Economic Study

Final Remark



Frequency Stability



System strength

IEEE Power System Dynamic Performance Committee, "Task force on stability definitions and characterization of dynamic behaviour in systems with high penetration of power electronic interfaced technologies," Tech. Rep., May 2020.

Dynamics and Control of Renewable-Rich Power Systems: The Australian NEM Case

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