Physics, engineering and economics of new essential system services

Prof Pierluigi Mancarella, FIEEE

Chair of Electrical Power Systems

The University of Melbourne

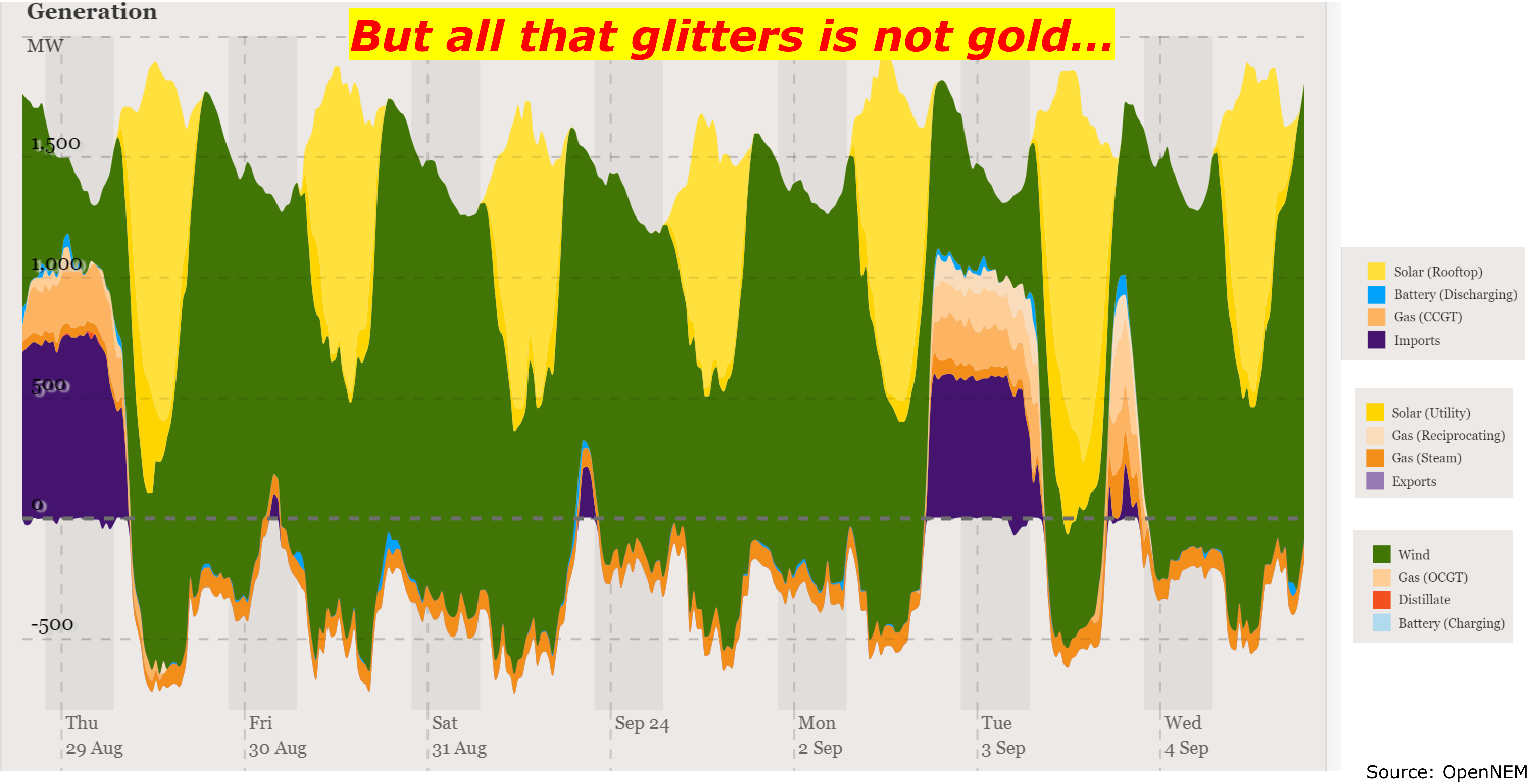
pierluigi.mancarella@unimelb.edu.au

EPICS International Meeting

CSIRO, Newcastle, Australia

January 2026

Fast forward to the future!



Source: OpenNEM

"New" physics and the "fragile grid"

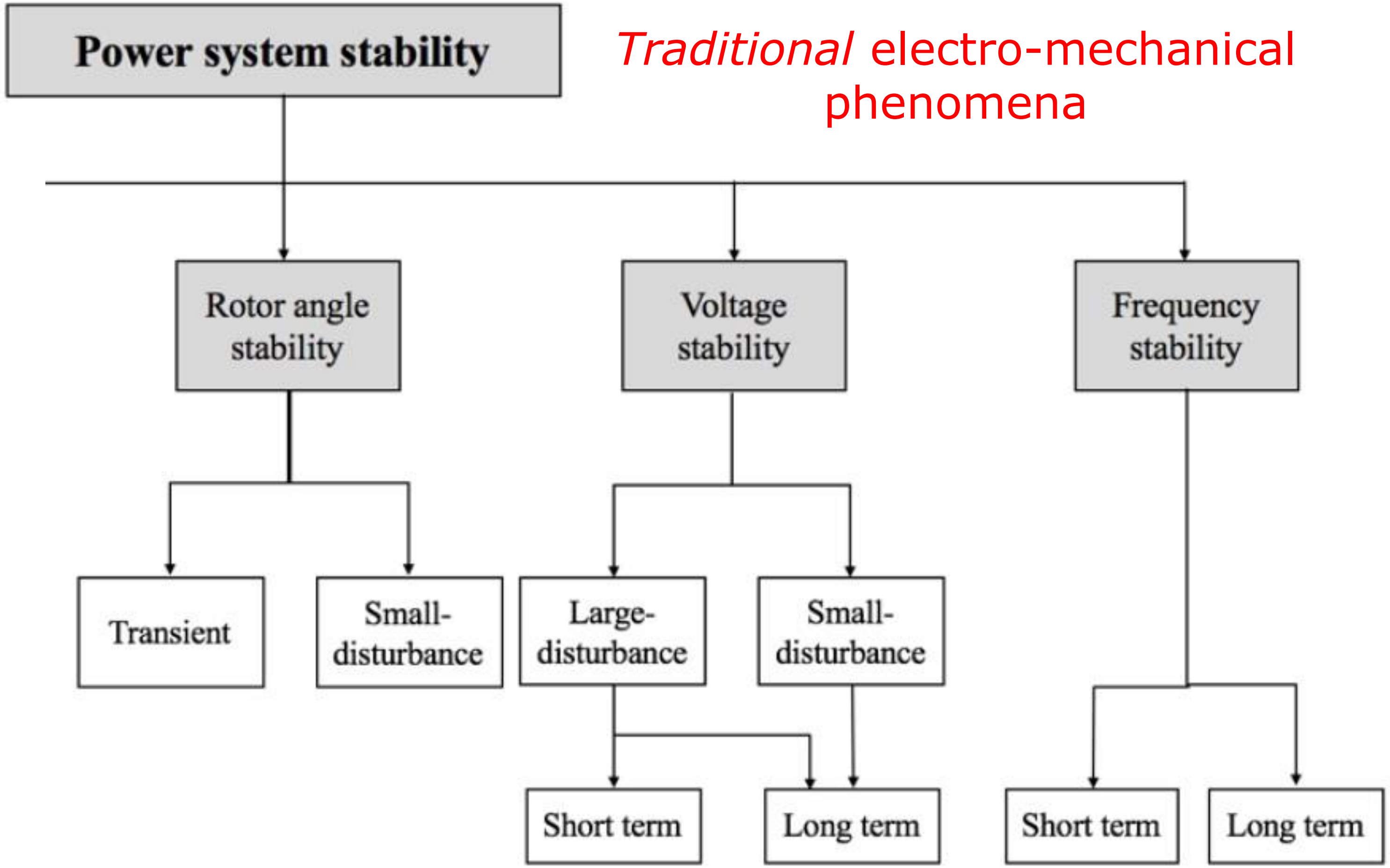
Risk	Emerging issues	Possible Mitigations
Frequency control and inertia	- Sustained frequency excursions (regulation) - High ROCOF following contingency - Insufficient regional inertia - Insufficient PFR - Risk of low-inertia and insufficient PFR after separation	- Minimum inertia levels - Compulsory droop response - Additional amount of PFR - Co-optimization of energy, frequency response, and (regional and system-level) inertia - Regional allocation of reserves - New sources of fast frequency response (e.g., batteries, electrolysers) - Management of largest contingency and interconnector flows (system at risk of regional separation)
Variability, uncertainty and visibility	- Large variation in net demand - Insufficient short- and medium-term and ramping reserves - Visibility of Distributed Energy Resources (DER)	- Better forecasting - Artificial intelligence to assess reserves (e.g., dynamic Bayesian belief network tools) - Use of more flexible resources including energy storage (e.g., pumped hydro)
System strength and immunity	- Fault current shortage - Voltage instability - Sustained voltage oscillations after fault - Fault-ride through issues - Minimum demand issues	- Minimum level of inertia and fault current (generators constrained on) - Synchronous condensers - STATCOM and SVC to improve voltage stability - Improvements of control loops (especially in solar farms) - Grid forming inverters

P. Mancarella and F. Billimoria, '**The Fragile Grid** – The physics and economics of security services in low-carbon power systems", *IEEE Power and Energy Magazine*, 2021

P. Mancarella, "**Electricity grid fragility and resilience in a future net-zero carbon economy**", *Oxford Energy Forum – Electricity Networks in a Net-Zero-Carbon Economy*, 124, pages 41-45, Sept 2020

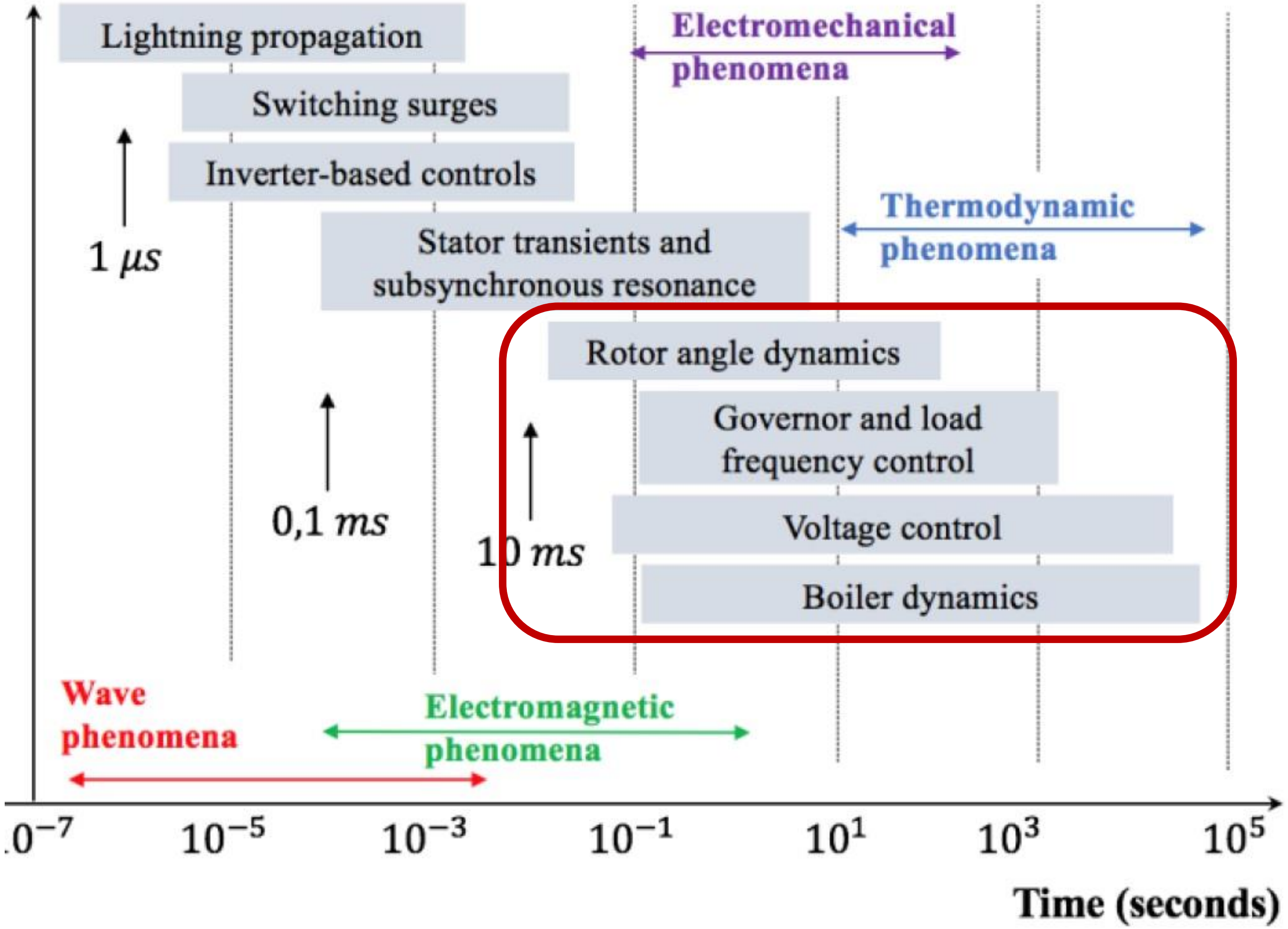
Power system stability classification

Traditional electro-mechanical phenomena



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,", 2020.

Power system timescales



Traditional electro-mechanical phenomena

Historical power system variables have been fundamentally influenced by the *physical characteristics of synchronous machines* and *their controls*

How can we synthetically characterise ‘classical’ power systems with respect to their stability performance?

Power system **variables** and stability types have historically been primarily influenced by the **physical characteristics** of **synchronous machines**

Voltages

System strength

Angles and frequency

Inertia

How can we synthetically characterise 'classical' power systems with respect to their stability performance?

Power system **variables** and stability types have historically been primarily influenced by the **physical characteristics** of **synchronous machines**

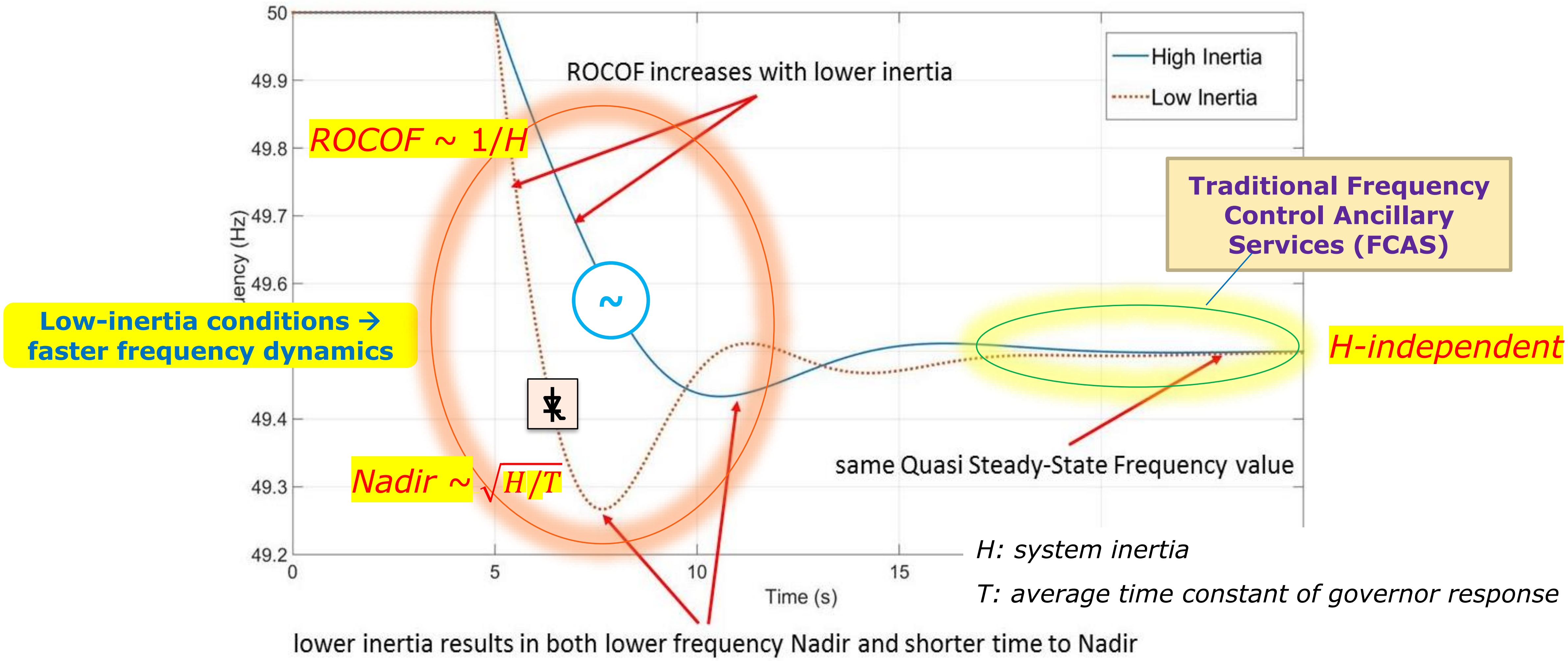
Voltages

System strength

Angles and frequency

Inertia

Frequency control challenges in low-inertia systems

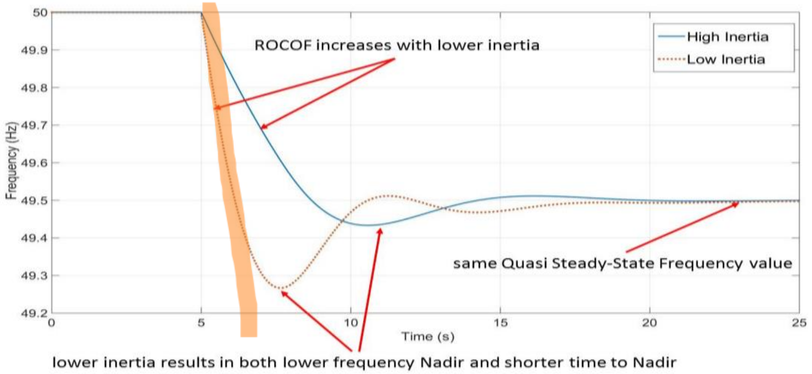


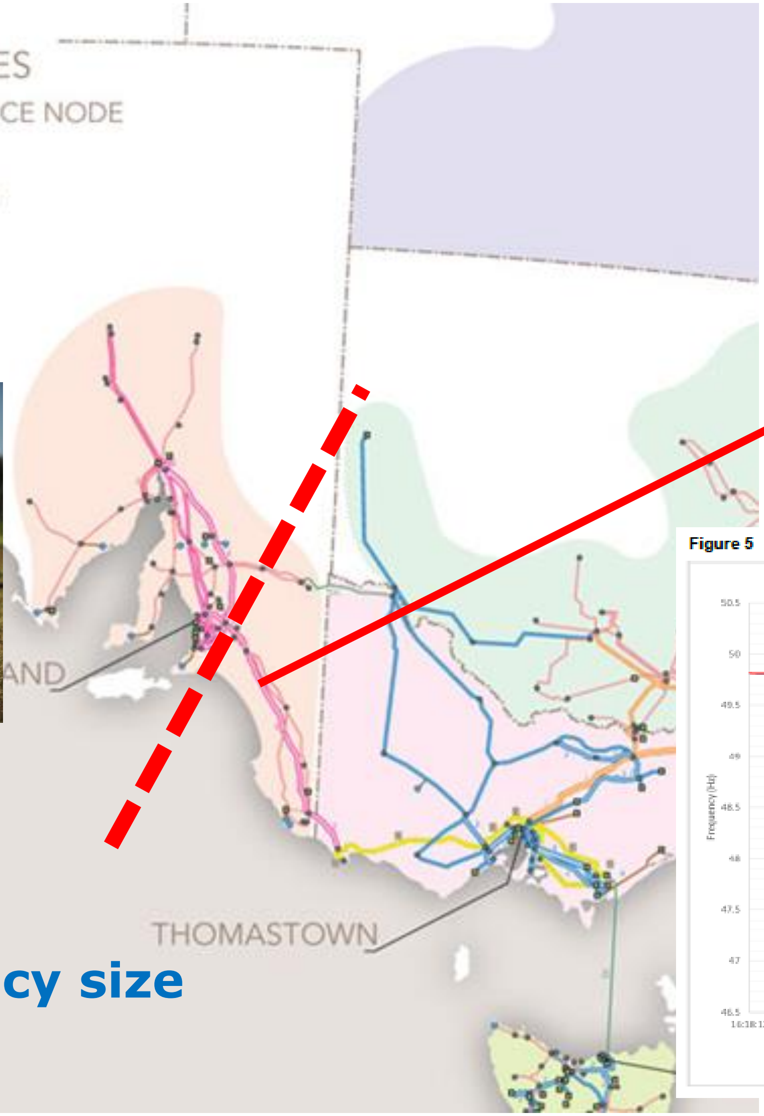
H: system inertia

T: average time constant of governor response

P. Mancarella et al., "*Power system security assessment of the future National Electricity Market*", Report in support of the "Finkel Review", June 2017

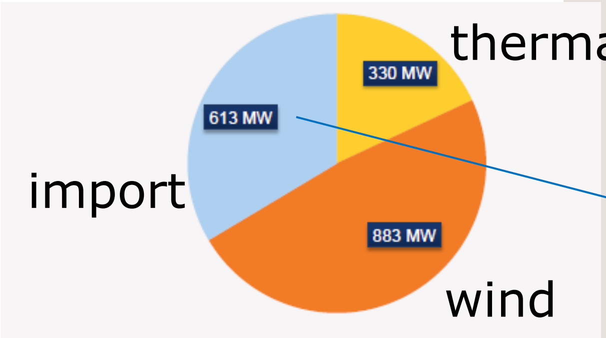
The first textbook example: The 2016 "black system" event



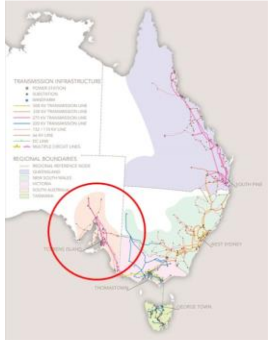


Source: ABC

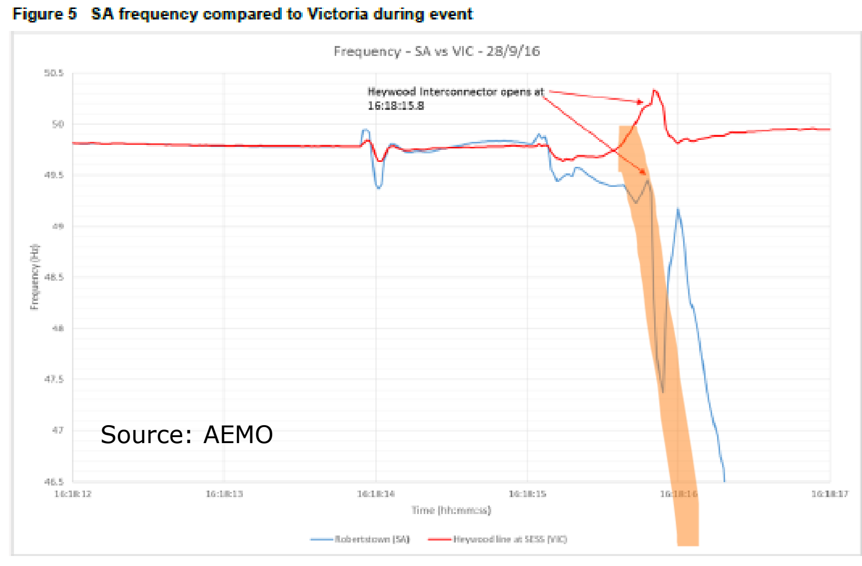
Source: AEMO



contingency size



Heywood AC Interconnector



Source: AEMO

How can we synthetically characterise ‘classical’ power systems with respect to their stability performance?

Power system **variables** and stability types have historically been primarily influenced by the **physical characteristics** of **synchronous machines**

Voltages

System strength

Angles and frequency

Inertia

How can we synthetically characterise 'classical' power systems with respect to their stability performance?

Power system **variables** and stability types have historically been primarily influenced by the **physical characteristics** of **synchronous machines**

Voltages

System strength

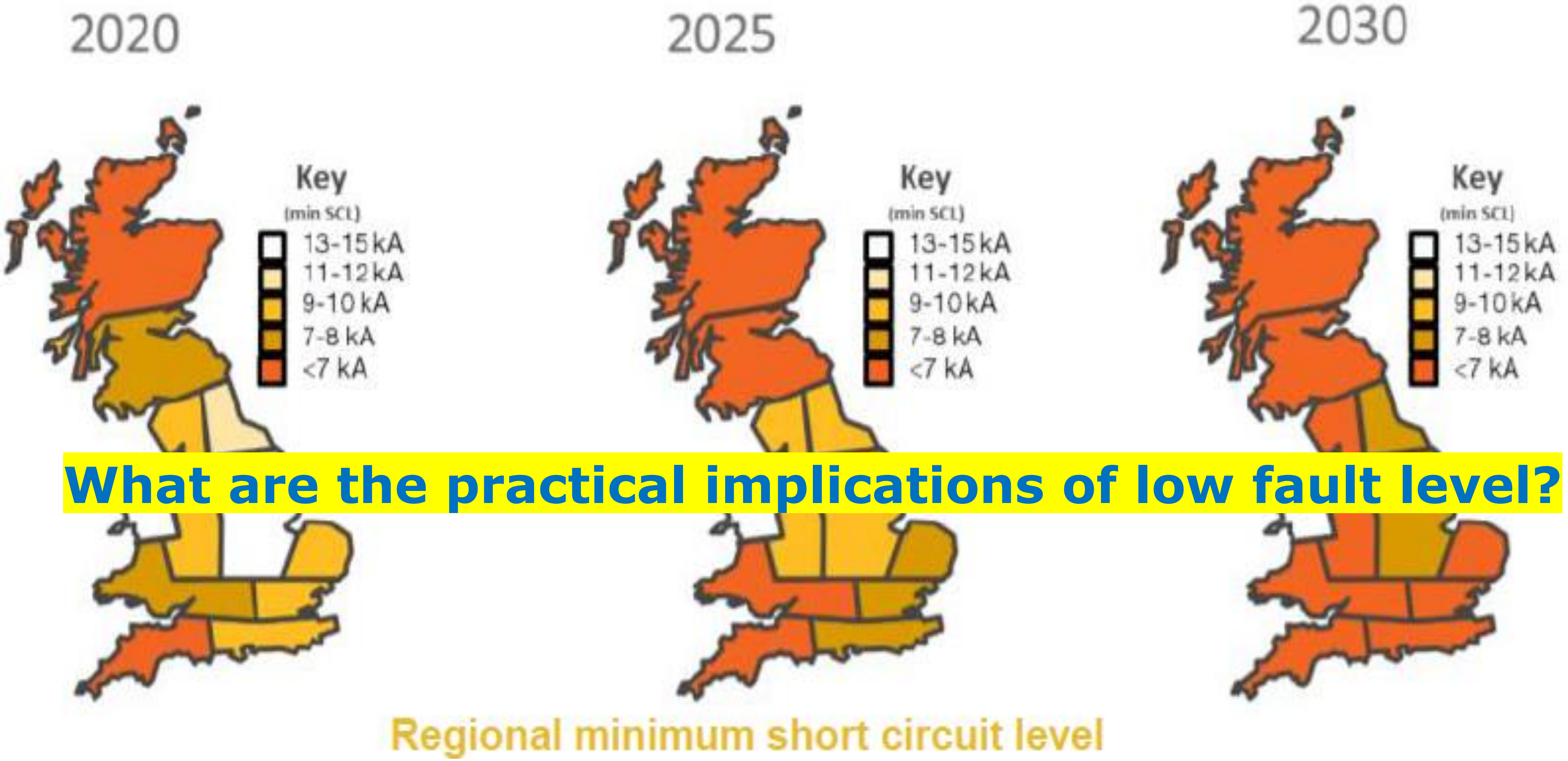
Sensitivity of voltage to power injection
≈
fault current

Angles and frequency

Inertia

System strength without coal power plants…

Projected system strength (fault levels) across GB from 2020 to 2030

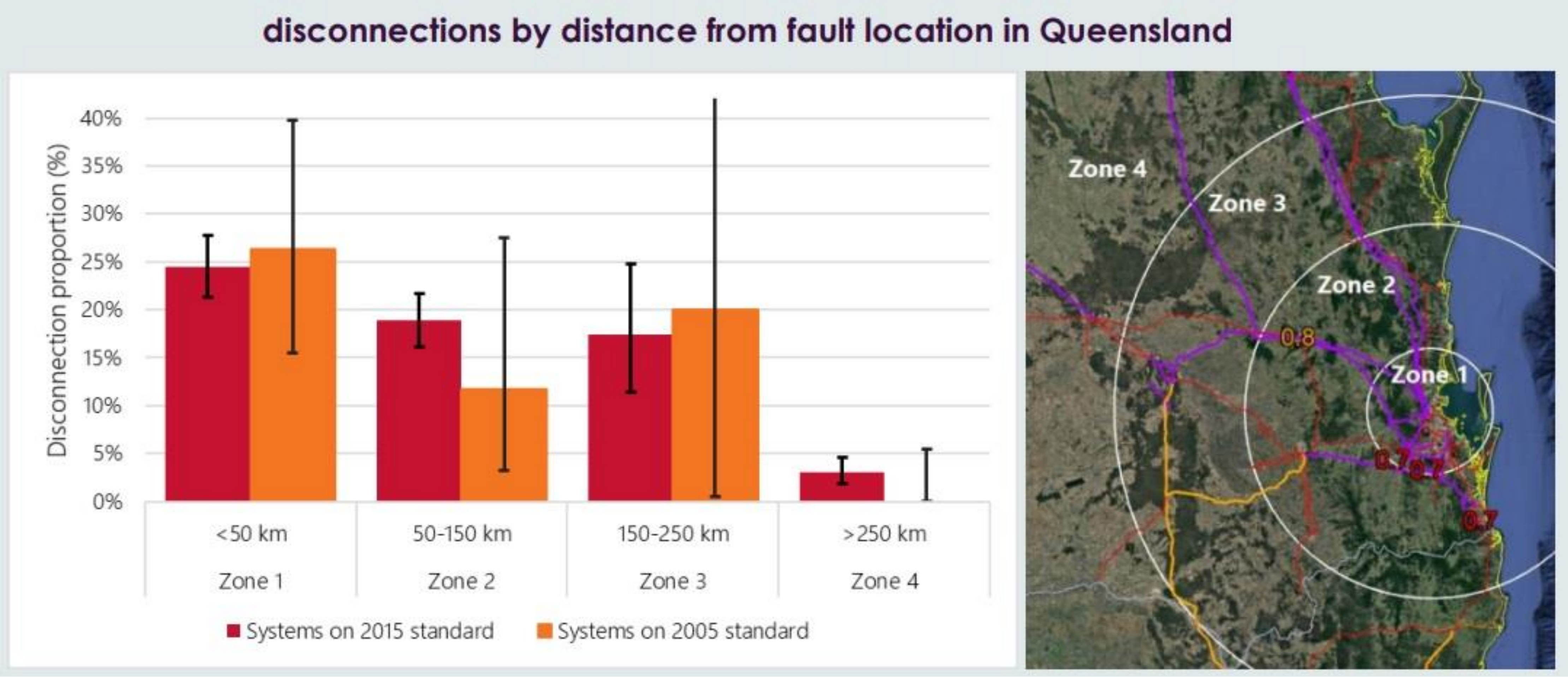


What are the practical implications of low fault level?

Source: NG ESO

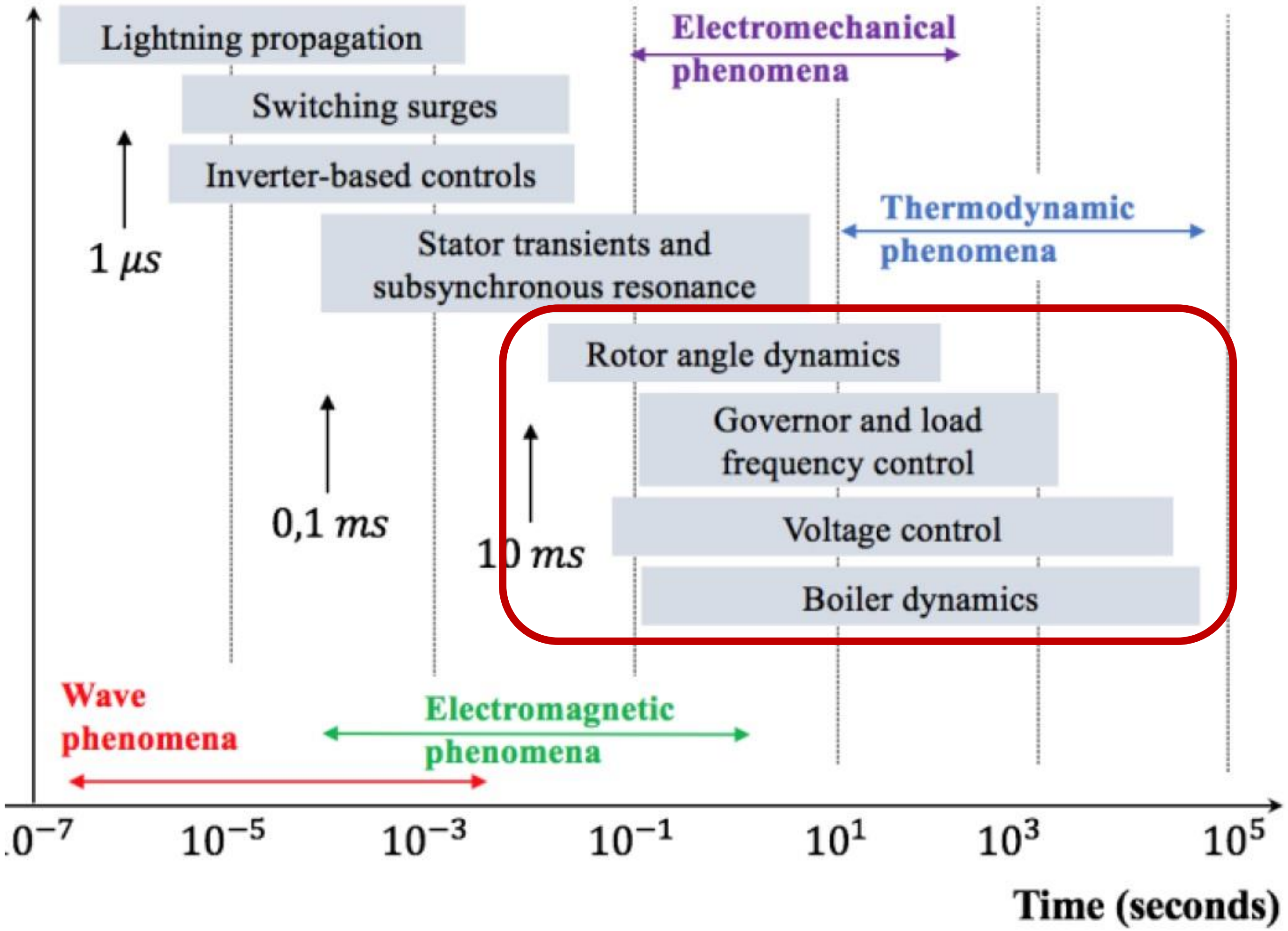
Fault level reduction impact on sympathetic DER tripping: November 2019

180 MW-310 MW PV disconnection following a fault



Source: AEMO

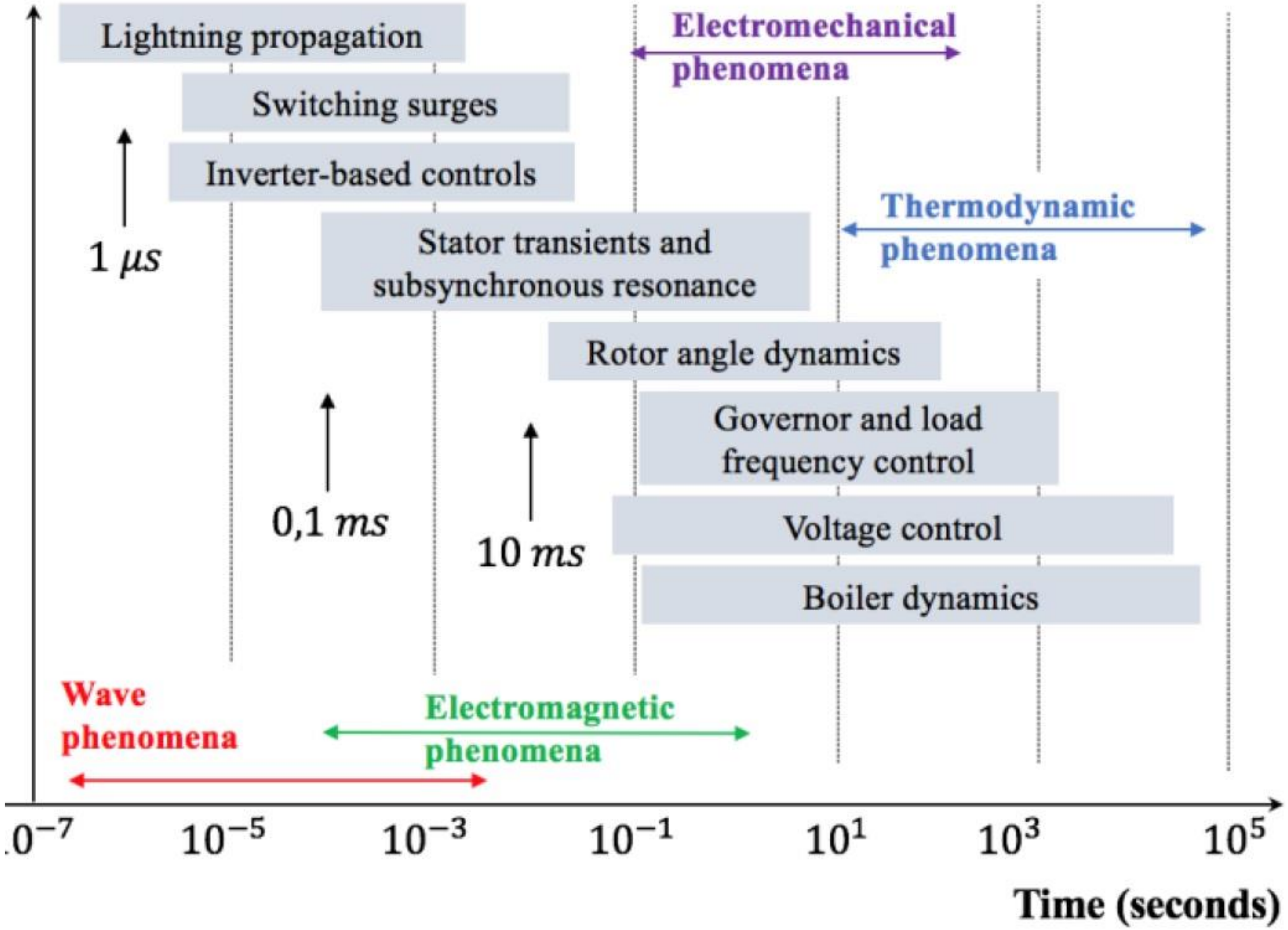
Power system timescales



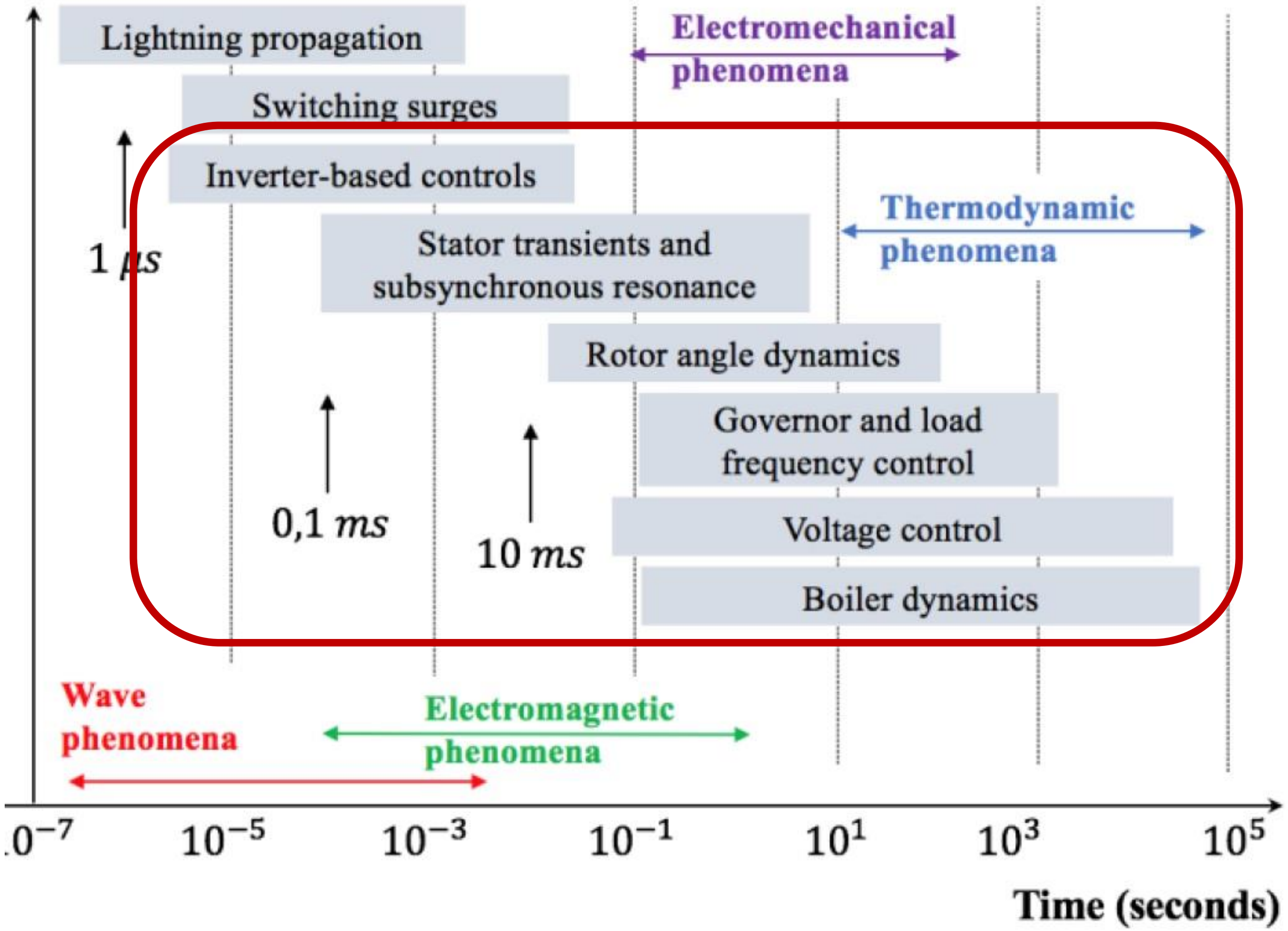
Traditional electro-mechanical phenomena

Historical power system variables have been fundamentally influenced by the *physical characteristics of synchronous machines* and *their controls*

Power system timescales



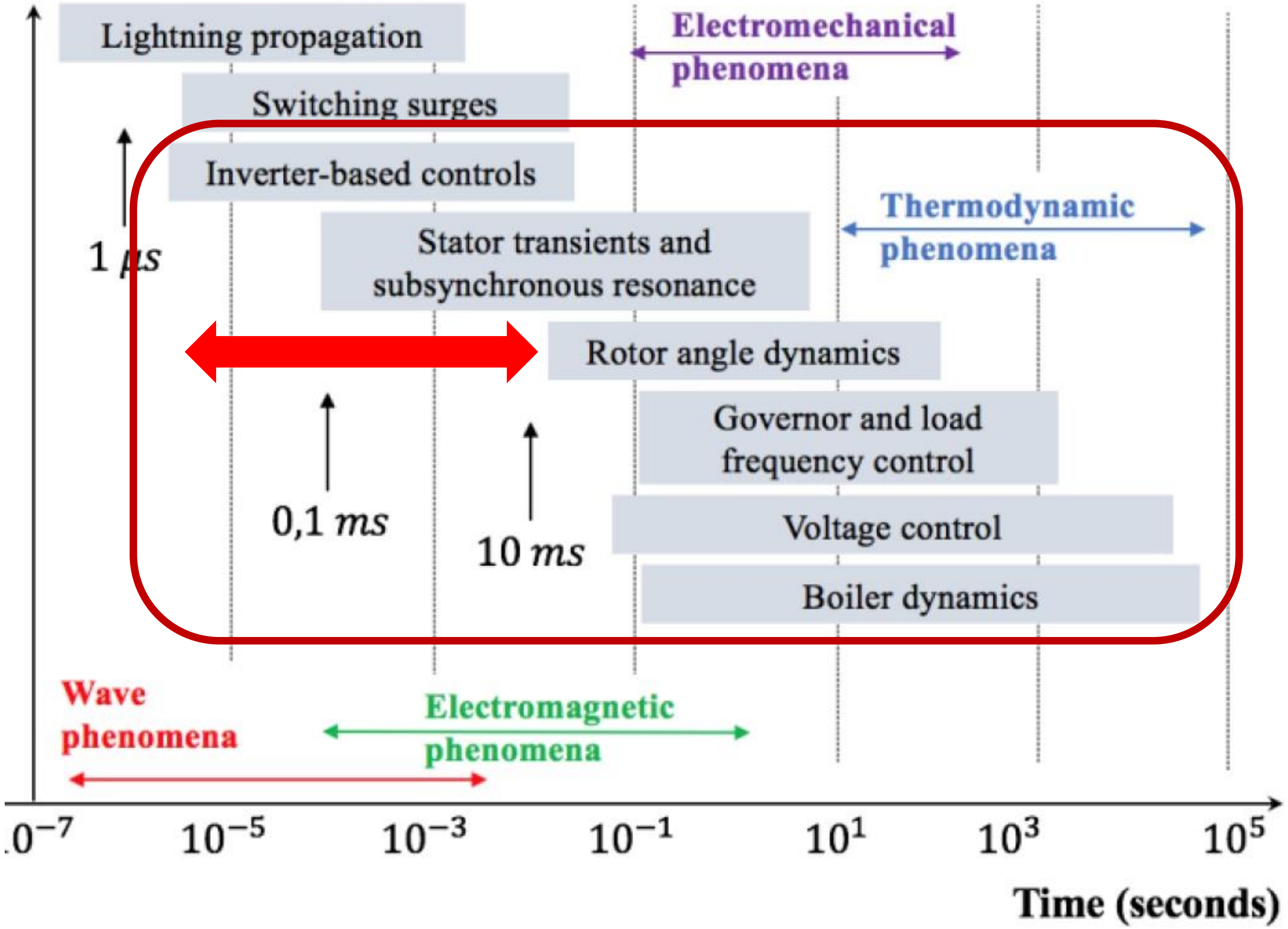
Power system timescales



Electro-mechanical phenomena and **IBR *fast controls***

***Controls* dominate the dynamics of IBRs (and IBR-rich systems)**

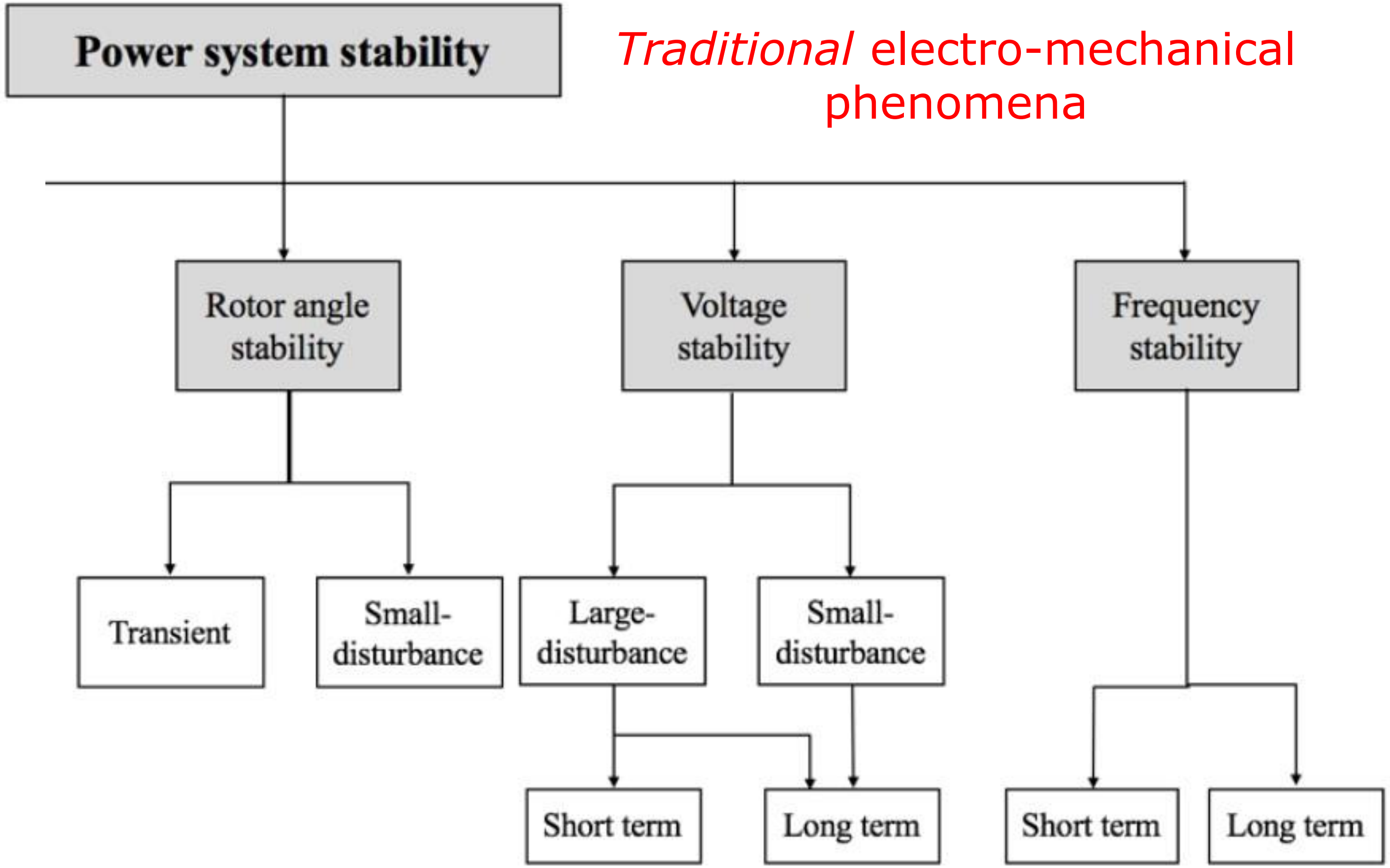
Power system timescales



Electro-mechanical phenomena and **IBR *fast controls***

System dynamics become *much faster* and at risk of *new instability issues*

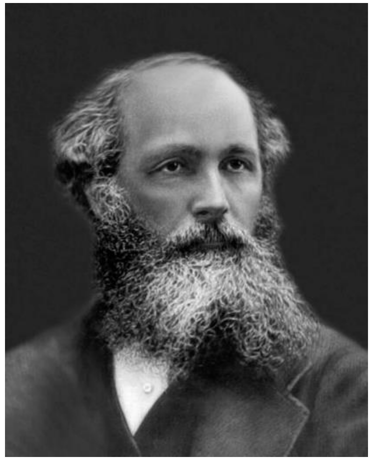
Power system stability classification

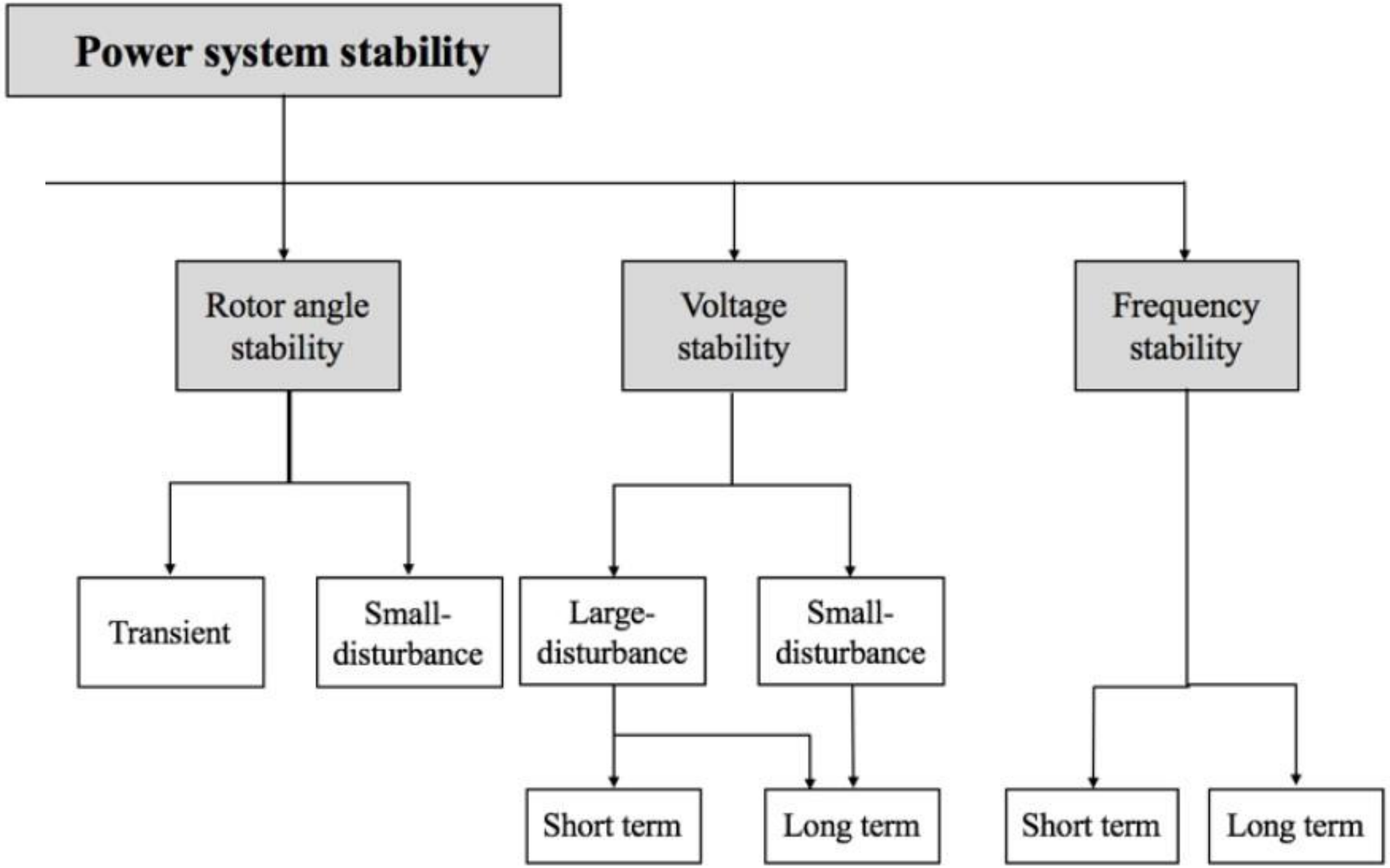


Traditional electro-mechanical phenomena

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,", 2020.

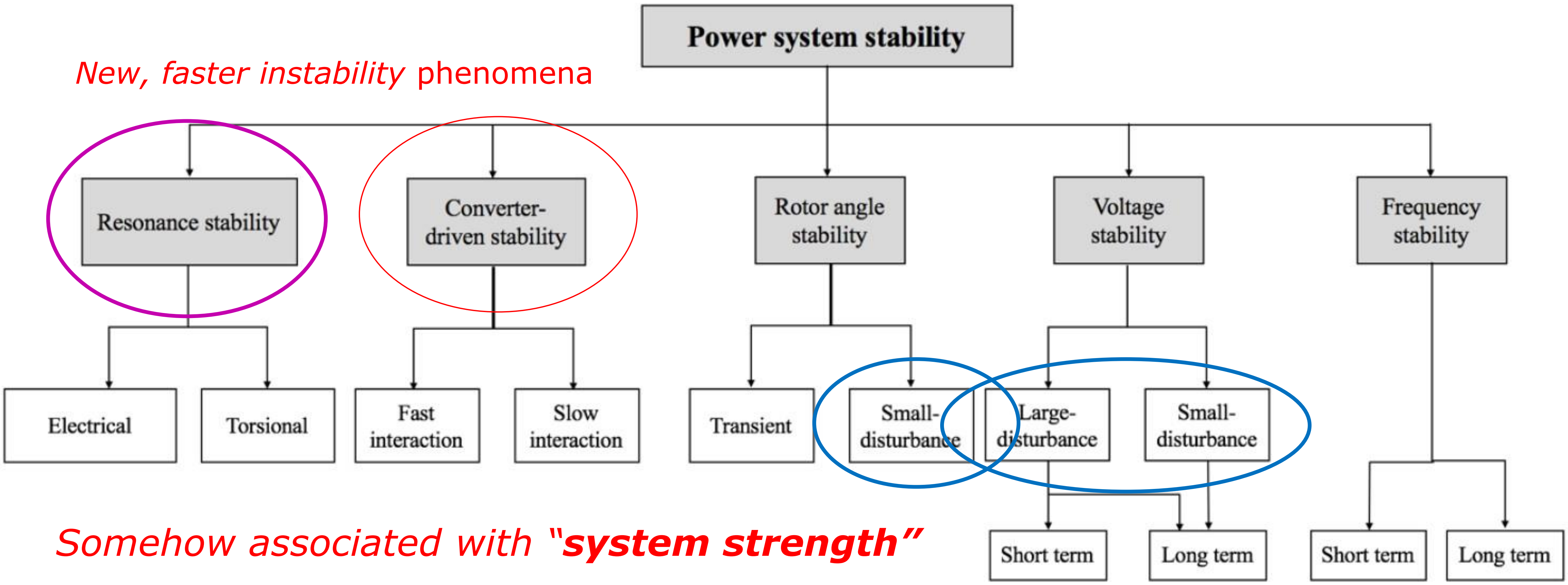
Power system stability classification





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,", 2020.

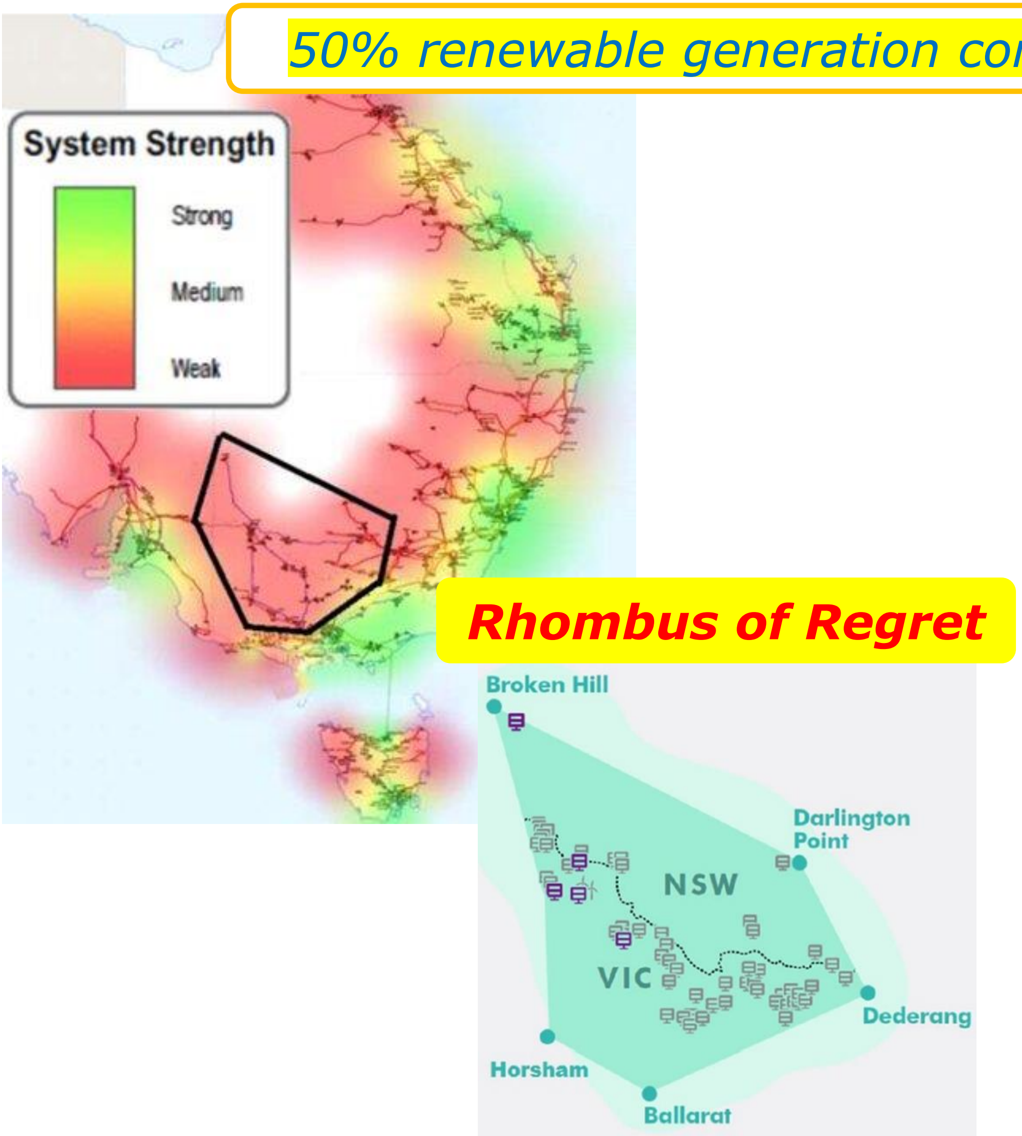
Power system stability classification



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,", 2020.

West Murray region sustained oscillations, 2020

50% renewable generation constraint, IBR disconnections, IBR control retuning



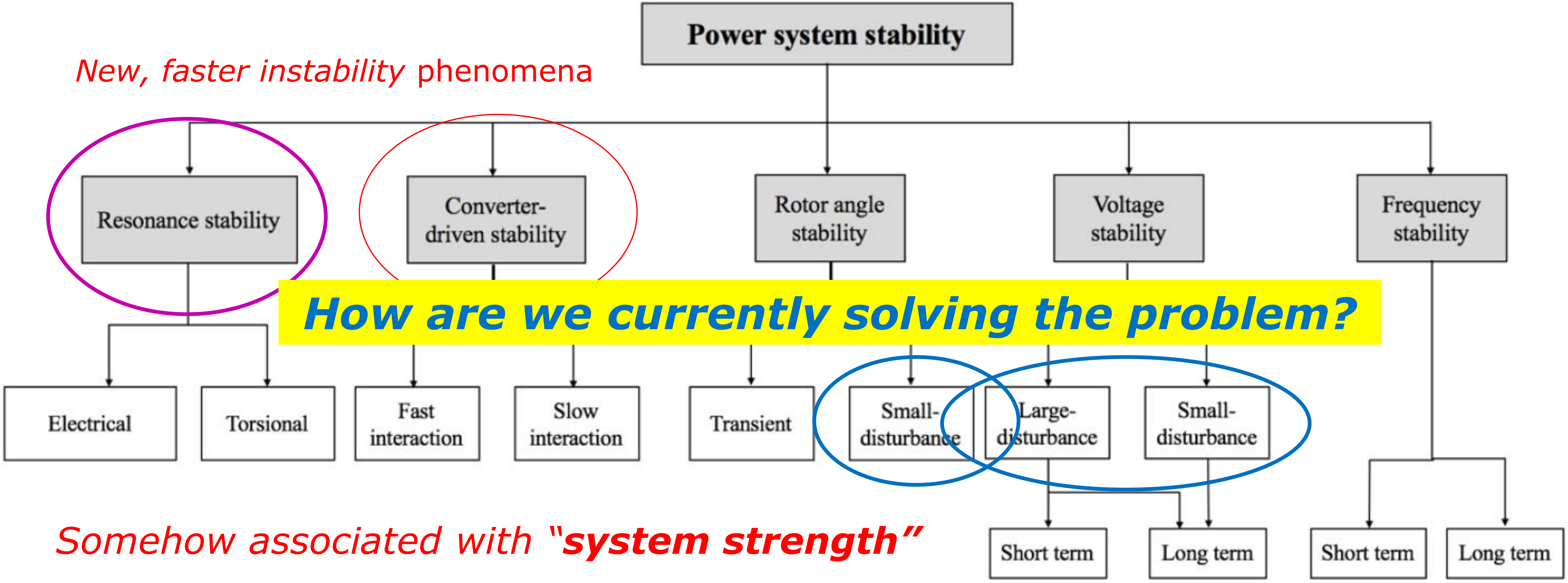
Oscillations occurring on 2 September 2020 with no known disturbance trigger

https://aemo.com.au/-/media/files/electricity/nem/network_connections/west-murray/high-level-summary-of-wmz-subsynchronous-oscillations.pdf?la=enh

Courtesy of Julius Susanto

Power system stability classification

New, faster instability phenomena



How are we currently solving the problem?

*Somehow associated with "**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,", 2020.

Source: IEEE Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies" 2020

Running an *old market* with the *new physics*

Next most widespread solution?

Why are these gas generators operating with negative market prices?

Source: AEMO and OpenNEM

F. Billimoria, P. Mancarella, R. Poudineh, "Market and regulatory frameworks for operational security in decarbonizing electricity systems: from physics to economics", *Oxford Open Energy*, Volume 1, January 2022, oiac007, https://doi.org/10.1093/ooenergy/oiac007

Progress by imitation

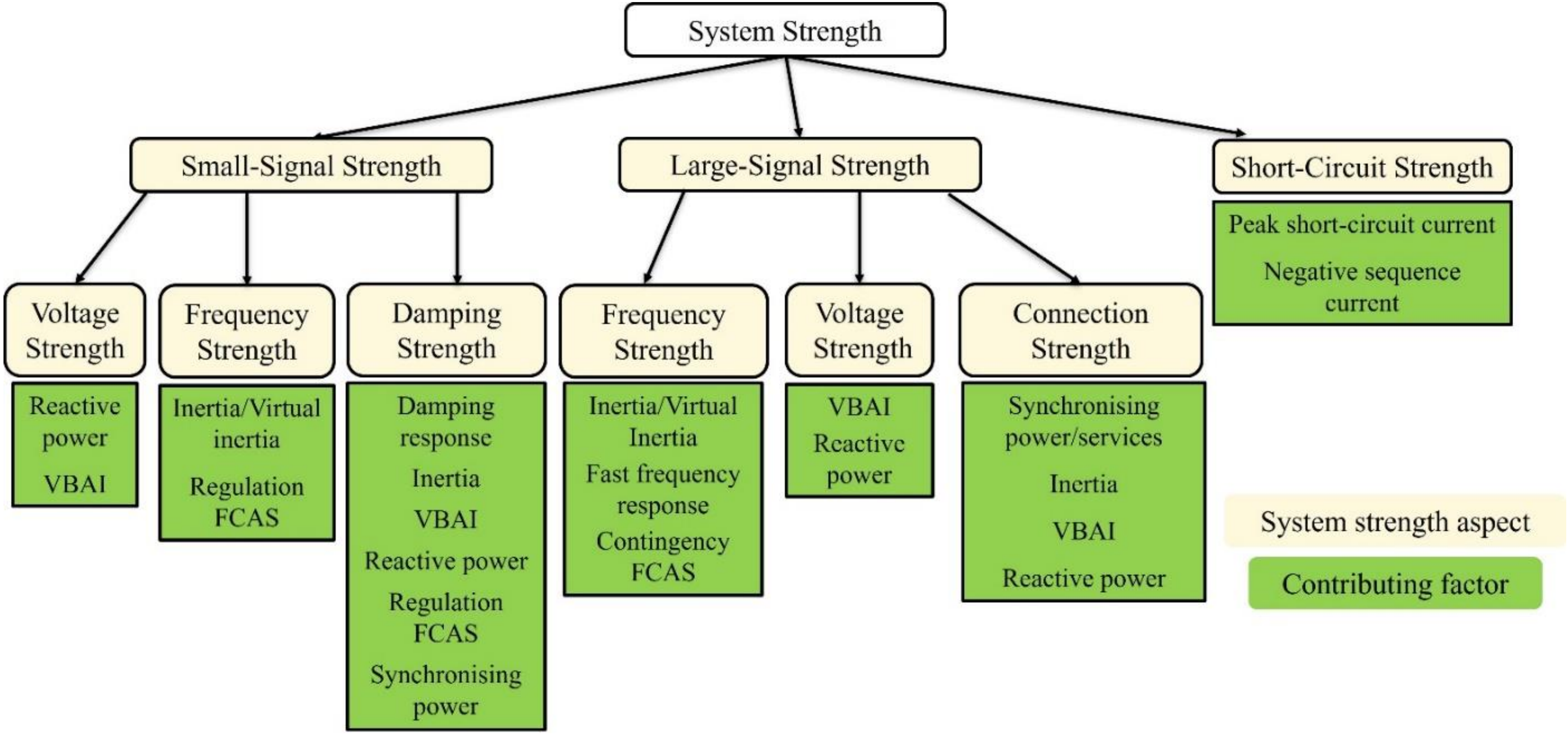

Source: Wikipedia


Pic sourced from the internet

But this is already a solution of a problem that is not clearly defined!

*What even is **"system strength"?***

What is "system strength"?



M. Ghazavi Dozein, B. Berry, J. V. Milanović, and P. Mancarella, "**System strength beyond fault level**", IEEE Access, 2025

New *engineering* options to deliver *system strength products*

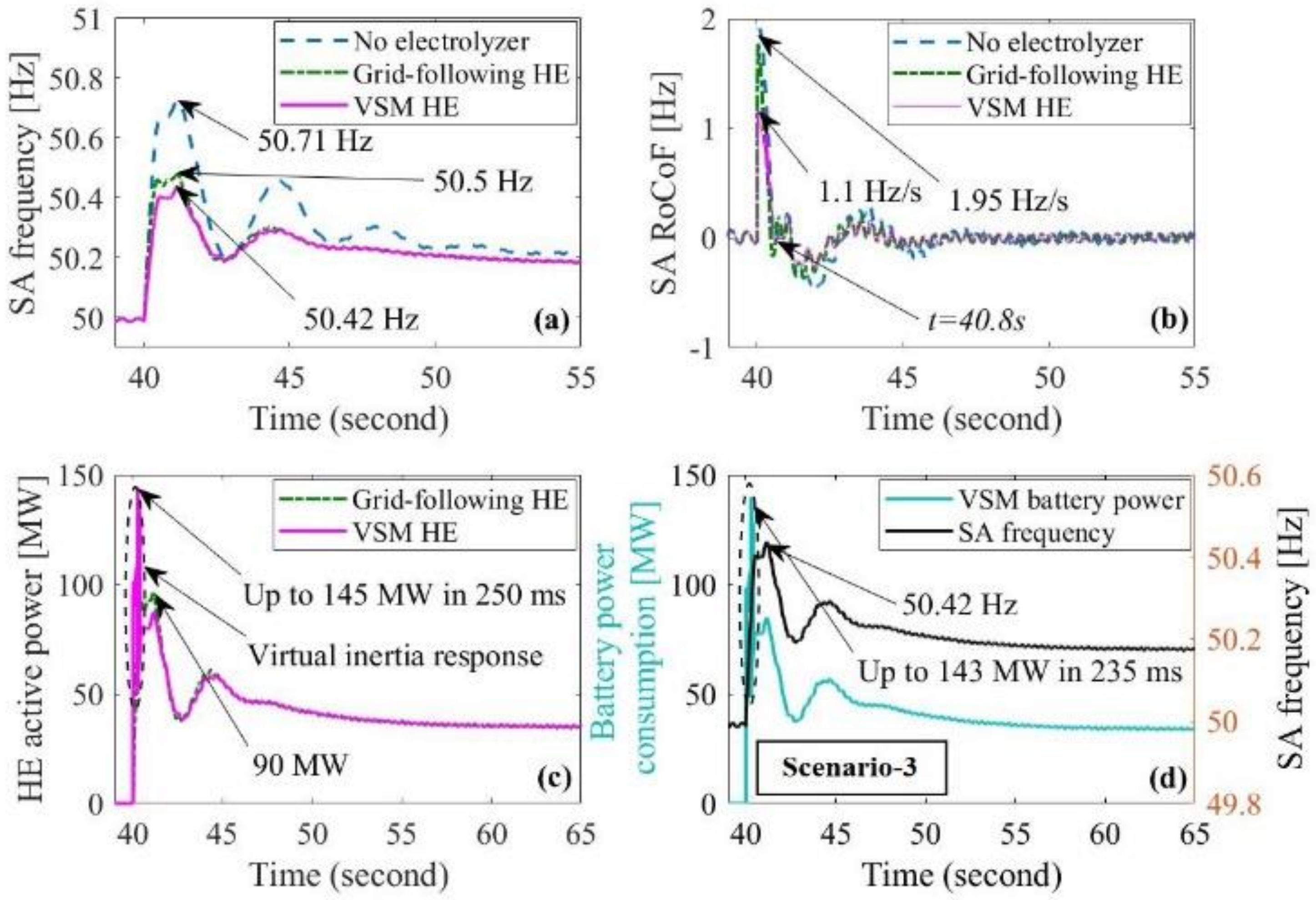
IBR Type		***Contributing Factors to System Strength***								
		Reactive power	VBAI	Virtual inertia	FFR	Cont. FCAS	Regulation FCAS	Peak current/negative component current	Damping	Synchronizing power/services
Grid following	Legacy									
	Enhanced									
Grid forming	Type 1									
	Type 2									
	Type 3									
	Type 4									

GFM currently under demonstration at scale…

But definitely it's not only about rotating machines…

M. Ghazavi Dozein, B. Berry, J. V. Milanović, and P. Mancarella, "**System strength beyond fault level**", IEEE Access, 2025

… and not only batteries either!
System services from *inverter-based loads*



M. Ghazavi Dozein, *et al.*, "**Fast frequency response** from utility scale hydrogen electrolysers", *IEEE Trans. Sustainable Energy*, 2021

M. Ghazavi Dozein, *et al.*, "**Virtual Inertia** Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers", *IEEE Tran. on Pow. Syst*, 2022

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

Final remarks

- "**New physics**" of power systems
- **Controls** increasingly dominate system dynamics
- The "new" grid is *more* ***fragile*** than the "old grid"
- **New security services** need to be appropriately and "granularly" **defined** (in space and time)
  - *To allow for economic efficiency, co-optimization and pricing, and fair resource competition*
  - Essential to consider the opportunities offered by new, **IBR**
- Markets need to increasingly align with the physics to avoid catastrophic events
  - See South Australia (2016) and the Iberian peninsula (2025)…

P. Mancarella and F. Billimoria, 'The Fragile Grid – Physics and economics of security services in low-carbon power systems: The case of Australia", *IEEE Power & Energy Magazine*, 2021
F. Billimoria *et al.*, "Market and regulatory frameworks for operational security in decarbonising electricity systems: from physics to economics", *Oxford Open Energy,* 2022

Selected references on low-carbon grid operation, services and markets

- M. Ghazavi Dozein, B. Berry, J. V. Milanović, and P. Mancarella, “System strength beyond fault level”, *IEEE Access*, 2025
- P. Mancarella and F. Billimoria, ‘The Fragile Grid – The physics and economics of security services in low-carbon power systems”, *IEEE Power and Energy Magazine*, 2021
- P. Mancarella, “Electricity grid fragility and resilience in a future net-zero carbon economy”, *Oxford Energy Forum – Electricity Networks in a Net-Zero-Carbon Economy*, 124, pages 41-45, Sept 2020
- F. Billimoria, P. Mancarella, R. Poudineh, “Market and regulatory frameworks for operational security in decarbonizing electricity systems: from physics to economics”, *Oxford Open Energy*, Vol. 1, Jan. 2022
- J. Eggleston, *et al.*, “From security to resilience: technical and regulatory options to manage extreme events in low-carbon grids”, *IEEE Power & Energy Magazine*, Sept/Oct 2021
- S. Püschel-Løvengreen, M. Ghazavi Dozein, S. Low, P. Mancarella, “Separation event-constrained optimal power flow to enhance resilience in low-inertia power systems”, *Elec. Pow. Syst. Res.*, 2020, 189, 106678
- P. Mancarella et al., “*Power system security assessment of the future National Electricity Market”*, Report in support of the “Finkel Review”, June 2017

Selected references on dynamics of low-carbon grids

- S. D. Tavakoli, *et al.*, "Grid-Forming Services From Hydrogen Electrolyzers", *IEEE Transactions on Sustainable Energy*, 2023
- M. Ghazavi Dozein, *et al.*, "Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers", *IEEE Transactions on Power Systems*, 2022
- M. Ghazavi Dozein, B. Pal, P. Mancarella, "Dynamics of Inverter-Based Resources in Weak Distribution Grids", *IEEE Transactions on Power Systems*, 2022
- M. Ghazavi, A. Jalali, and P. Mancarella, "Fast frequency response from utility scale hydrogen electrolysers", *IEEE Transactions on Sustainable Energy*, 2021
- L. Meegahapola, P. Mancarella, D. Flynn, and R. Moreno, "Power System Stability in the Transition to a Low Carbon Grid: A Techno-Economic Perspective on Challenges and Opportunities", *Wyres Energy and Environment*, 2021, Invited Paper
- M. Ghazavi Dozein, O. Gomis-Bellmunt and P. Mancarella, "Simultaneous Provision of Dynamic Active and Reactive Power Response from Utility-scale Battery Energy Storage Systems in Weak Grids," *IEEE Transactions on Power Systems*, 2020

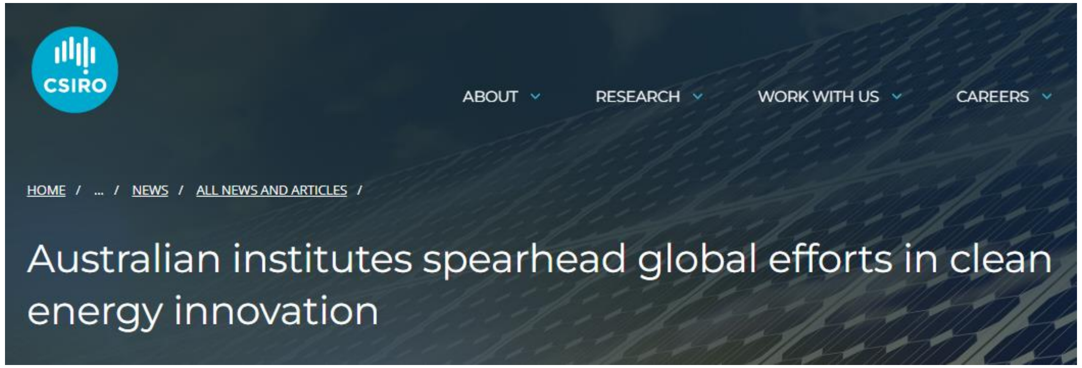
Acknowledgements

- NSF, EPSRC and CSIRO for the **“EPICS” Global Centre**
- CSIRO and AEMO for the “*Planning*” topic as part of the GPST/AR-PST project stream
- C4NET for the *“ESP-V”* project
- My research teams!

Electric Power Innovation for a Carbon-free Society (EPICS)

New Global Research Centre to provide EPIC clean energy boost

The new Electric Power Innovation for a Carbon-Free Society (EPICS) Centre will address challenges in clean energy production and storage.



GLOBAL PST CONSORTIUM

https://www.csiro.au/en/news/All/News/2023/September/Australian-institutes-spearhead-global-efforts-in-clean-energy-innovation

https://www.unimelb.edu.au/newsroom/news/2023/september/new-global-research-centre-to-provide-epic-clean-energy-boost

IEEE PES GTD ASIA 2027

29 September - 2 October 2027

Melbourne Convention & Exhibition Centre (MCEC)

Melbourne, Australia

Powering Asia's transformation through advanced grid technologies and energy innovation

Visit out website:
ieeegtd2027.org

Proudly supported by

Melbourne Convention Bureau
Visit Victoria
Business Events Australia

Meet you in Melbourne!

Thank you!
Any question?

pierluigi.mancarella@unimelb.edu.au

Physics, engineering and economics of new essential system services

Prof Pierluigi Mancarella, FIEEE

Chair of Electrical Power Systems

The University of Melbourne

pierluigi.mancarella@unimelb.edu.au

EPICS International Meeting

CSIRO, Newcastle, Australia

January 2026