The Evolving Power Grid Towards a Greener Future

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香港城市大學
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IEEE CAS
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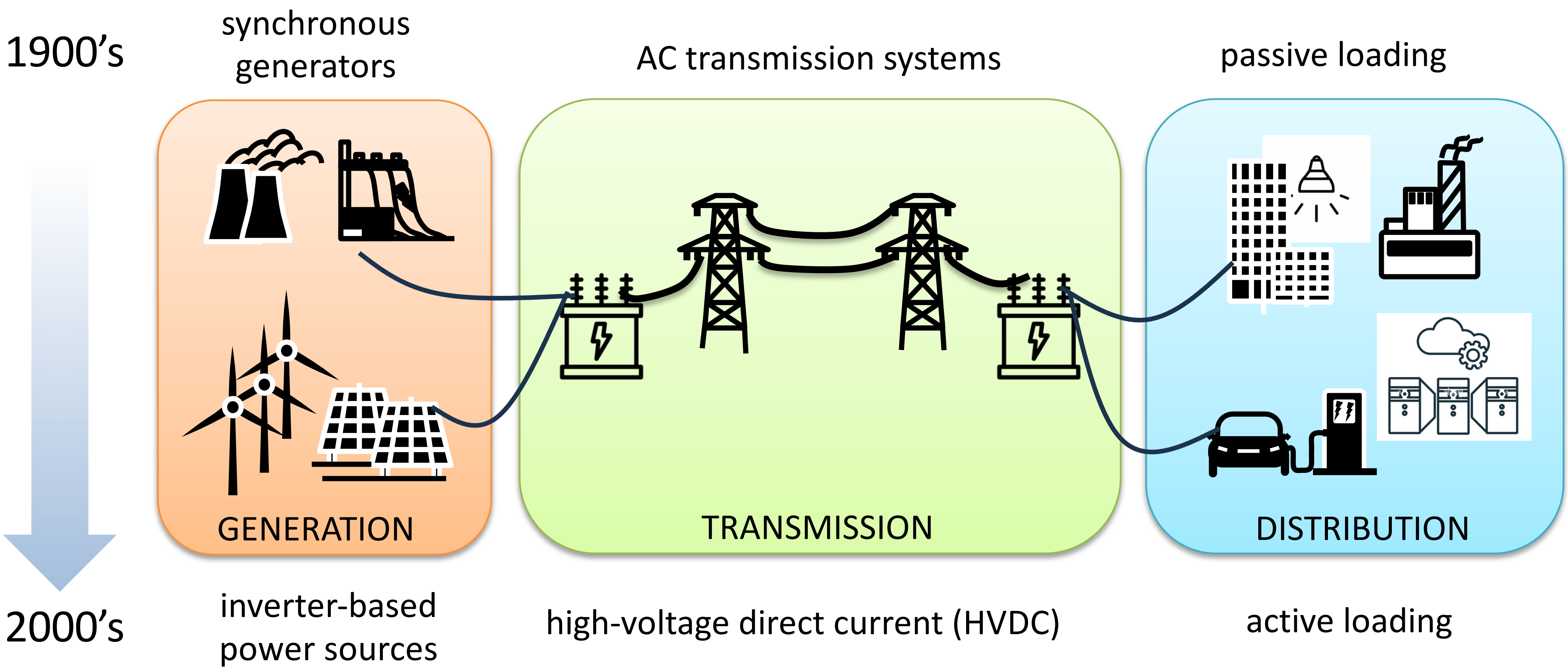
Power Grid

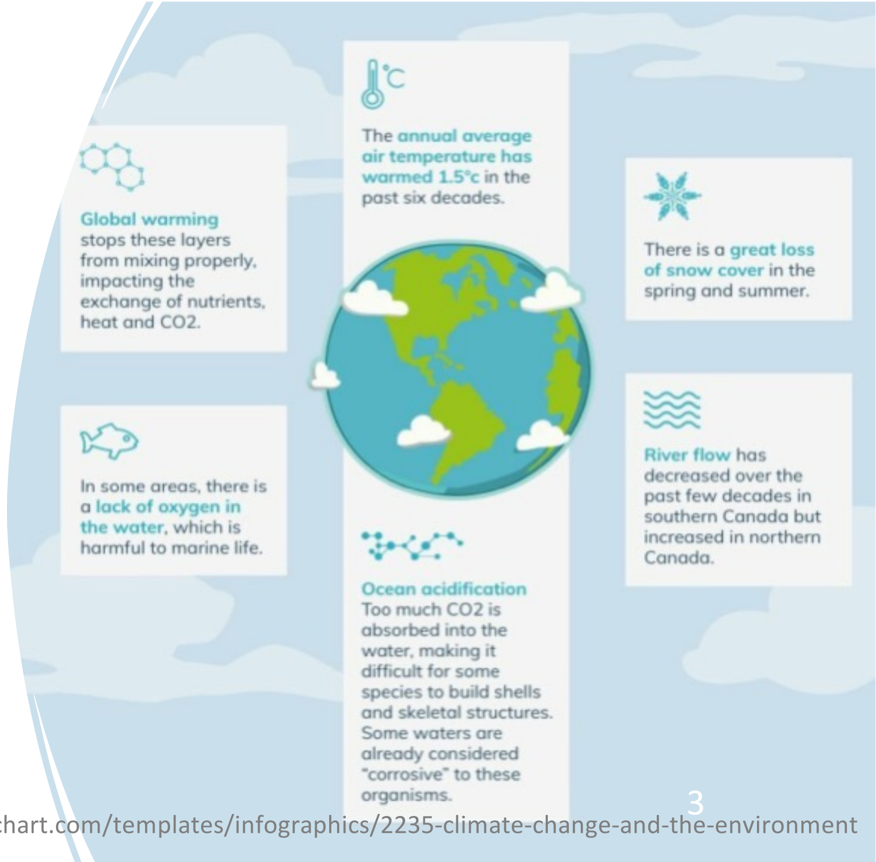


1900’s
synchronous generators
AC transmission systems
passive loading
GENERATION
TRANSMISSION
DISTRIBUTION
2000’s
inverter-based power sources
high-voltage direct current (HVDC)
active loading

Factor 1:
Recent Climate Action

- More **renewable** energy use
- More **efficient, high-performance** power conversion equipment

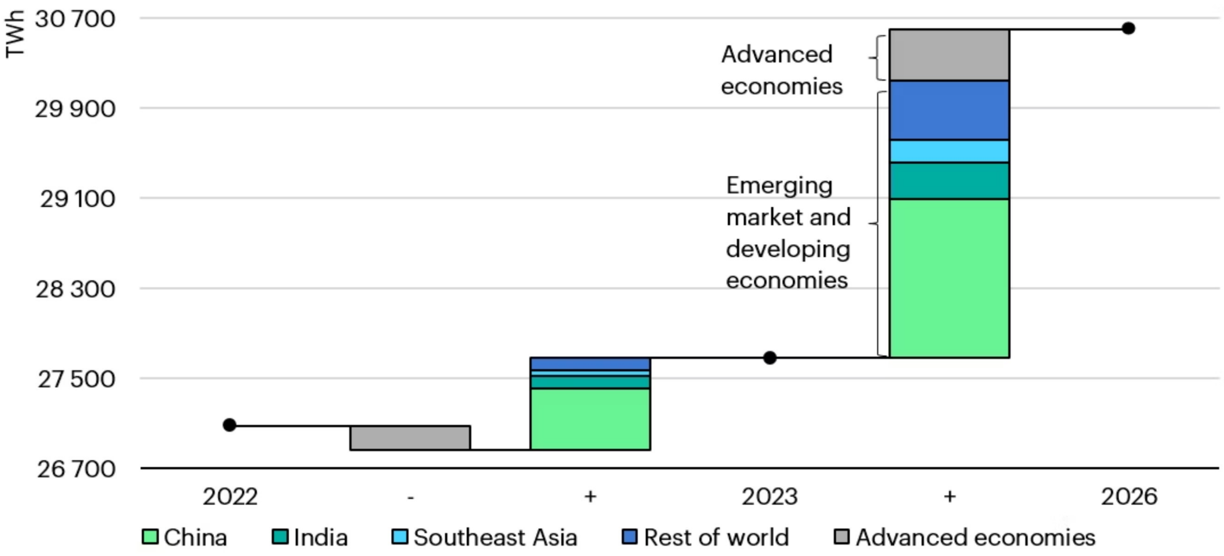
Both are *bad* for the conventional grid!



https://piktochart.com/templates/infographics/2235-climate-change-and-the-environment

Factor 2: Fast Growing Electricity Demand

Scaling up of power generation and distribution



Global electricity demand from data centers, cryptocurrencies and AI expected to double in three years, predicts IEA

The Evolving Power Grid

Power Generation

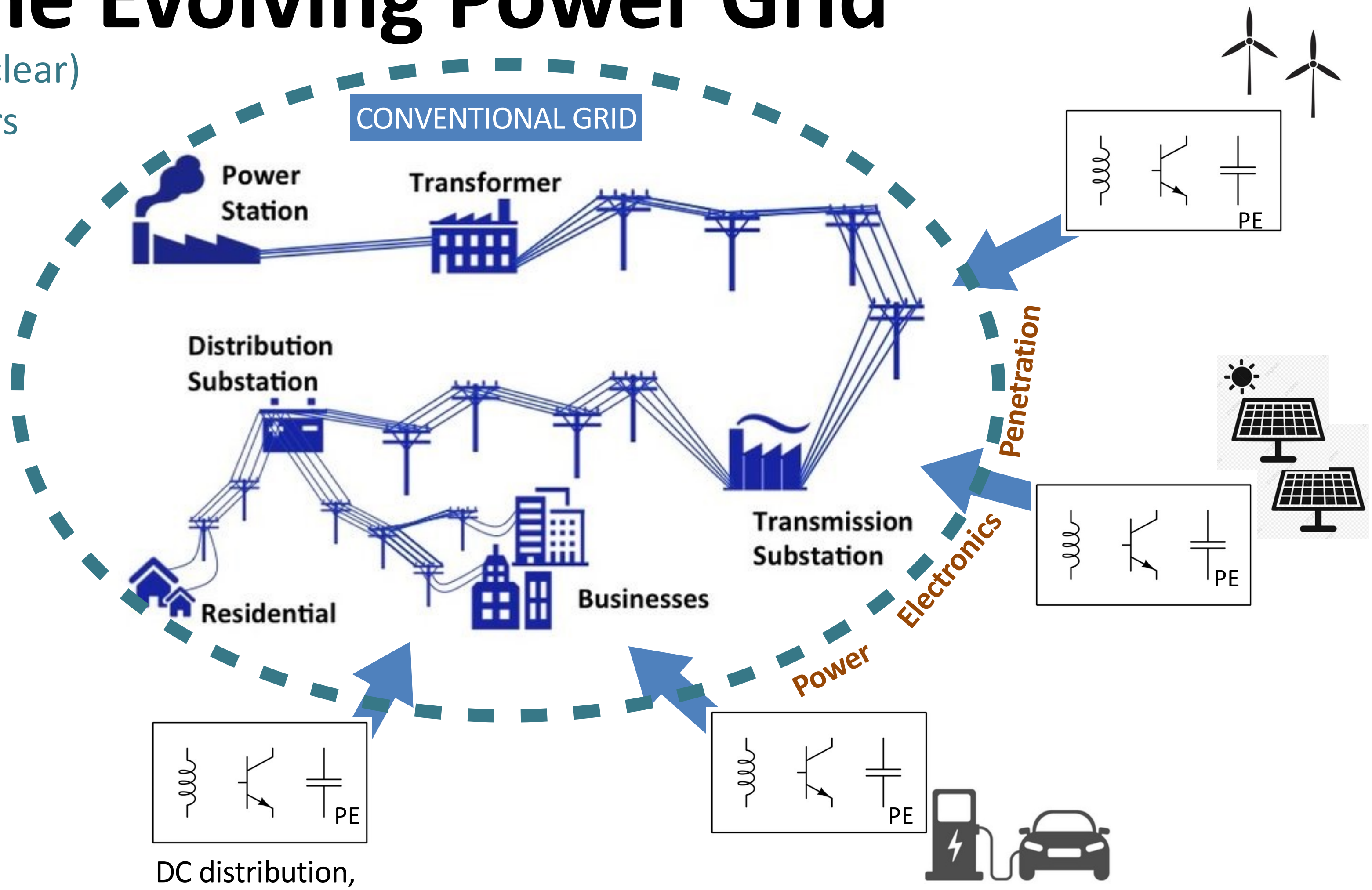
- Power plants (coal, nuclear)
- Synchronous generators
- Increasing number of renewable sources (IBRs)

Distribution

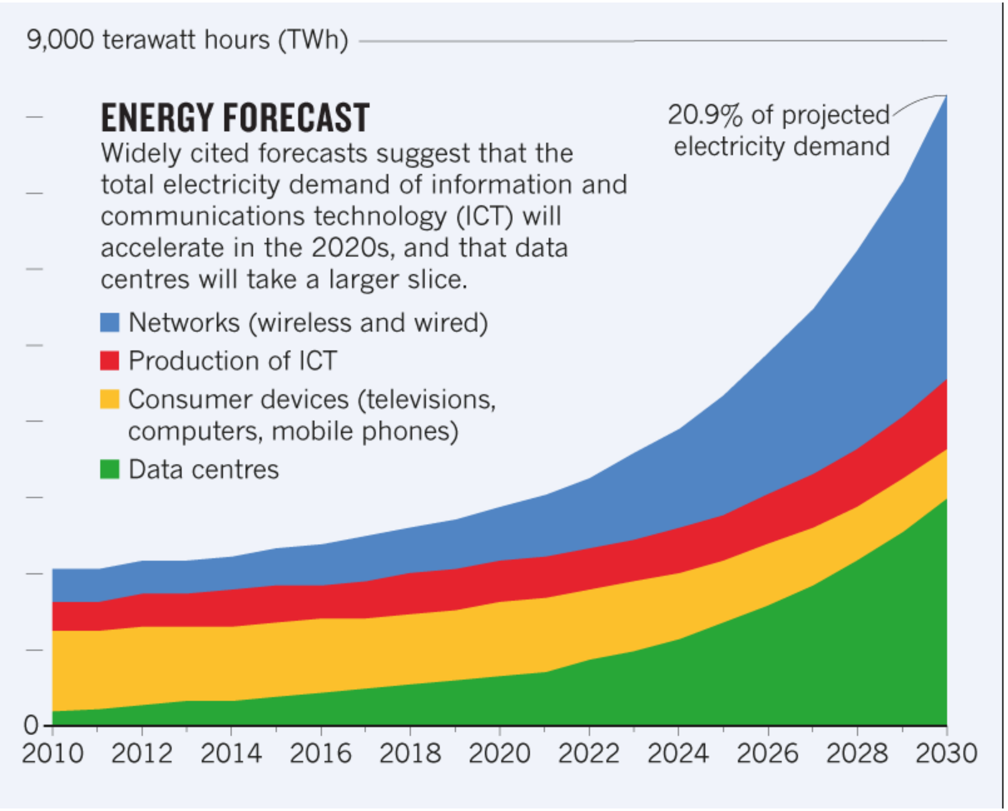
- Transmission
- Transformation
- More PE

Consumption

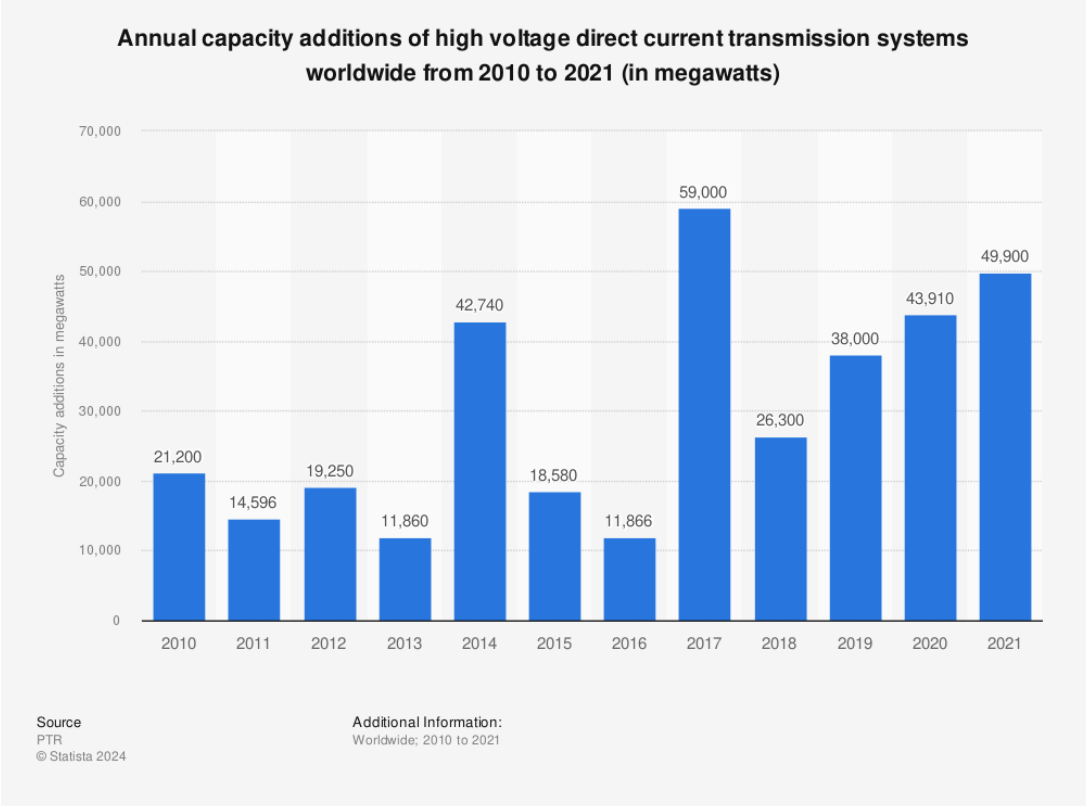
- Passive loads
- Active regulated loads
- More PE



More EVs, Data Centers …

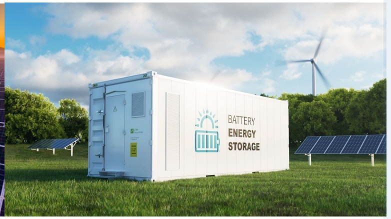


More HVDCs …

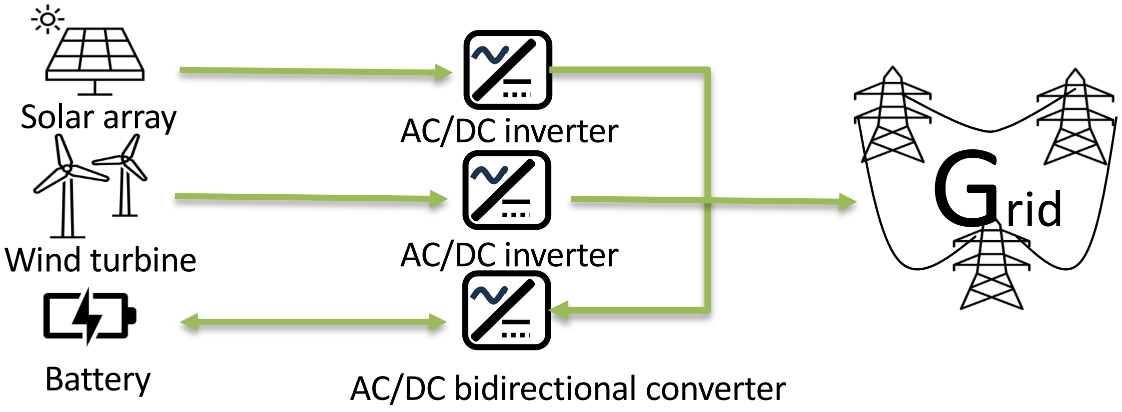


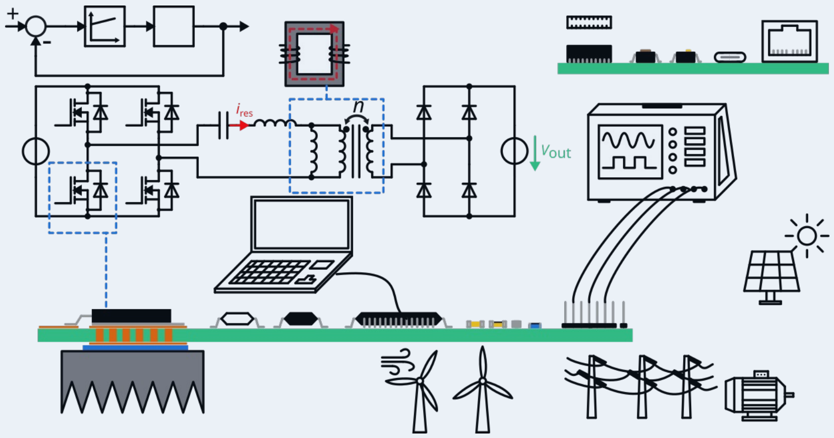
Consequences

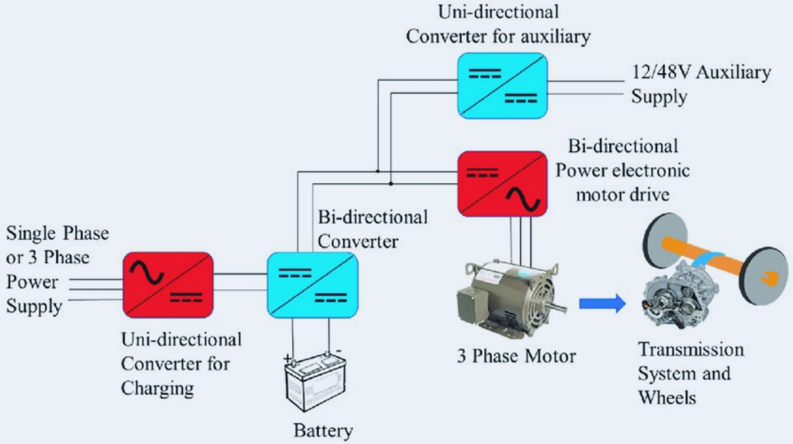
- More Renewable Resources
- More Data Centers, efficient Storages



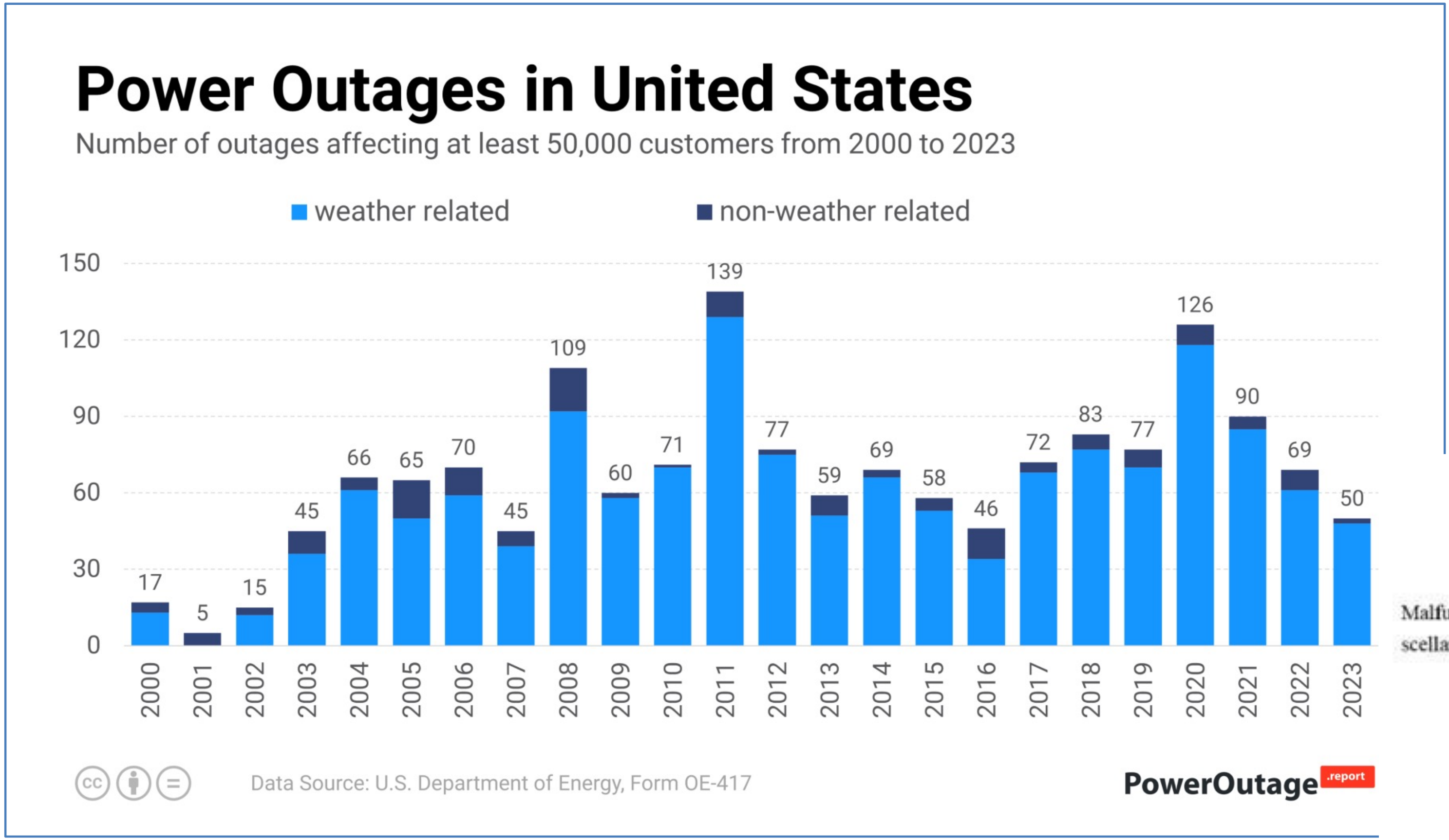
- ***More Power Electronics Equipment***

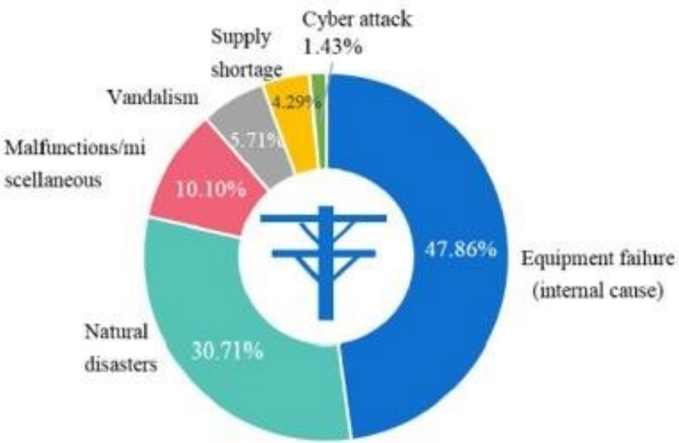






More Blackouts Due to Penetration of Power Electronics





The frequency of power outages does not significantly decrease during the evolution of the power grid.

How could CAS help?

The synchronous machine based grid is being seriously challenged by increasing use of power electronics.

We have a large problem menu, but all within CAS fields of interest:

- Lack of inertia for control → Control and system analysis
- Complex instability causes at circuit level → Nonlinear large-signal problems
- Connected system dynamics → Complex network models
- Power flow dynamics with changing topologies → System formulation with circuit governing physics and operating principles
- Changing parameters → Bifurcation analysis

METHODS:

Control and system analysis

Nonlinear large-signal problems

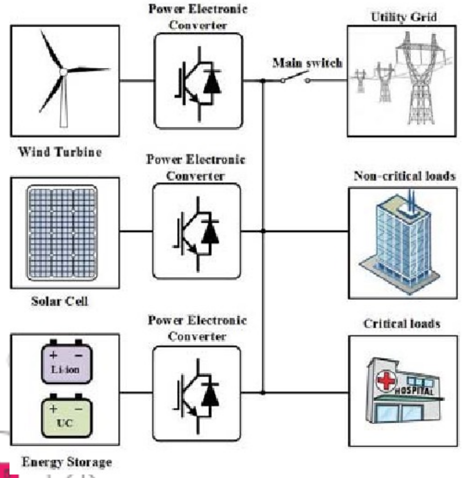
Complex network models

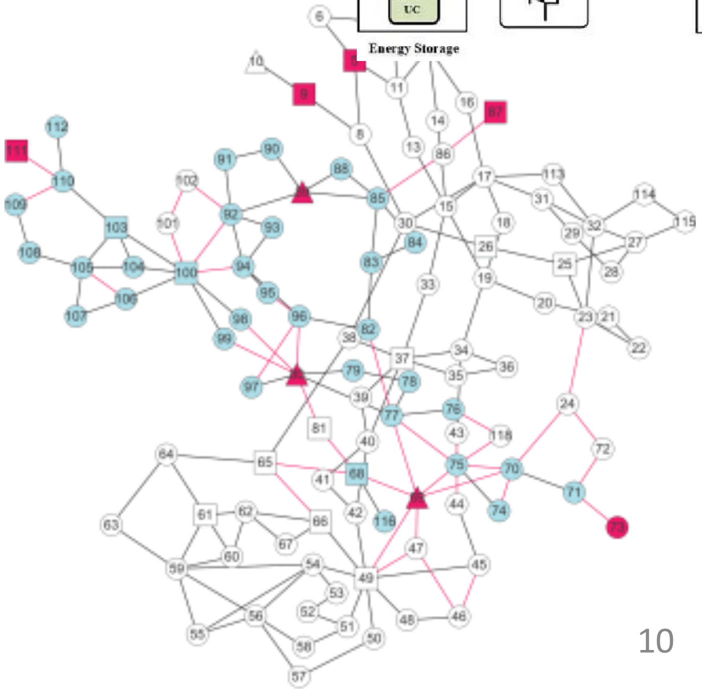
System formulation with circuit governing physics and operating principles

Bifurcation analysis

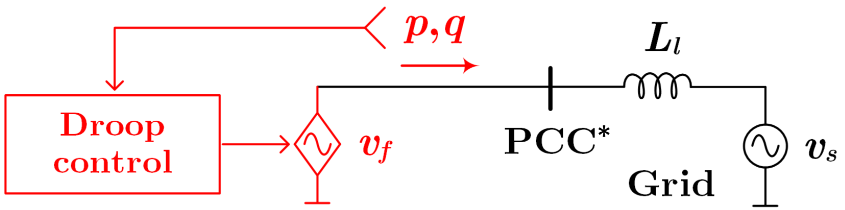
Questions to be answered from two angles:

- **From circuit/device level:** How to identify the causes of instability in converter-dominated systems and provide solutions
    - *Circuit-level modeling and analysis.*
- **From system/network level:** How to uncover the occurrence process of major blackout incidents and develop mitigation strategies based on the cascading failure evolution mechanisms
    - *Network-based modeling and analysis.*

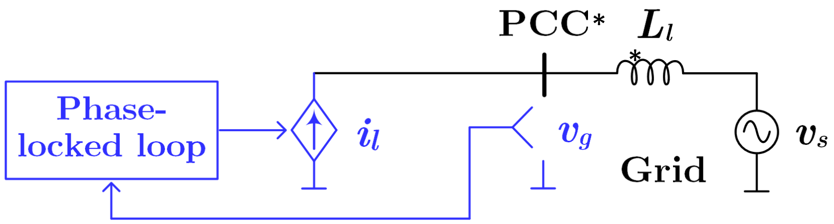




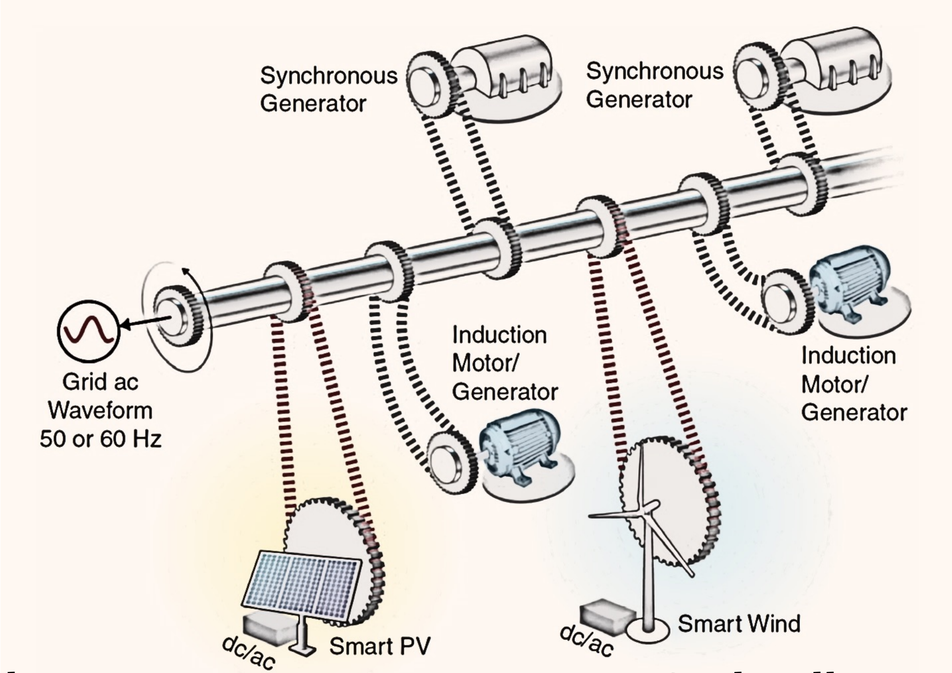
Grid-Forming and Grid-Following Converters



Grid-Forming Converter



Grid-Following Converter

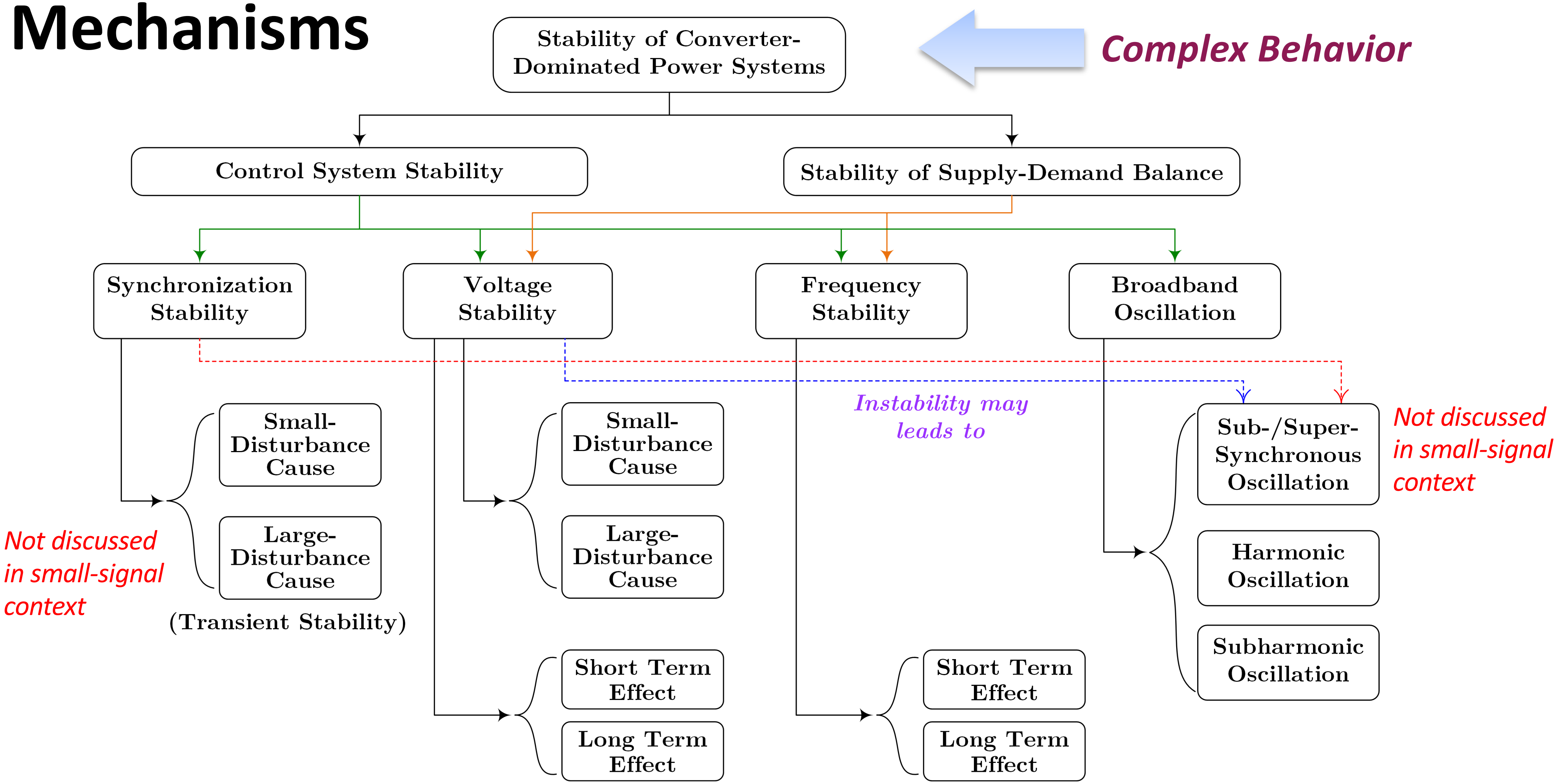


Grid-Forming Converter

Grid-Following Converter

*PCC: Point of Common Coupling

Mechanisms


Complex Behavior
Stability of Converter-Dominated Power Systems
Control System Stability
Stability of Supply-Demand Balance
Synchronization Stability
Voltage Stability
Frequency Stability
Broadband Oscillation
Small-Disturbance Cause
Large-Disturbance Cause
(Transient Stability)
Not discussed in small-signal context
Small-Disturbance Cause
Large-Disturbance Cause
Short Term Effect
Long Term Effect
Instability may leads to
Short Term Effect
Long Term Effect
Sub-/Super-Synchronous Oscillation
Not discussed in small-signal context
Harmonic Oscillation
Subharmonic Oscillation

Case Study:

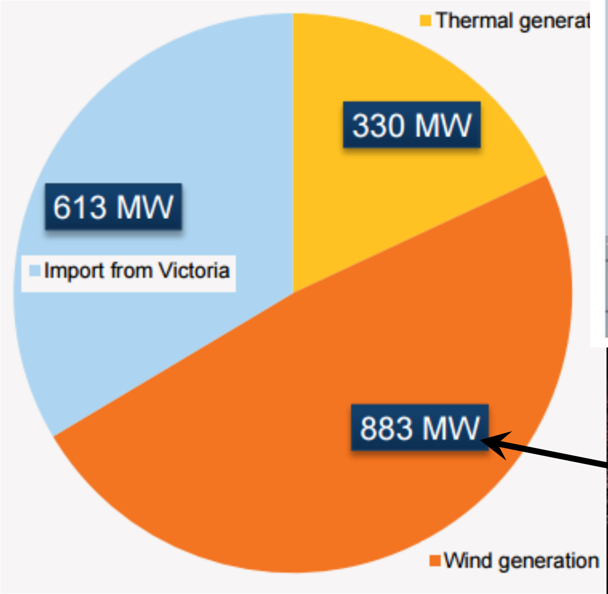
Blackout in South Australia on September 28, 2016

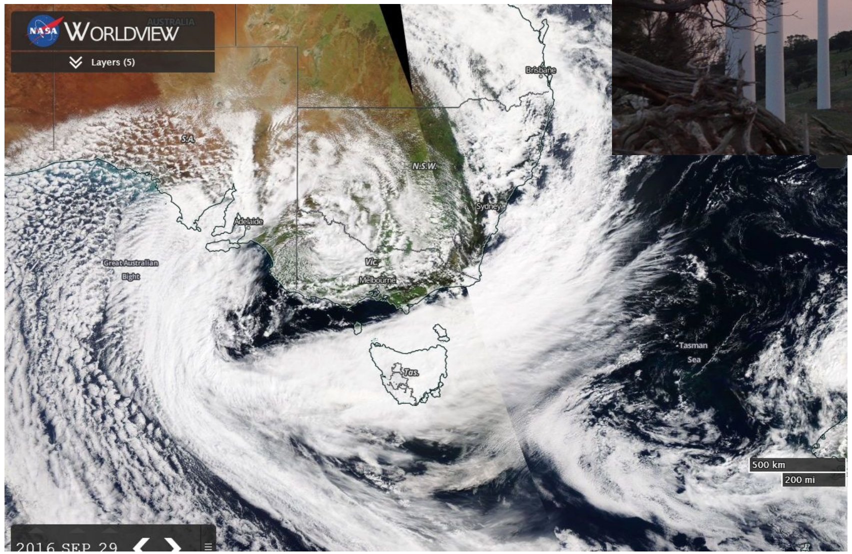
1 PRE-EVENT

< September 28, 2016
High penetration of renewables

Severe **weather** warning

Before the blackout





Technical Report
https://apo.org.au/sites/default/files/resource-files/2017-03/apo-nid74886.pdf

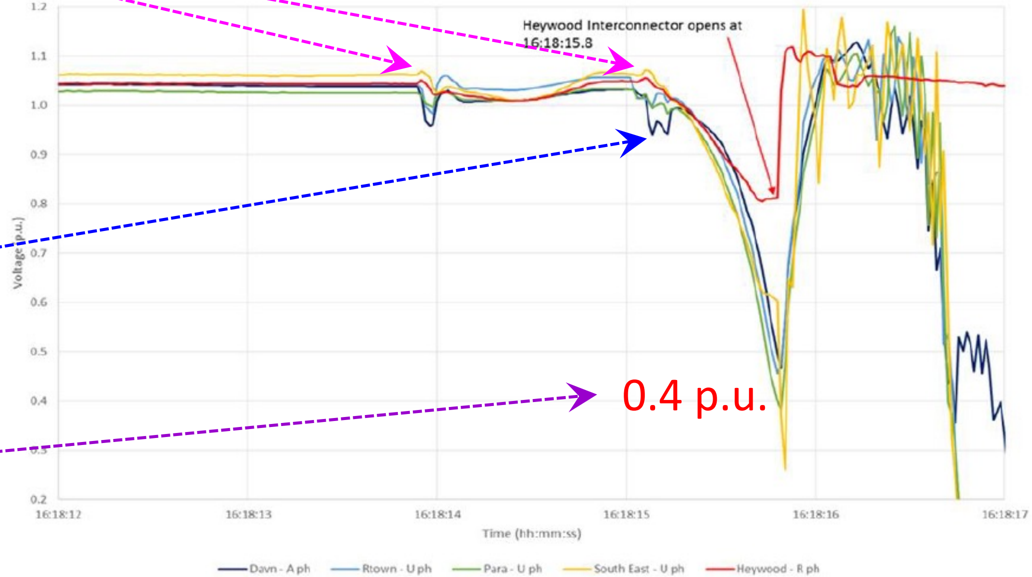
② EVENT

September 28, 2016

16:16 hr
Severe WEATHER damaged transmission assets

Shutdown of wind farms (456.3 MW)

Voltage instability



BLACK SYSTEM SOUTH AUSTRALIA 28 SEPTEMBER 2016 – Final Report

3 EVENT

September 28, 2016

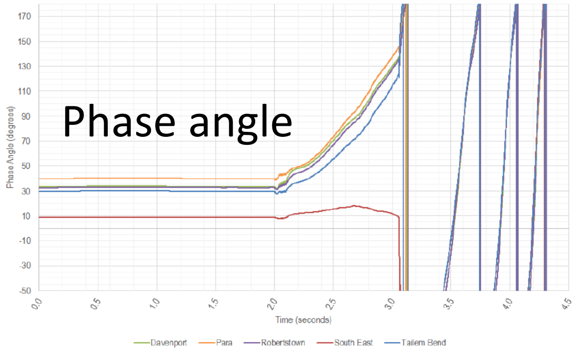
Individual events

Loss of synchronization between South Australia and Victoria

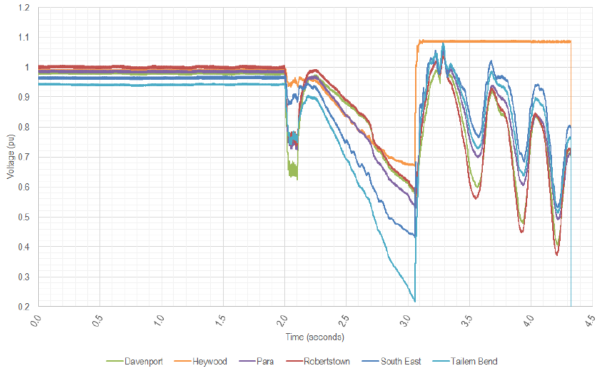
Supply-demand imbalance

Frequency instability

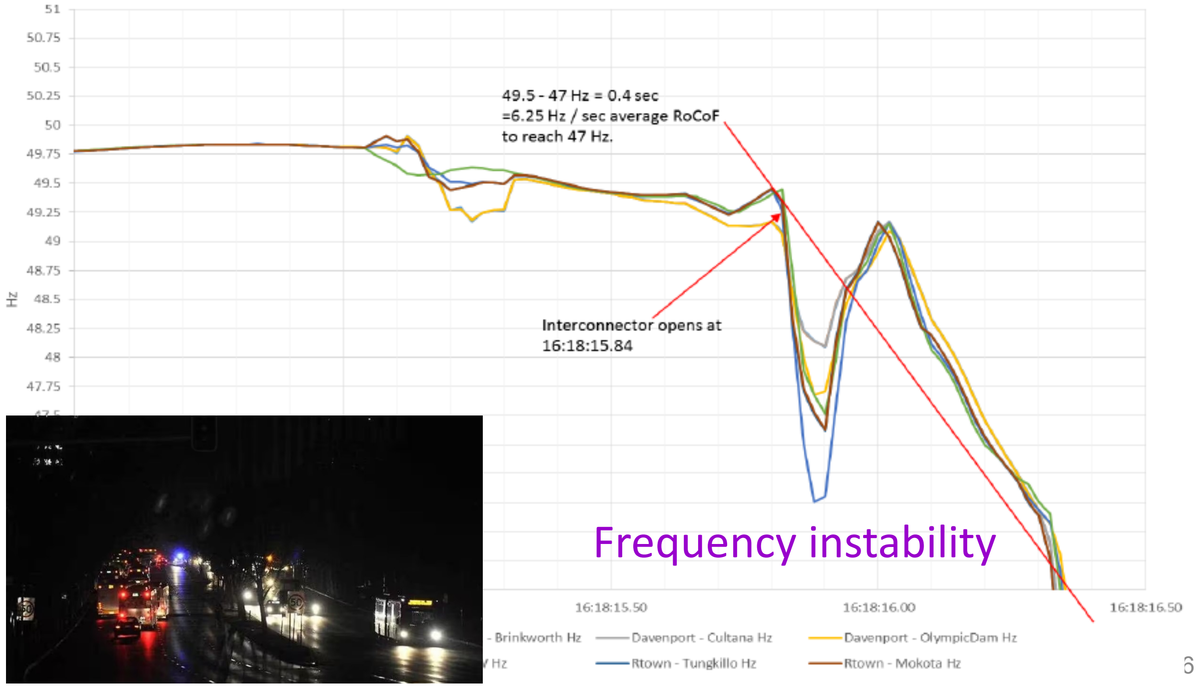
South Australia went black



Loss of synchronization



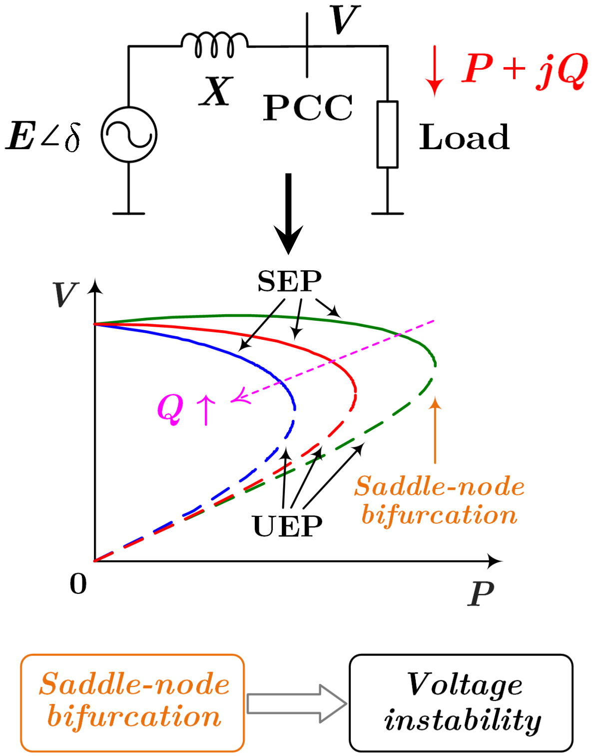
Sub-synchronous oscillations



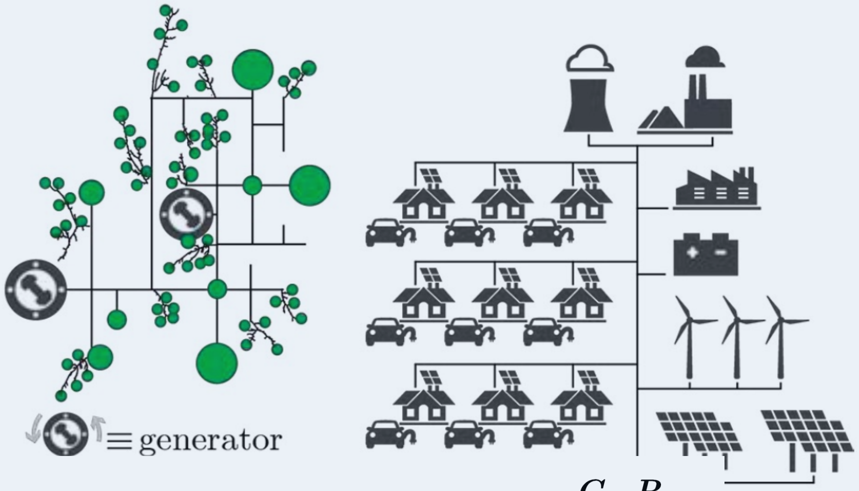
Frequency instability

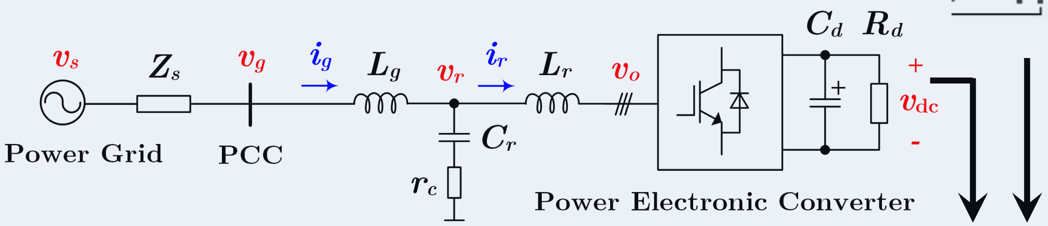
CAS Viewpoint 1: Voltage Instability

Conventional Analysis

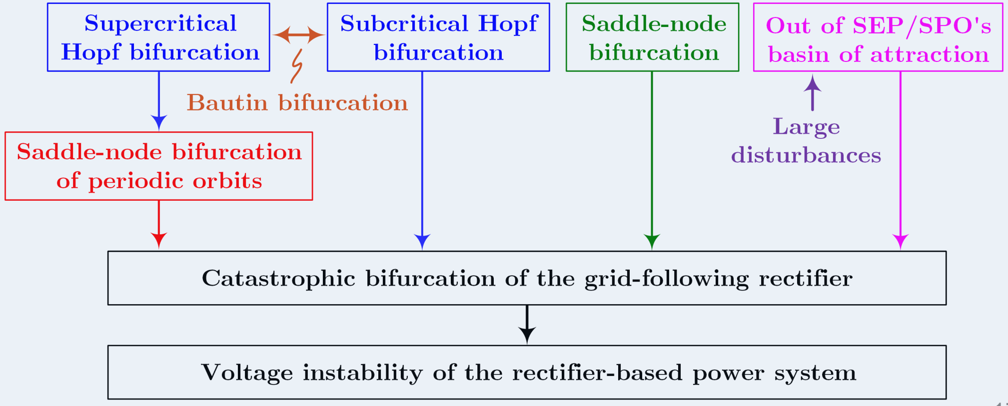


Converter-Based Power System



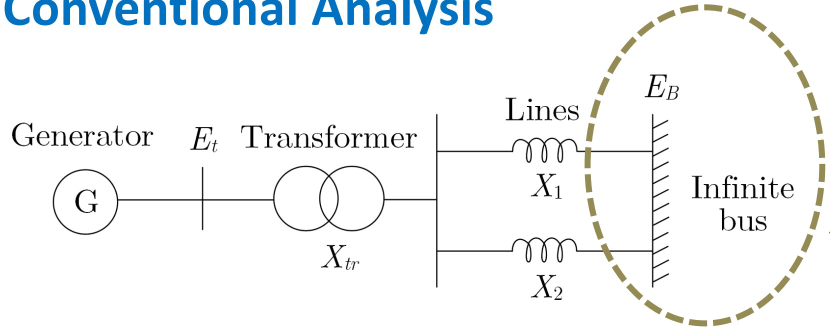


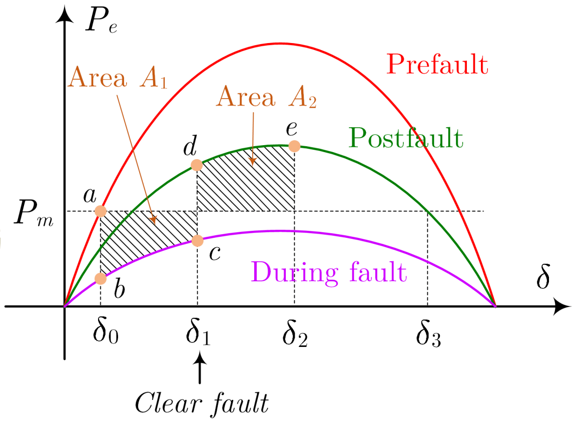
More routes to instability



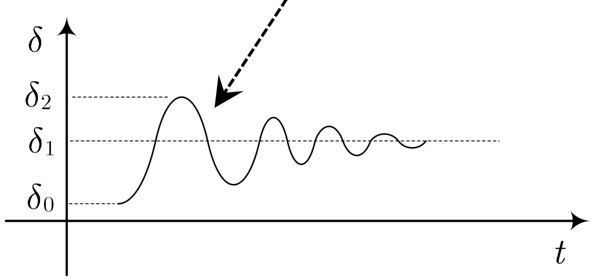
CAS Viewpoint 2:
Loss of Synchronization Under Transient Disturbances

Conventional Analysis

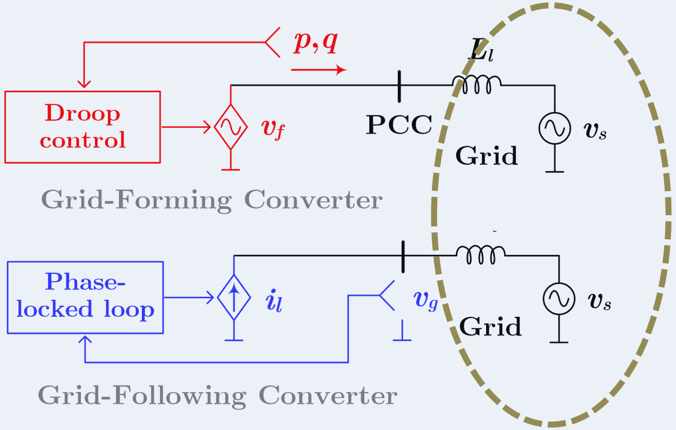


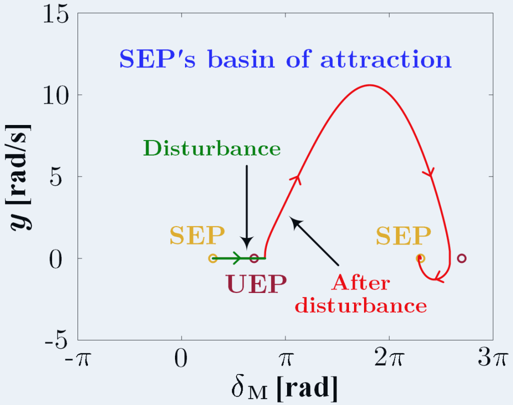


first-swing stability

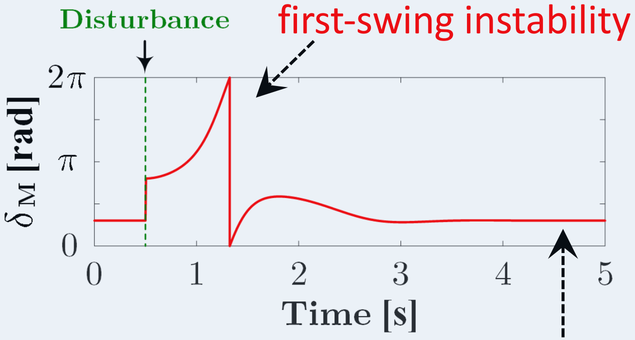


Converter-Based Power System





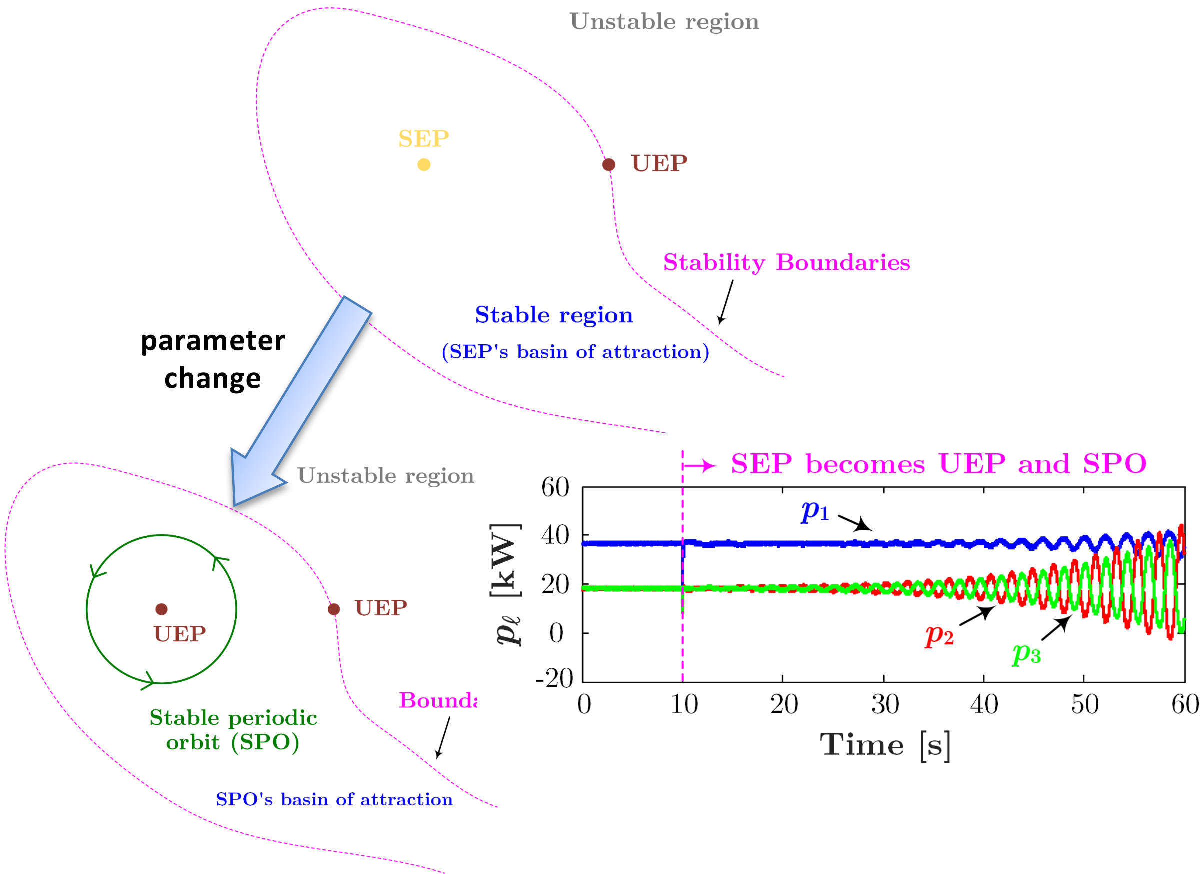
first-swing instability



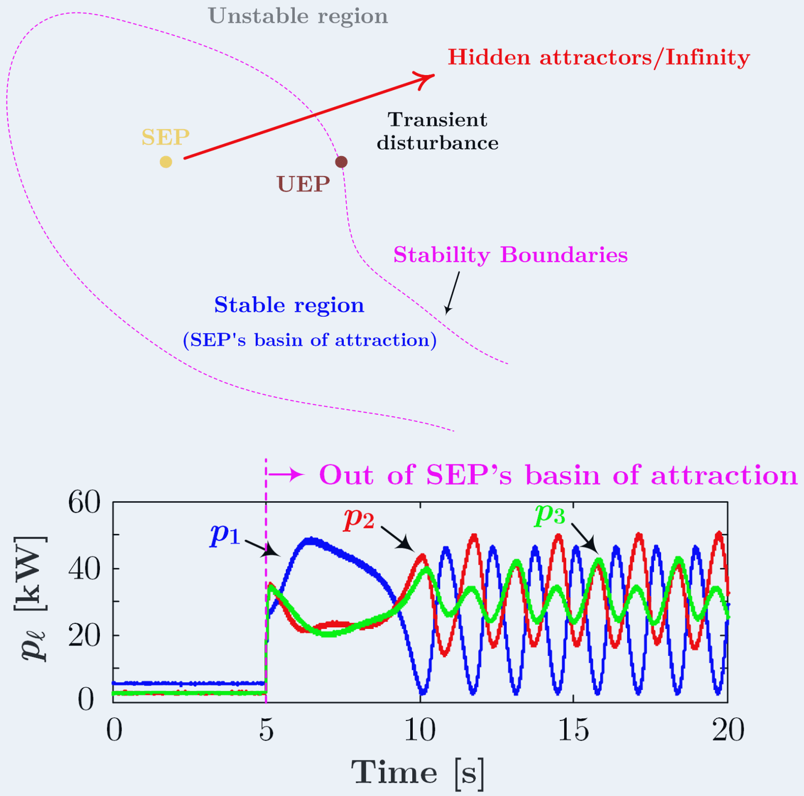
Multi-swing stability

CAS Viewpoint 3: Sub-synchronous Oscillations Under Transient Disturbances

Conventional Route

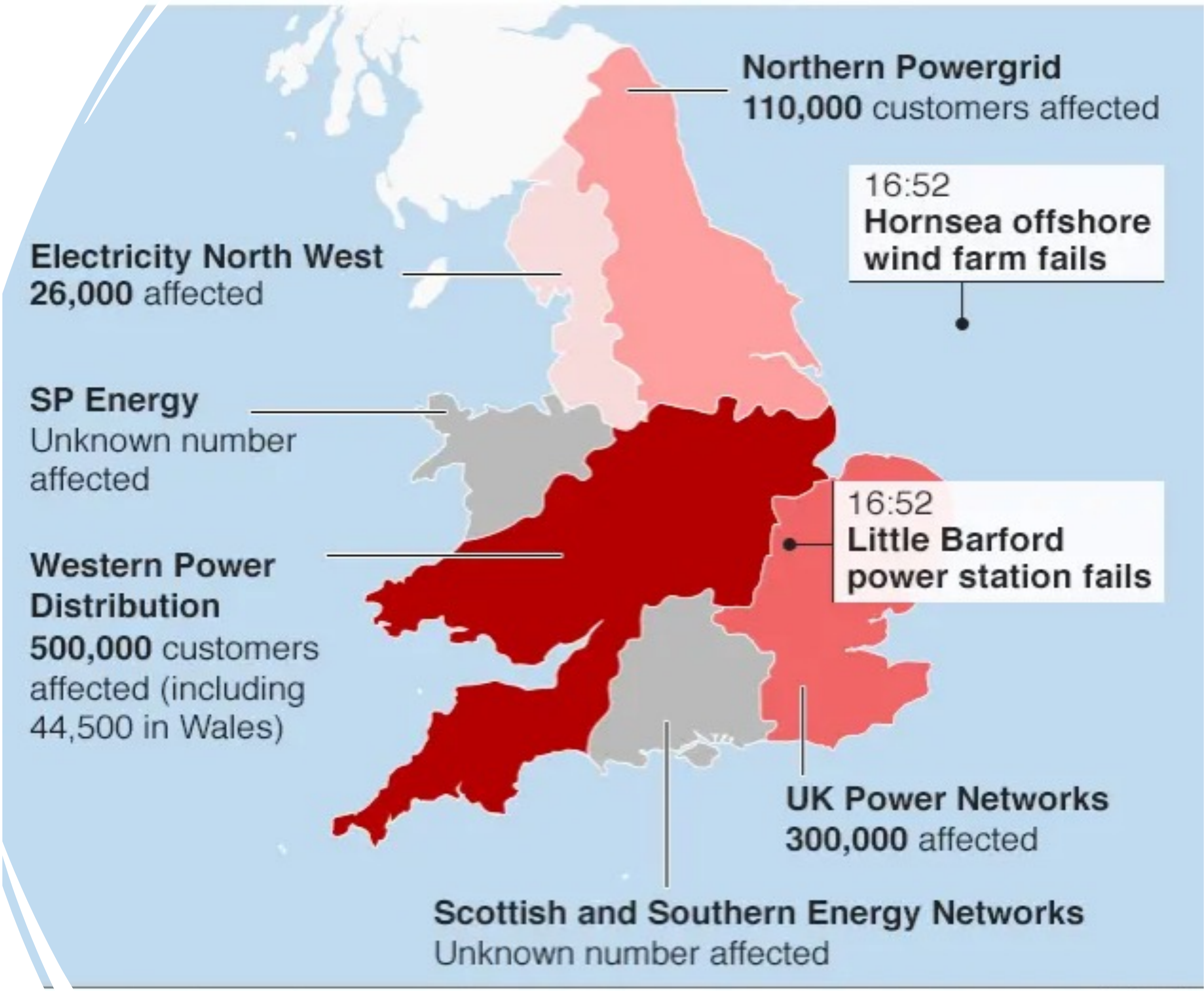


New Route



Case Study:

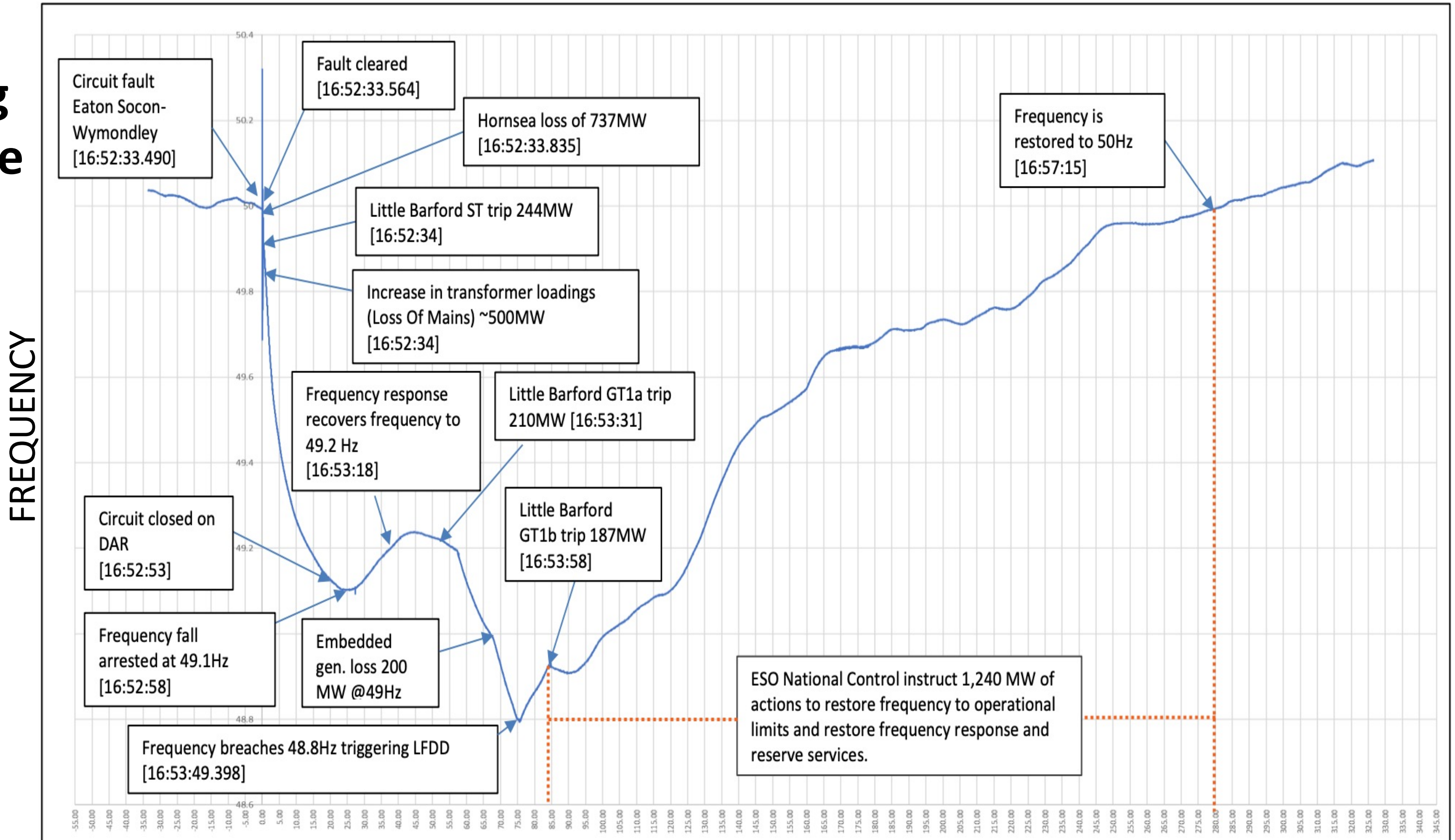
England and Wales Power Cut on August 9, 2019



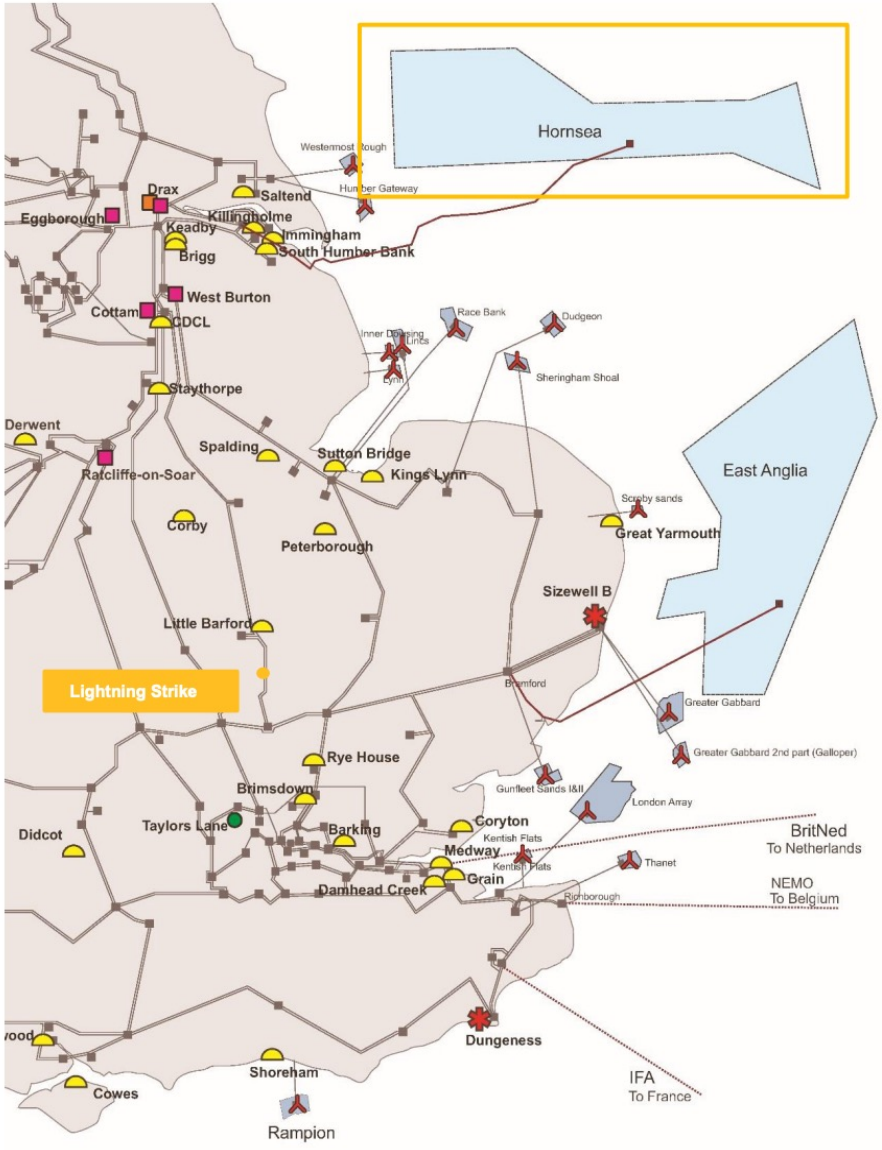
Events Analysis:

Variation of frequency during the power outage incident

The rapid decline in frequency leads to a large amount of generation loss



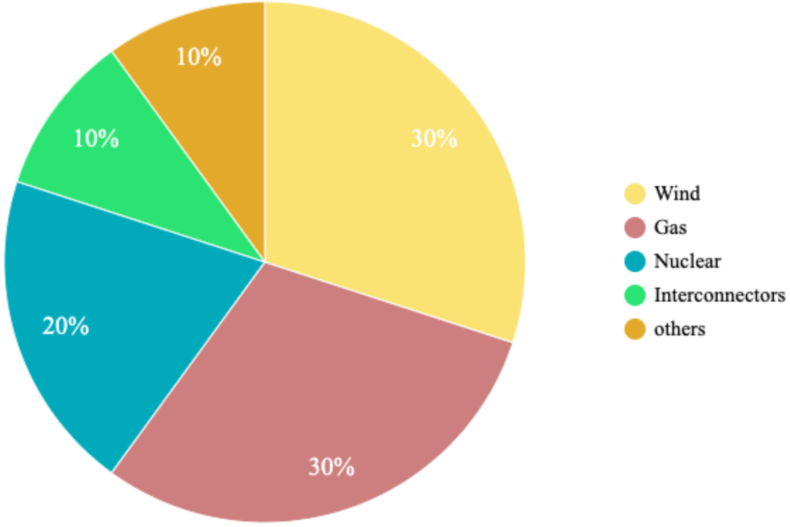
Technical Report on the Events of 9 Aug. 2019, 2019, [online] Available: https://www.ofgem.gov.U.K./sites/default/files/docs/2019/09/eso_technical_report_-_final.pdf.



Events analysis: penetration and location of inverter-based resources in the UK power grid

"Two almost simultaneous unexpected power losses – at the Hornsea off-shore wind farm (737MW) and the steam turbine at the Little Barford gas-fired power station (244MW)"

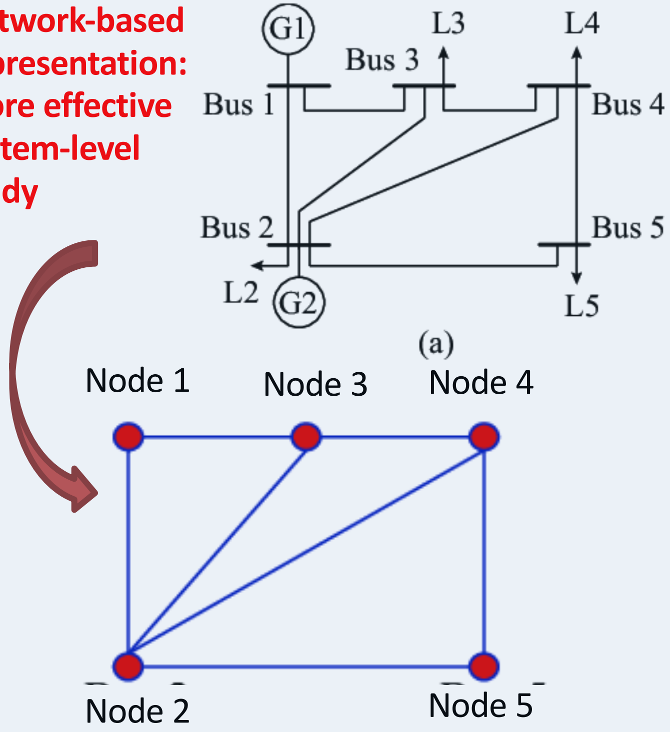
Technical Report on the Events of 9 Aug. 2019, 2019, [online]: https://www.ofgem.gov.U.K./sites/default/files/docs/2019/09/eso_technical_report_-_final.pdf.



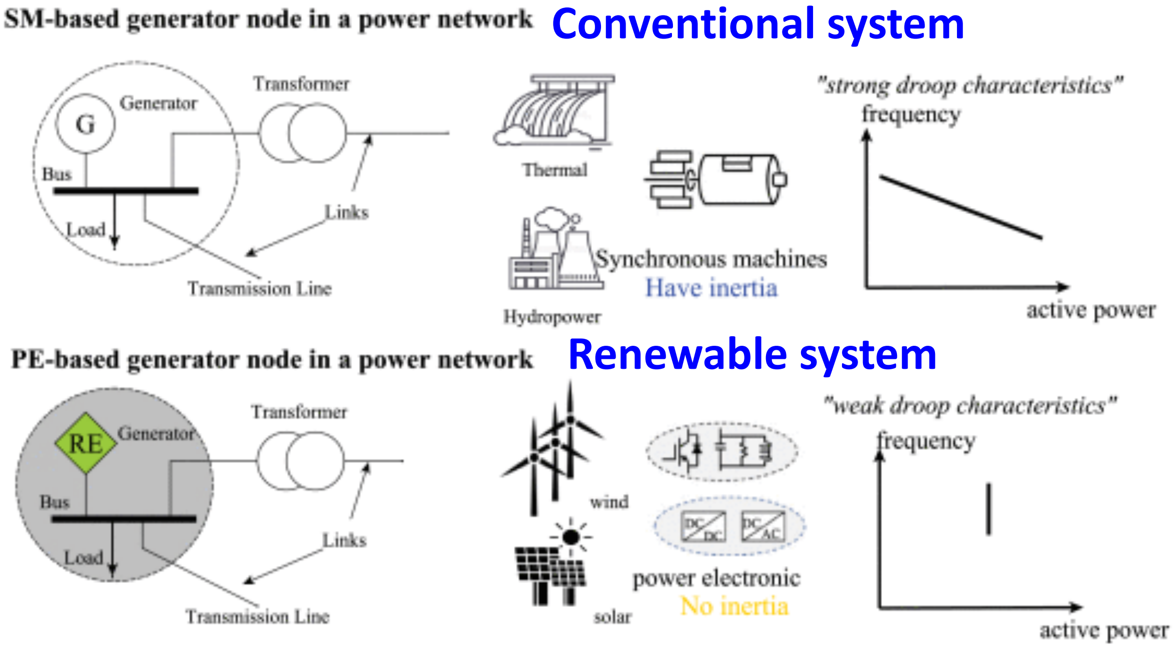
CAS Viewpoint 4: Effect of Frequency Response on Cascading Failure

Synchronous machine-based generator node *VS* Power electronic-based generator node

Network-based representation: more effective system-level study



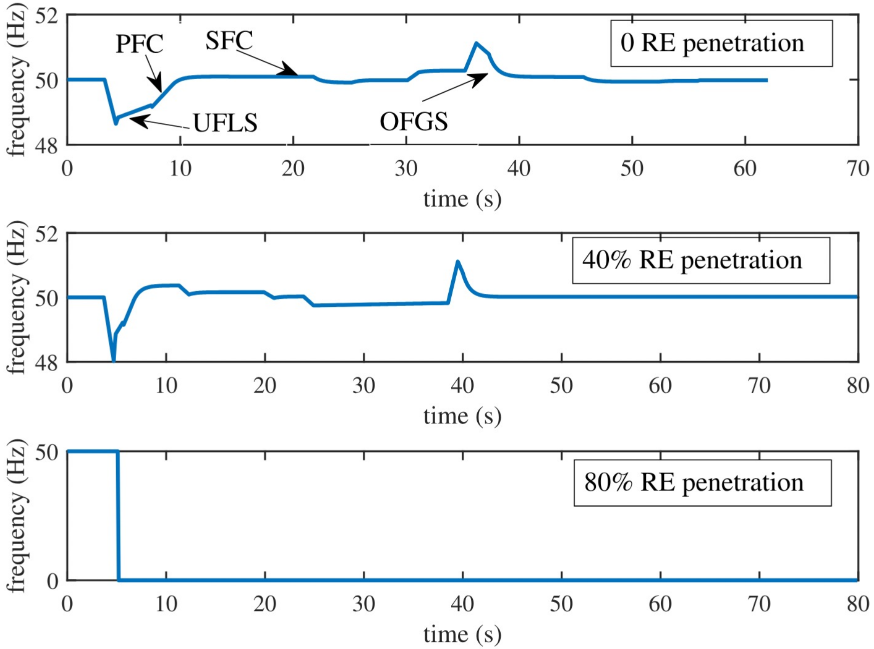
When renewable energy resources are increasingly deployed

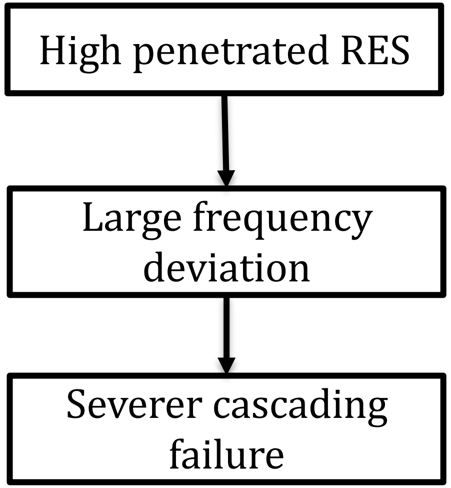


D. Liu, X. Zhang, and C. K. Tse, "Effects of high level of penetration of renewable energy sources on cascading failure of modern power systems," *IEEE Journal of Emerging and Selected Topics in Circuits and Systems*, vol. 12, no. 1, pp. 98-106, March 2022.

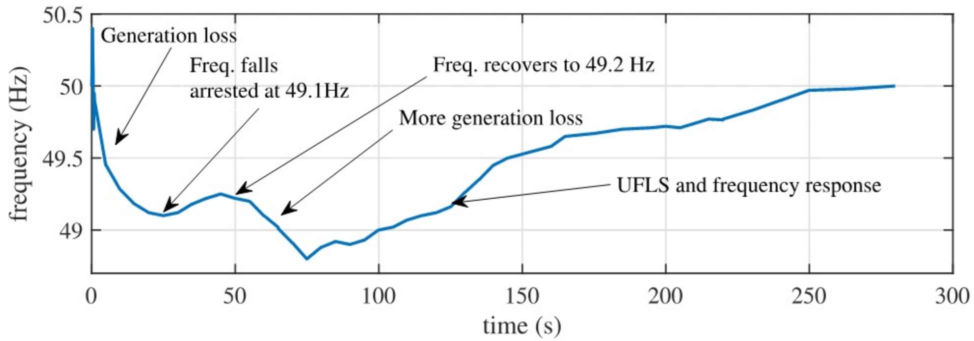
Using Network-Based Analysis

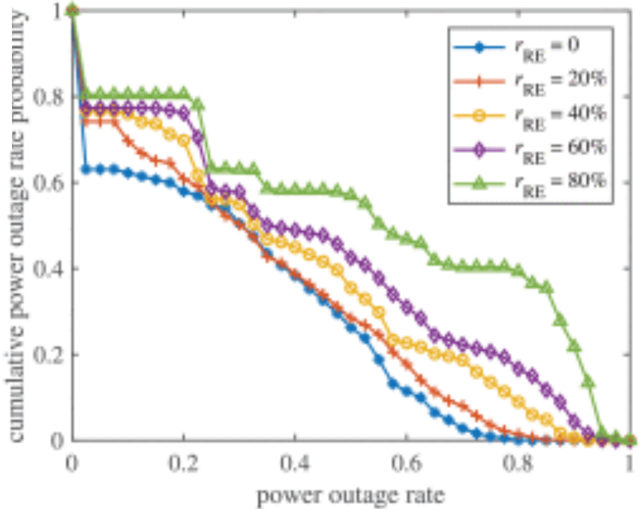
Raising the penetration level of renewable sources increases the risk of the occurrence of a large-scale power blackout





Compared to UK events:



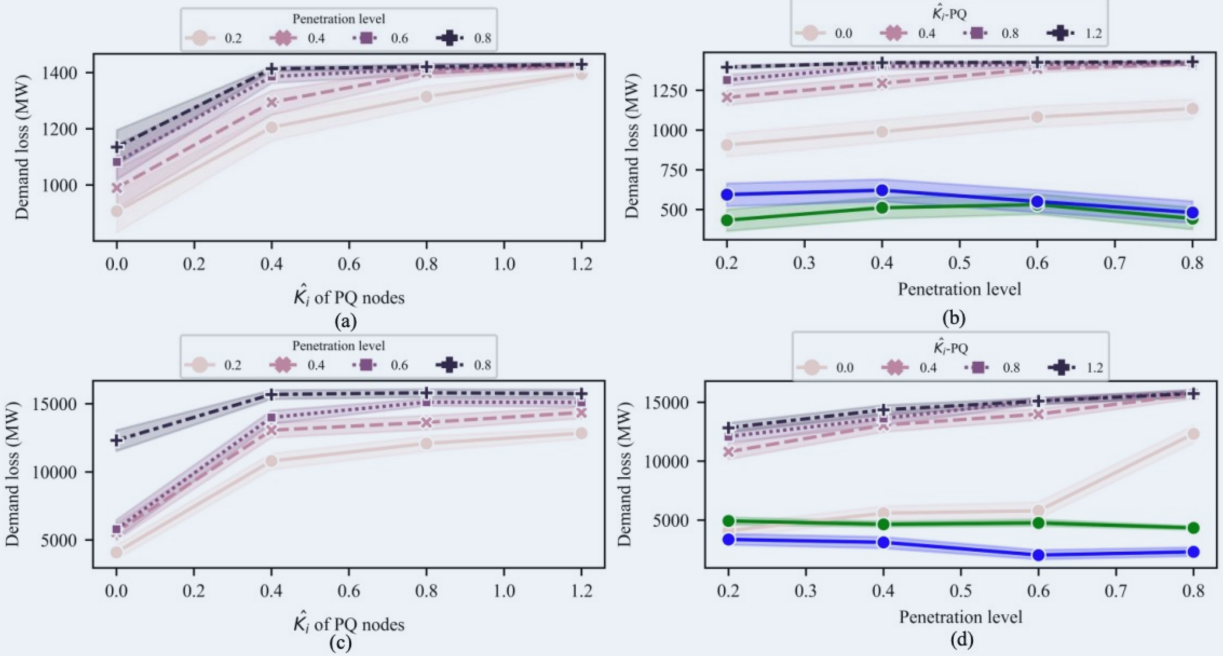


CAS Viewpoint 5: Effects of inverter-based resources (IBRs) penetration on cascading failure

Replacing synchronous generators with inverter-interfaced generations increases the size of power outages.

We can also study the effects of the location of IBRs on cascading failure.

Using Network-Based Analysis



Influence of design parameter for droop controller and penetration level of frequency responsive inverter nodes on demand loss. Different percentages of PV buses are assigned as inverter nodes.

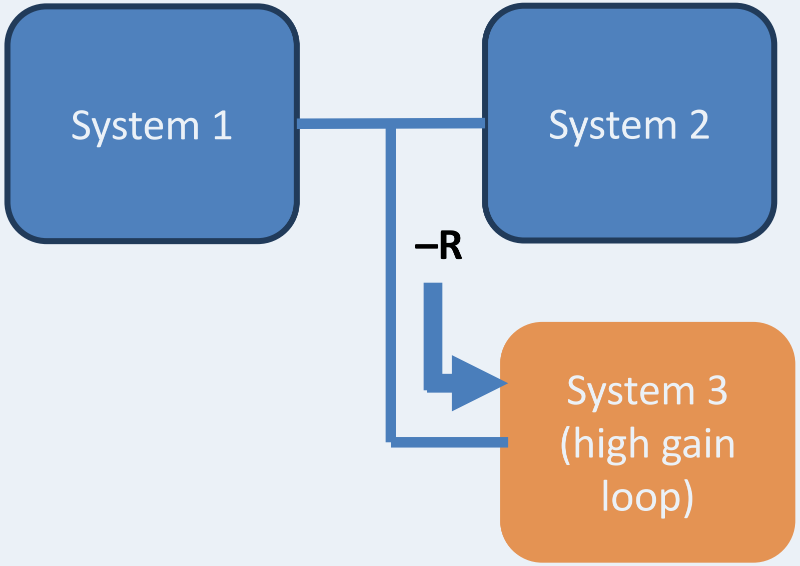
M. J. Li and C. K. Tse, "The impact of inverter-based resources (IBRs) on cascading failures in power systems," *IEEE Transactions on Power Systems*, to appear.

M. J. Li and C. K. Tse, "Where should inverter-based resources be located in power networks?" *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 71, no. 3, pp. 1456-1464, March 2024.

Case Study:

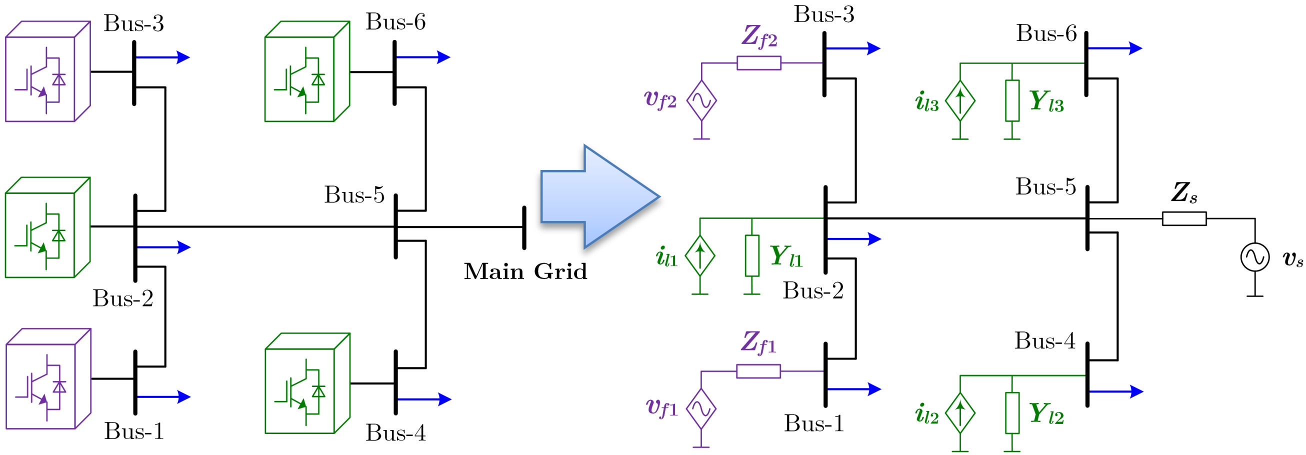
Link Oscillation

Individually designed to be **high-performance** systems



What if they do interact?

CAS Viewpoint 6: Complex interaction between converters



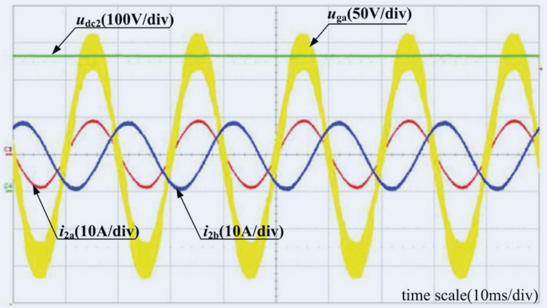
Conventional Analysis

- Small-signal
- Linearization near EQP
- Simple behavior

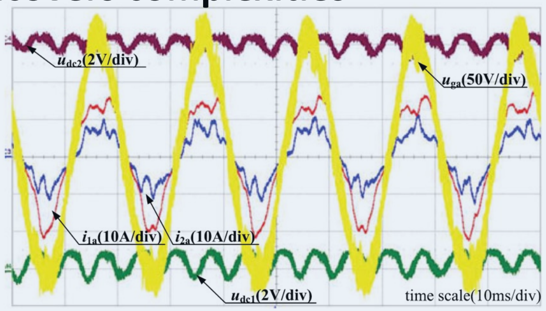
Connected Analytical Approach

- Large-signal
- Multi-time scale
- Effective for varying EQP
- Complex behavior

bifurcation analysis uncovers complexities

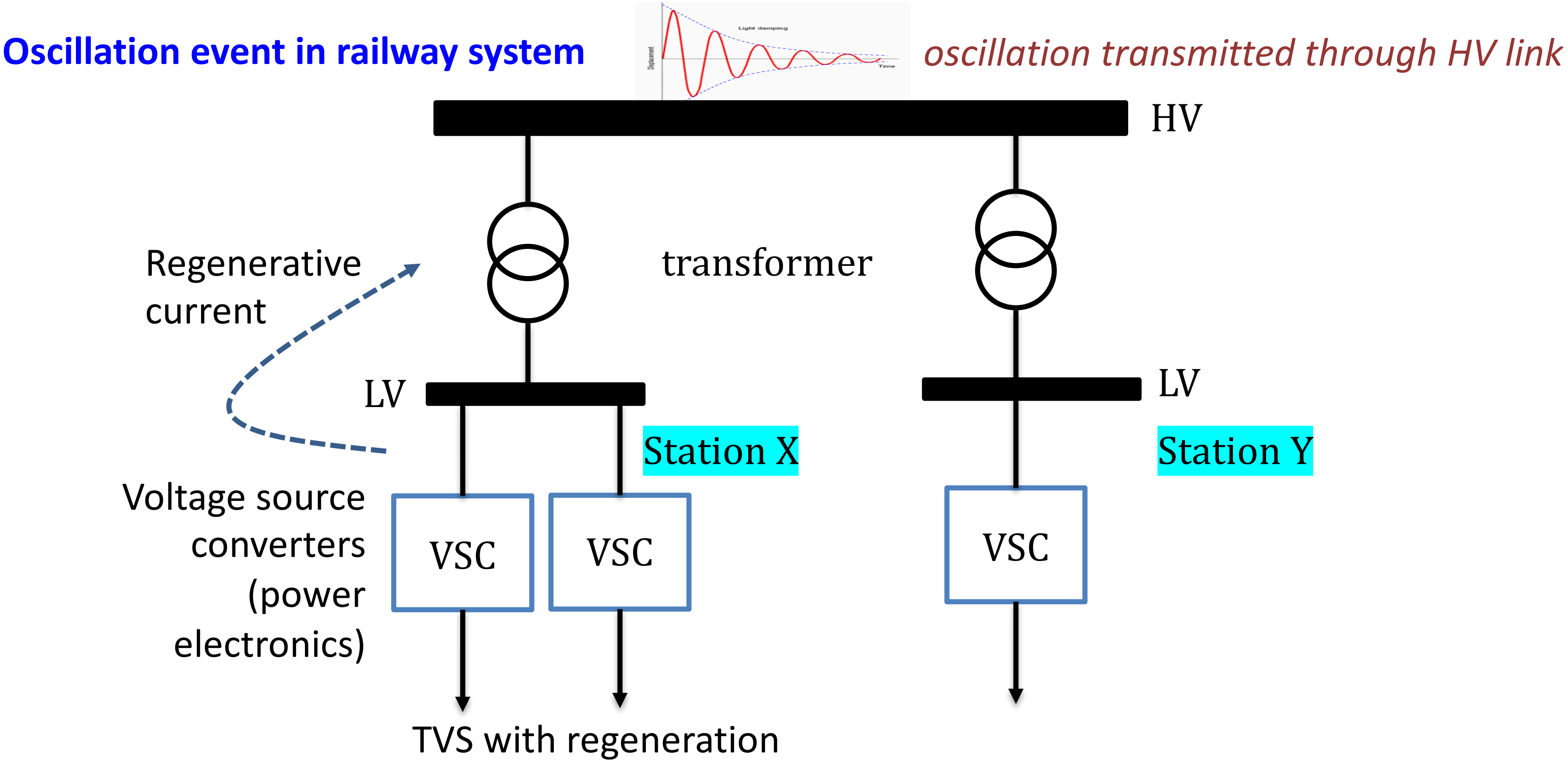


converters operate independently



interact strongly

CAS Viewpoint 7: Interaction between power systems and other systems — connected networks viewpoint



CONCLUSIONS

The power grid has been evolving with

- More renewable deployment
- More active load use
- Higher consumption demand
- More interaction between loads and subsystems
- More complex behavior
  - ➢ Complex stability issues
  - ➢ Complex robustness issues
    - Requires novel modeling methods
    - Requires advanced analytical methods
      - ➢ **More reliable grid**

ACKNOWLEDGMENTS

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- Dr Xi Zhang

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- Miss Jade Li