



EE3123 Introduction to Electric Power Systems

Future Trends in Smart Systems

Dr. CQ Jiang

Many thanks to Prof. Michael Tse

Keynote Lecture at Australasian Universities Power Engineering Conference 2021

Public Lecture at IEEE International Symposium on Circuits and Systems 2020



Conventional power grid

Power Generation

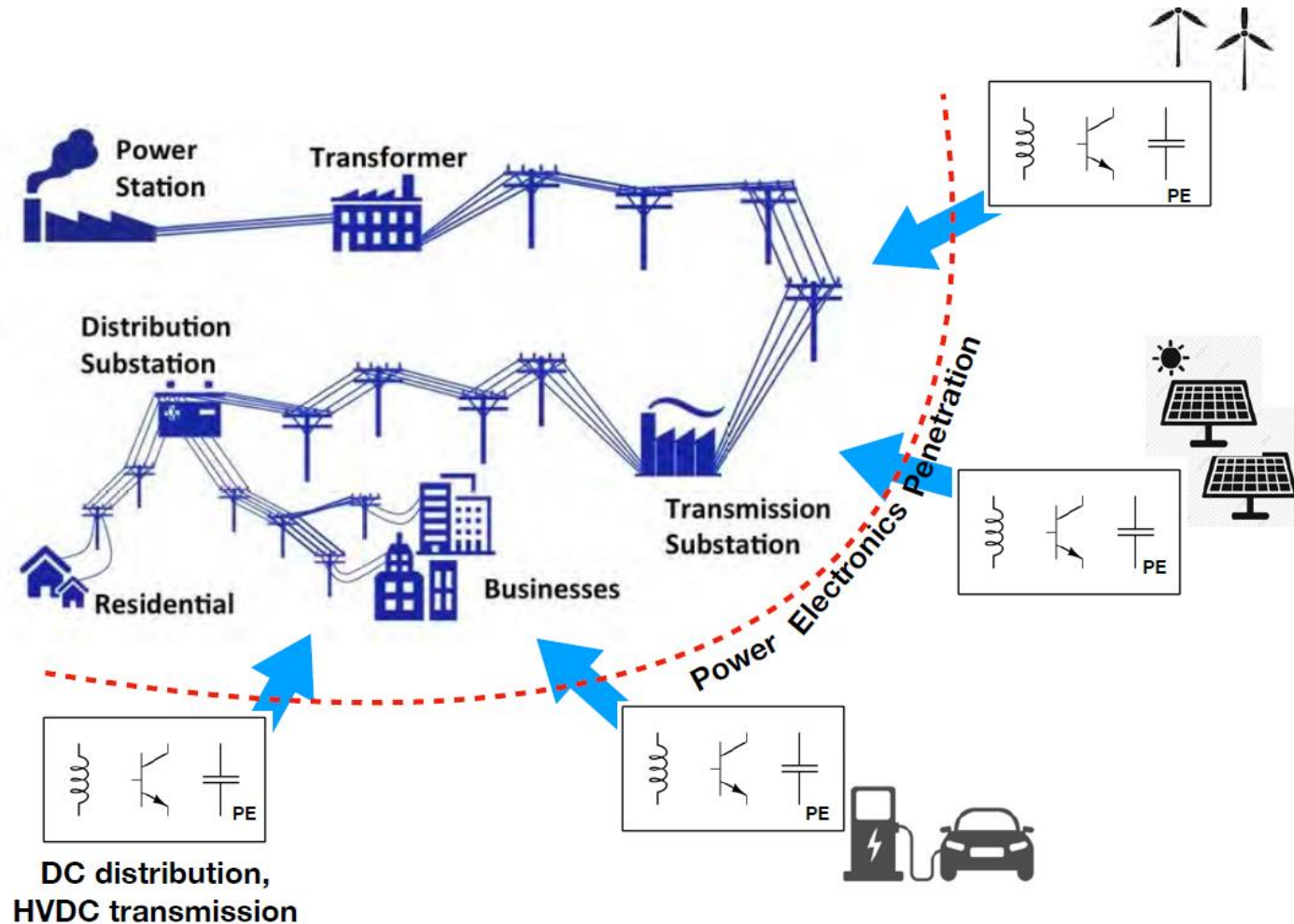
Power plants (coal, nuclear)
Synchronous generators
Small number of renewable sources

Distribution

Transmission
Transformation

Consumption

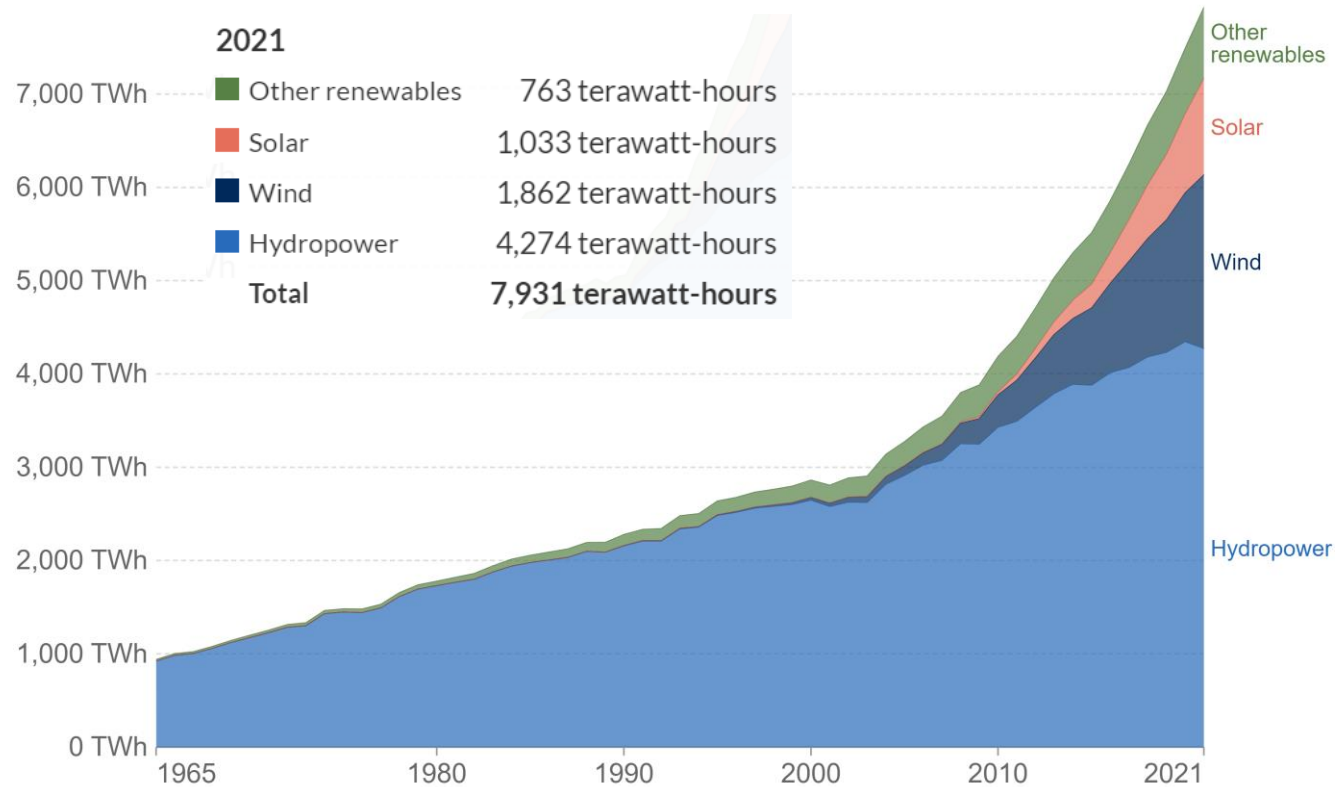
Loads
Active regulated loads



Renewable energy trends

Renewable energy generation, World

Our World
in Data



Source: BP Statistical Review of Global Energy

OurWorldInData.org/renewable-energy • CC BY

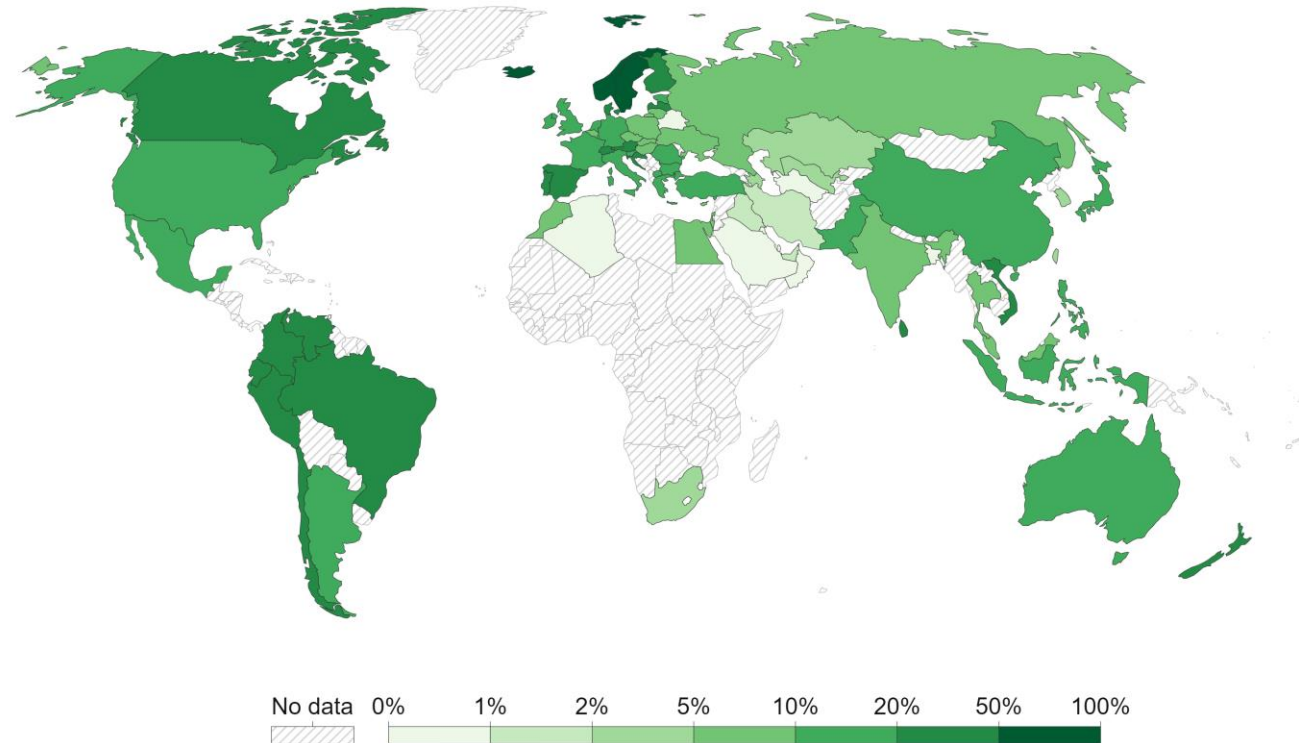
Note: 'Other renewables' refers to renewable sources including geothermal, biomass, waste, wave and tidal. Traditional biomass is not included.

Renewable energy trends

Share of primary energy from renewable sources, 2021

Renewable energy sources include hydropower, solar, wind, geothermal, bioenergy, wave, and tidal. They don't include traditional biofuels, which can be a key energy source, especially in lower-income settings.

Our World
in Data



Source: Our World in Data based on BP Statistical Review of World Energy (2022)

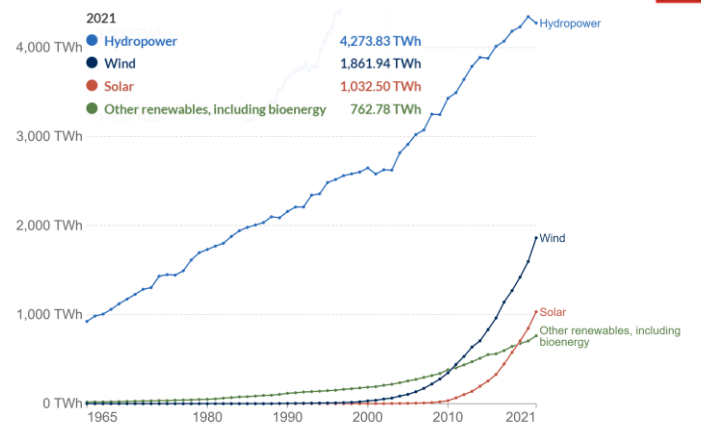
OurWorldInData.org/energy • CC BY

Note: Primary energy is calculated using the 'substitution method', which accounts for the energy production inefficiencies of fossil fuels.

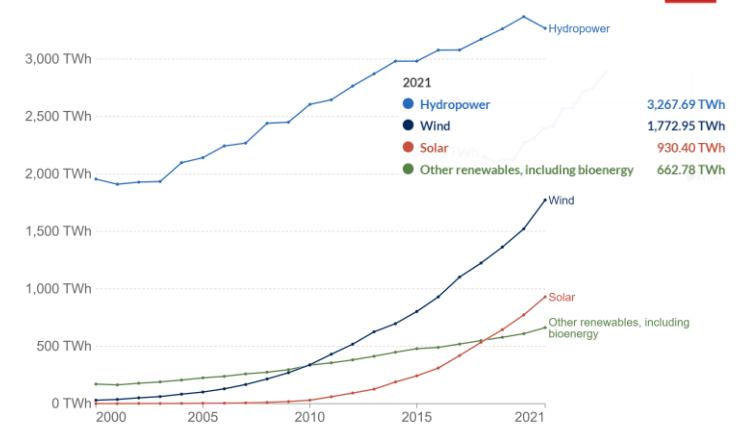
Renewable energy generation by source



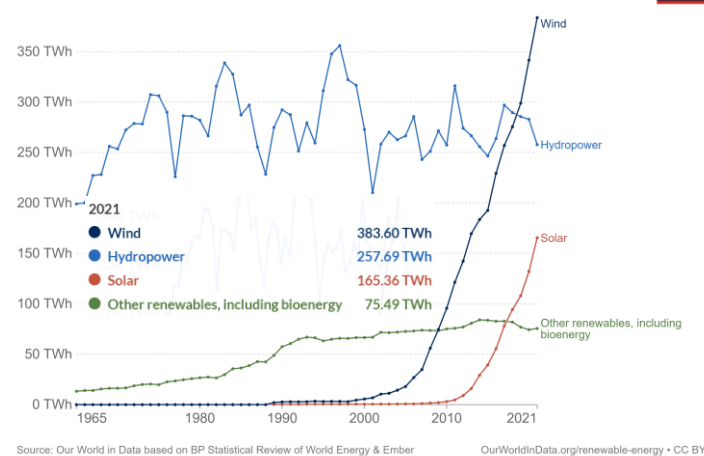
Modern renewable energy generation by source, World



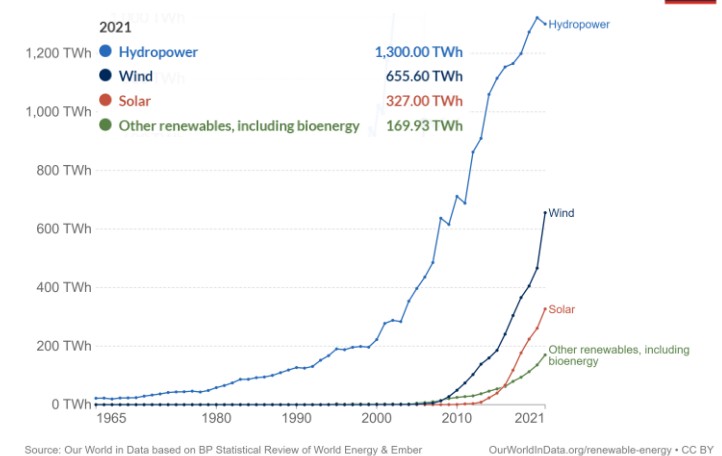
Modern renewable energy generation by source, G20 (Ember)



Modern renewable energy generation by source, United States



Modern renewable energy generation by source, China



Modern grid

Features

Clustering

Intercluster connections

Generators

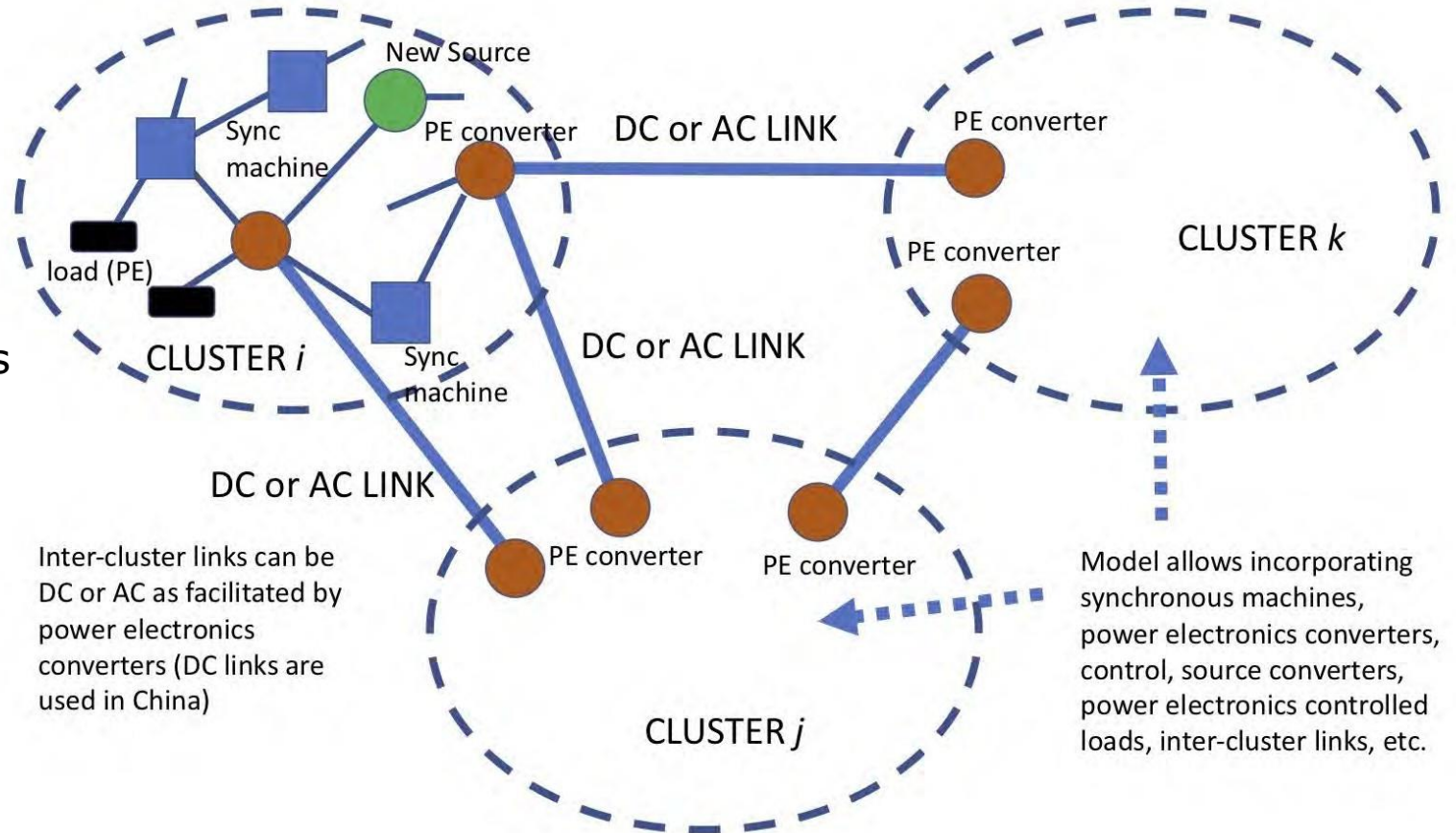
Sync power generators

Renewable power sources

Loads

Conventional loads

Active regulated loads



Driving factors

Towards use of power electronics

Ageing equipment

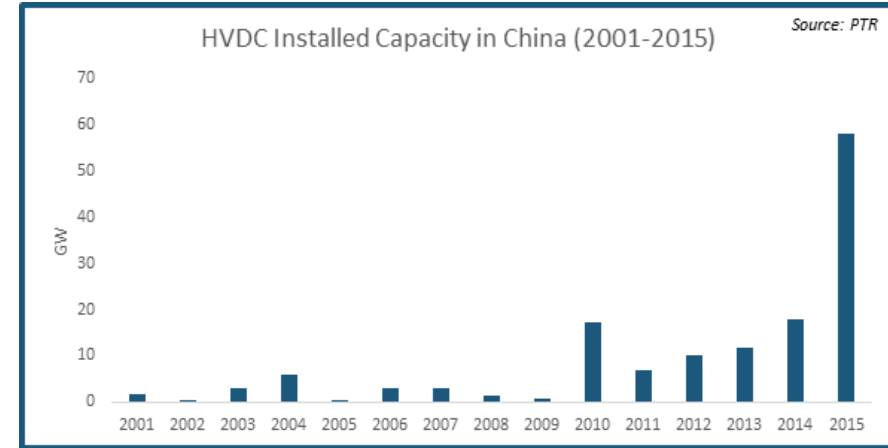
- 70% of transformers are 25 years old
- 60% of circuit breakers are 30 years old (USA, as of 2014)

Power electronics substations

- Solid state transformers (more compact, smaller)
- Control for power quality
- Facilitating DC distribution & transmission

Energy Trading

Bulk power transmission due to uneven source distribution

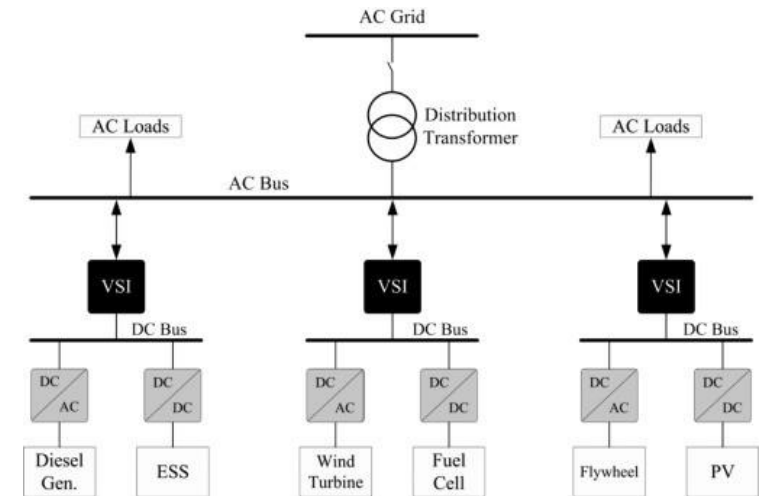


Roughly 60% of the HVDC projects installed after 2010 were 3GW or more in China. State Grid of China (SGCC) plans to spend roughly \$90B just in UHVDC interconnections from 2009 to 2020, and it aims to make more than 20 UHVDC transmission links operational by 2030. The Changji-Guquan UHVDC link, which was commissioned in 2019, will set new records in voltage level, transmission capacity and transmission line length. This 1100 kV UHVDC link is expected to deliver 12GW of power through DC transmission lines spread across 3000 km. It has the capability to transfer 50% more power than 800kV UHVDC transmission links.

Consequence: more deployment of PE

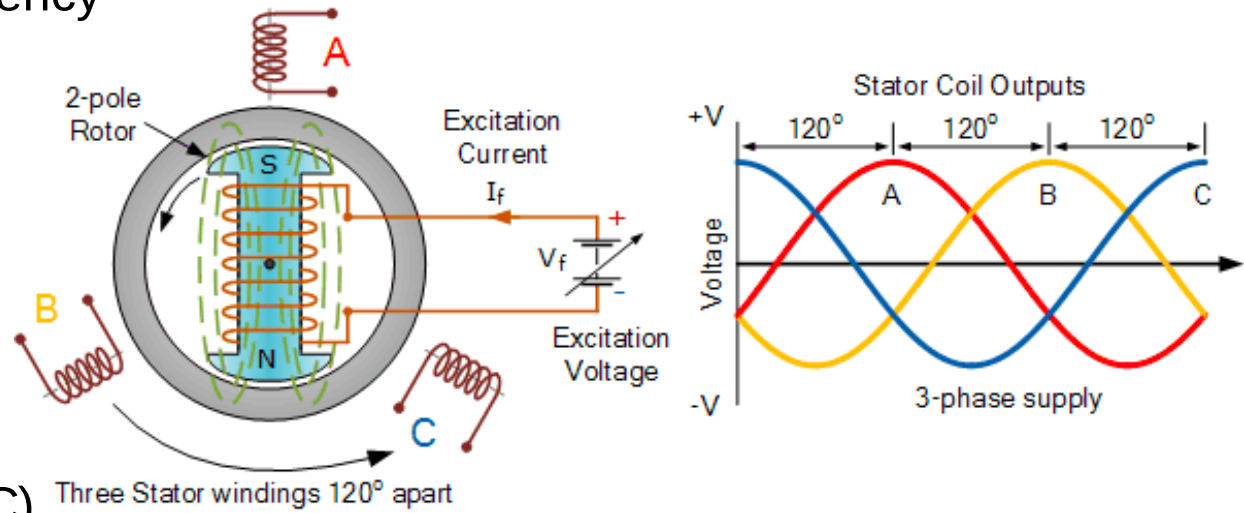


Extensive use of power electronics
for power control
In generation, distribution and
end-user management.

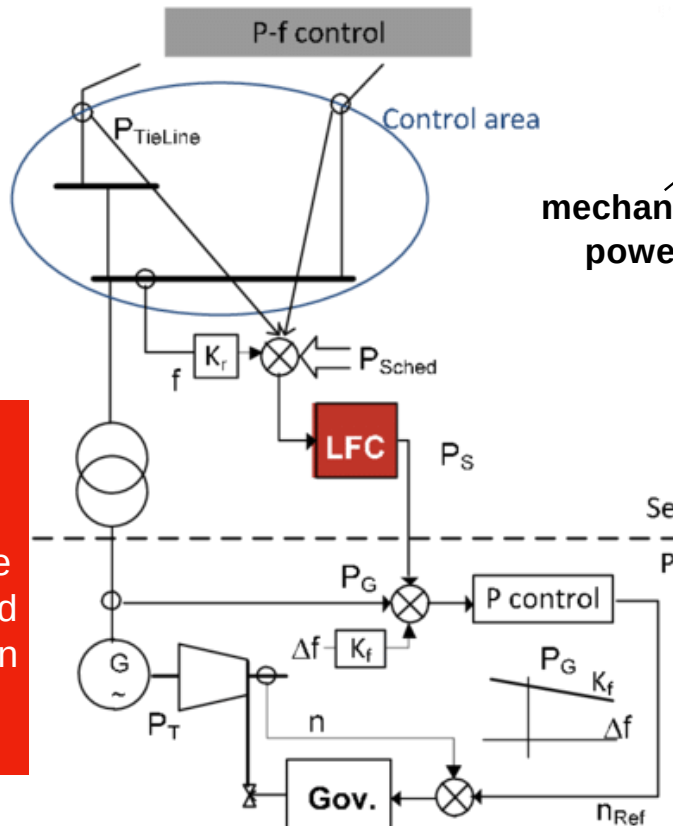


Conventional grid control

- Synchronous machine dominated
 - Rotor creates rotating magnetic field cutting the windings of stator, generating electric current at the same rotor's frequency
- Conventional Control
 - Power $\leftarrow$ shaft torque
 - Output voltage $\leftarrow$ field current
- Automatic Generation Control (AGC)
 - Detects frequency variation and changes torque to balance power
 - Detects voltage variation and changes excitation of generation



Conventional grid control



Frequency-
Power Control

Detects change
in frequency and
adjusts torque in
rotating shaft

Figure Source: K. Máslo and
Z. Hruška, J Energy Power
Sources 2(3), 2015

$$P_m - P_e = T_J \frac{d\omega}{dt}$$

mechanical power electromagnetic power inertia Frequency

Purpose

Maintain a stiff grid with stable frequency and voltage

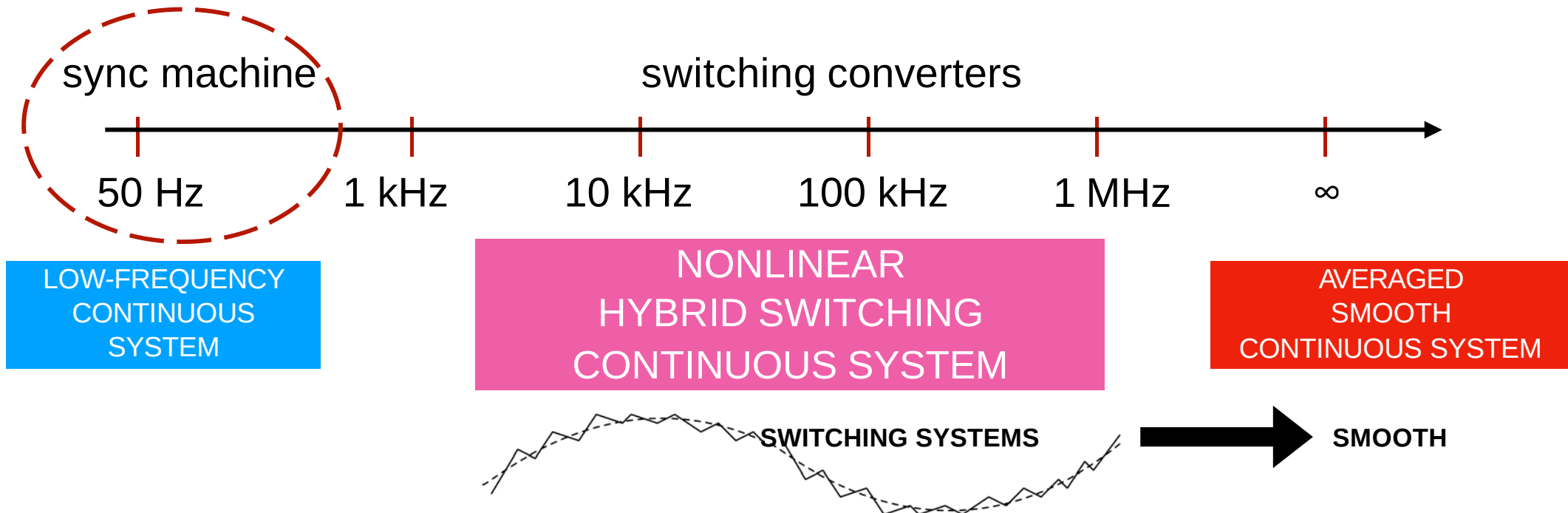
If power electronics converters are added, they try to perform their functions by relying on the stiff grid providing stable voltage and frequency! That's the so-called **grid-following** converter system.

This only works as long as the grid is still stiff, i.e., dominated by synchronous machines!

Power electronics - What's the difference?

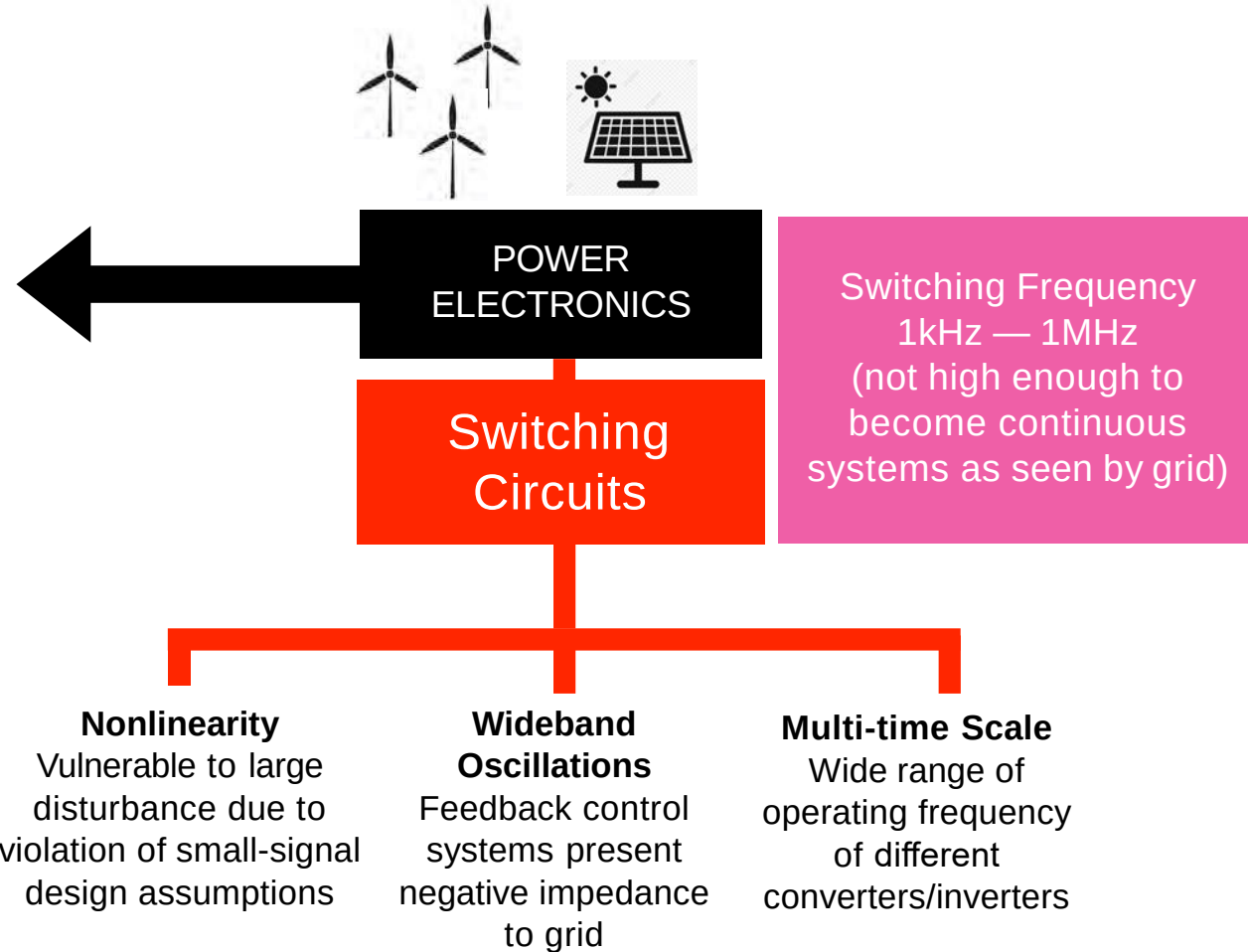
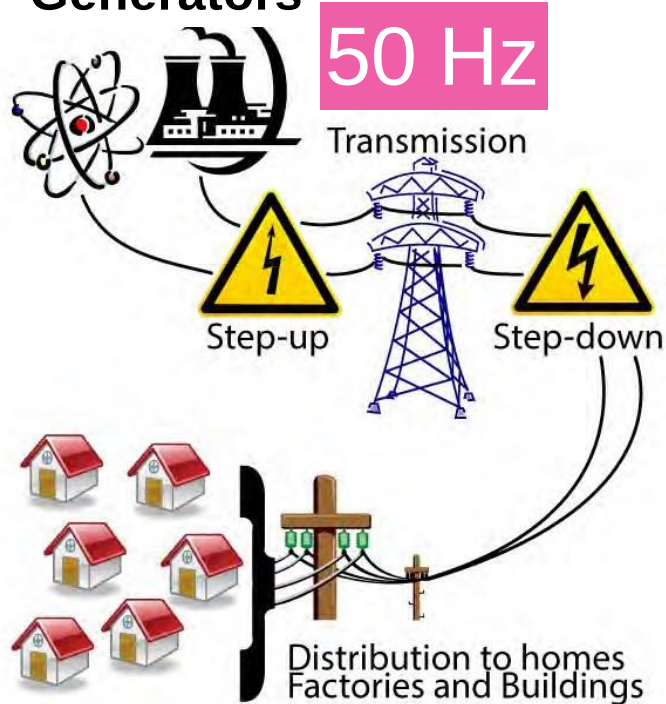
Power electronics is the application of **electronics** to the control and conversion of **electric power**.

Power converters work in switching mode, i.e., toggling of two or more circuit topologies to modulate power flow, but there is ***NO STANDARD switching frequency!***



Power systems vs power electronics

Synchronous Generators



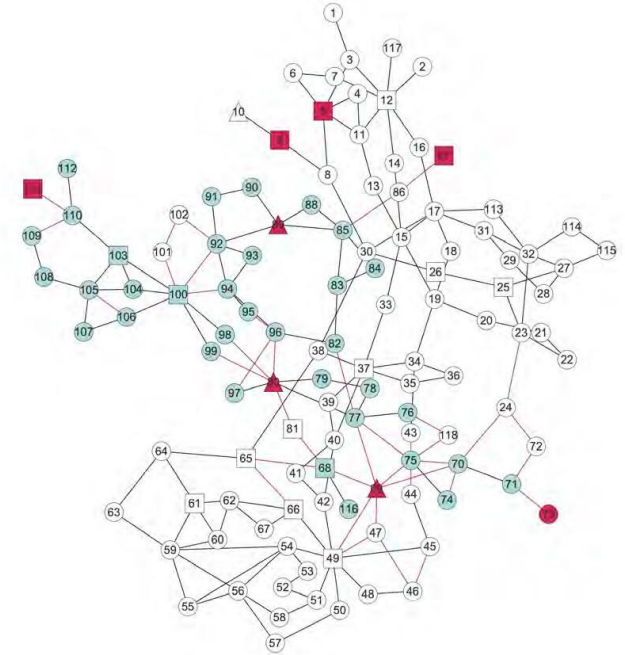
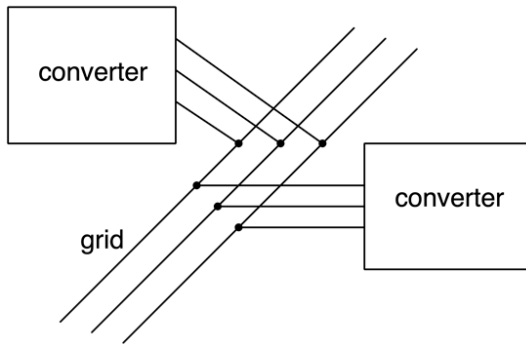
Basic issues

- LARGE DISTURBANCE
 - Nonlinear systems linearized for small-signal design
 - Violation of small-signal assumption leads to design inconsistency
- OSCILLATION (INSTABILITY)
 - Power converters are control systems with feedback to optimize performance. High performance needs high-gain and wideband loop, presenting to grid as *negative impedance!*
- MULTI-TIME SCALE
 - Variety of operating switching frequencies. Analysis is not scalable!

Two distinct approaches

Bottom-up (circuits with grid connection) approach

- Gives detailed views of the dynamics of devices at specific locations or groups of grid-connected devices.
- Does not offer a comprehensive view of the entire connected system (e.g., when the effects of dynamic processes or events in one local area extend to other parts of the system).



Top-down (networked systems) approach

- Considers the grid as a large-scale network with groups of subsystems sharing similar properties, and examines phenomena at global level.
- Does not offer detailed circuit-level mechanisms, e.g., unstable operations.

[No mature method developed so far.]

Samples of methods

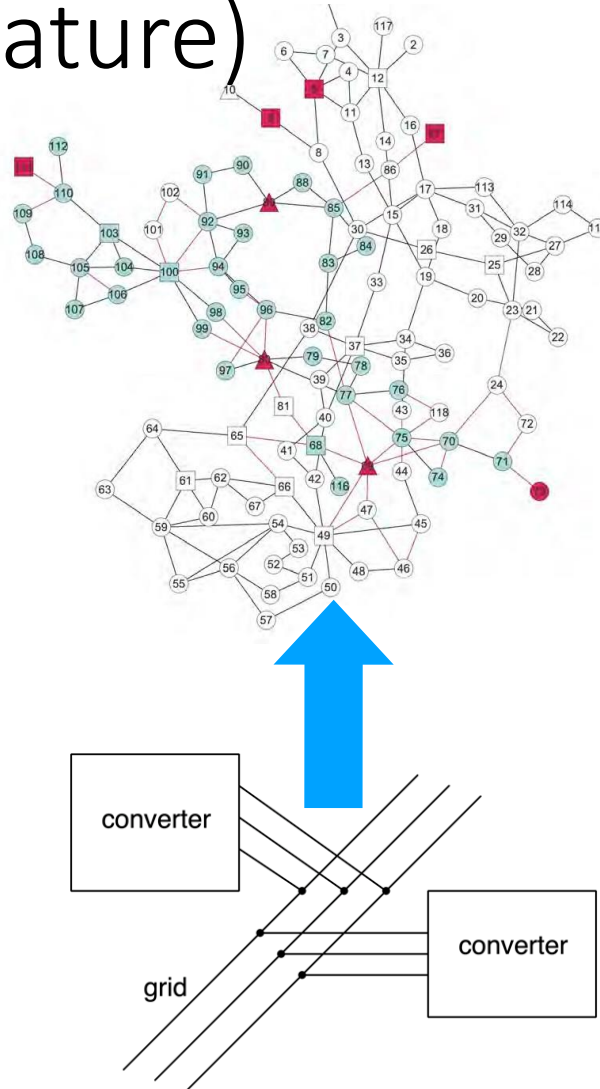
BOTTOM-UP (LOCAL)

Approaches	Perspectives	Sample Issues	Sample Methods
Bottom-up	Local	Stability - Oscillation - Bifurcation - Operating boundaries - Effects of parameter changes - Mutual interactions	Small-signal model Impedance method Large-signal model Circuit theory Differential equation Frequency-domain method Switching dynamical circuit analysis Parameter analysis Sensitivity analysis

TOP-DOWN (GLOBAL)

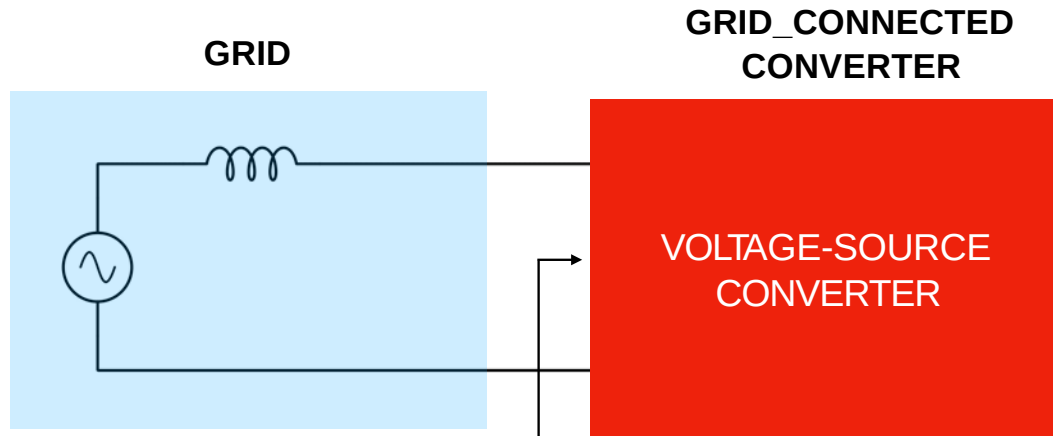
Approaches	Perspectives	Sample Issues	Sample Methods
Top-down	Global	Stability - Synchronization Robustness - Failure events - Cascading failure - Metrics Effects of topology Effects of coupling Dynamic state estimation	Network theory Multi-timing dynamic system model Power flow analysis Topology analysis Markov chains Stochastic processes Probability theory Game theory Complex network concepts & metrics Cyber-physical system model Nonlinear Kalman filtering

Review of bottom-up approach (relatively more mature)

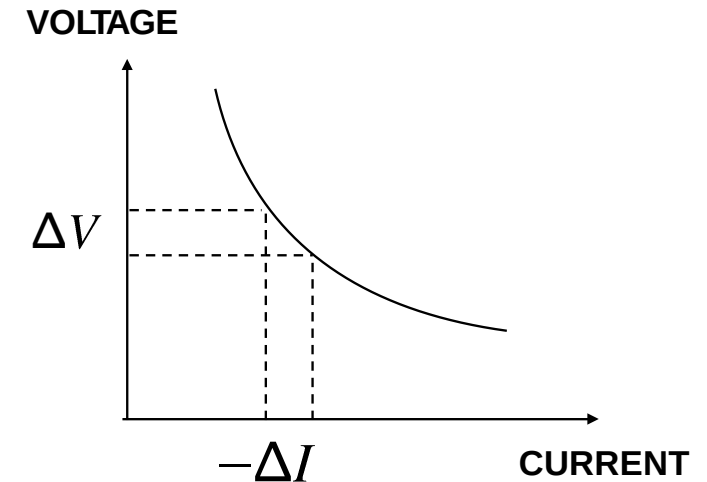


Conventional methods

- Traditional small-signal models and linearized analysis
- Impedance based stability criteria (e.g., Middlebrook's criterion, Nyquist, ...)

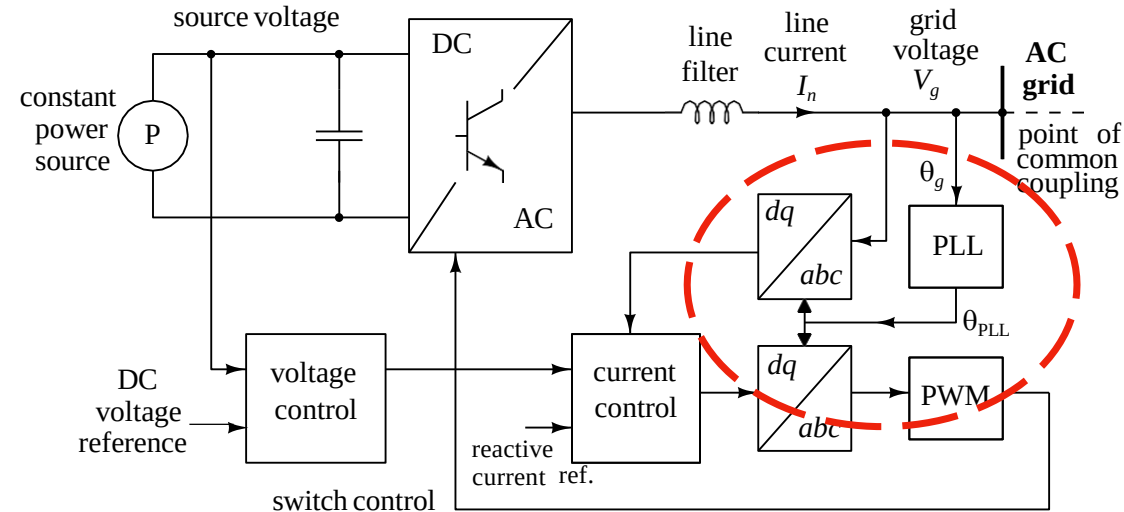


Negative Impedance if the VSC is very tightly regulated such that its output delivers **CONSTANT POWER**



Sources of nonlinearity

- **Power synchronization control contains PLL which is nonlinear.**
- Saturation nonlinearity from hard limiter.
- Overmodulation leading to saturation, causing irreversible instability
- Converters' interaction via grid coupling



Nonlinear damping of PLL

Nonlinear phase detector:

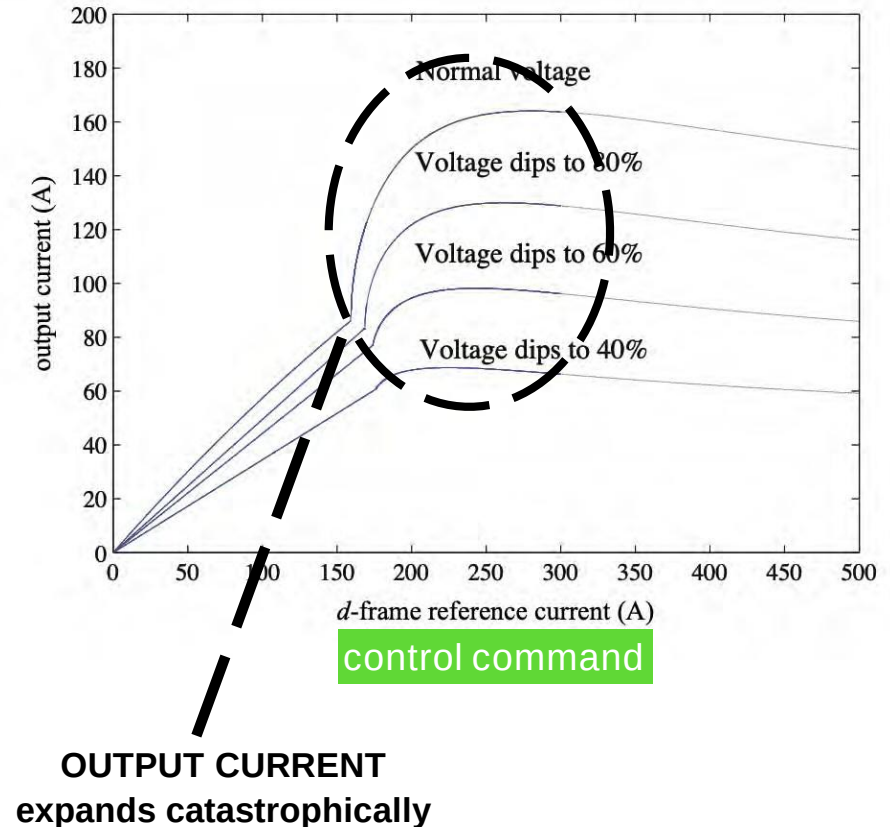
- Rapid drop in damping at small short-circuit ratio (weak grid)
- Short-circuit ratio = $V_g / I_n Z_s$

grid voltage
line current
source impedance of grid

- Unstable operation as damping weakens

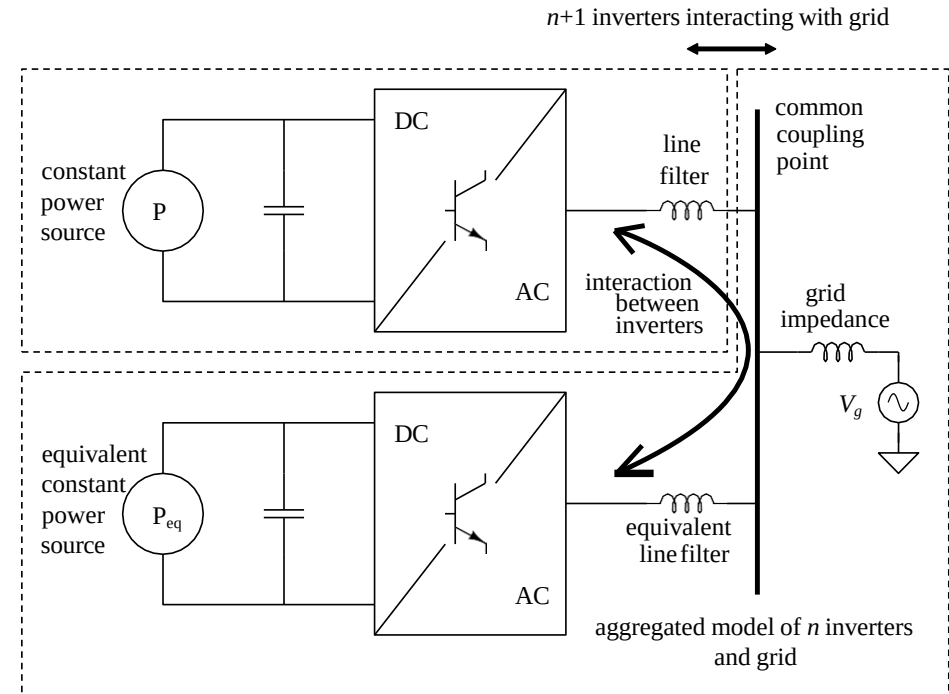
Sources of nonlinearity

- Power synchronization control contains PLL which is nonlinear.
- **Saturation nonlinearity from hard limiter.**
- **Overmodulation leading to saturation, causing irreversible instability**
- Converters' interaction via grid coupling



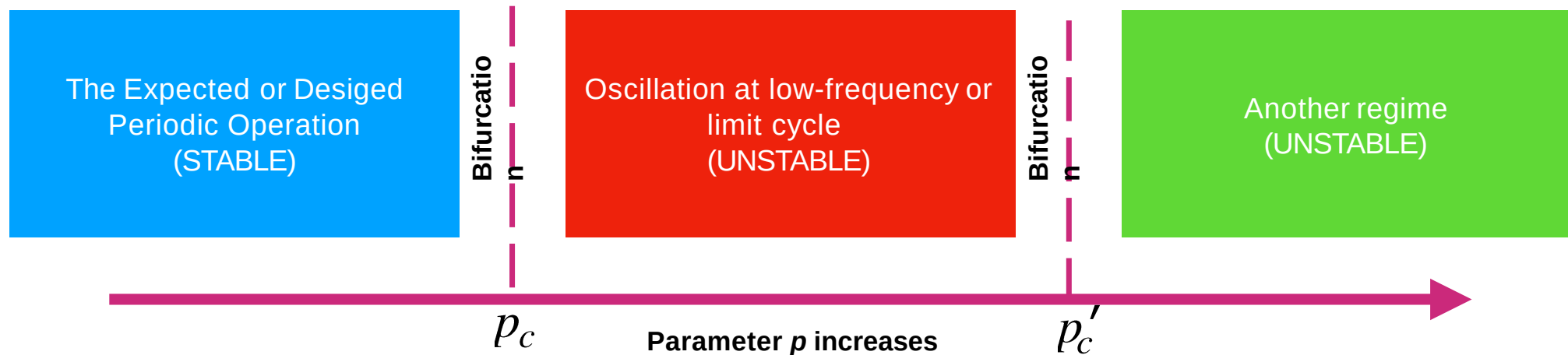
Sources of nonlinearity

- Power synchronization control contains PLL which is nonlinear.
- Saturation nonlinearity from hard limiter.
- Overmodulation leading to saturation, causing irreversible instability
- **Converters' interaction via grid coupling**

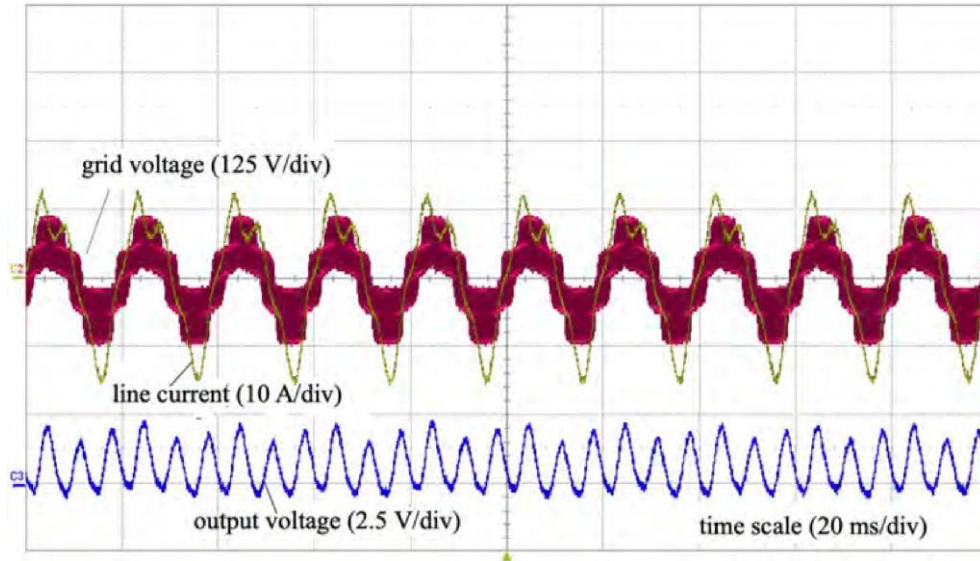


Bifurcation analysis

- Bifurcation — *Change in qualitative behavior as one or more parameters are varied.*
- It is basically a study of STABILITY, if we define one kind of behavior as the stable operation (one of the regimes).
- Bifurcation analysis is therefore nothing but stability analysis extended to MORE THAN one operating regimes.



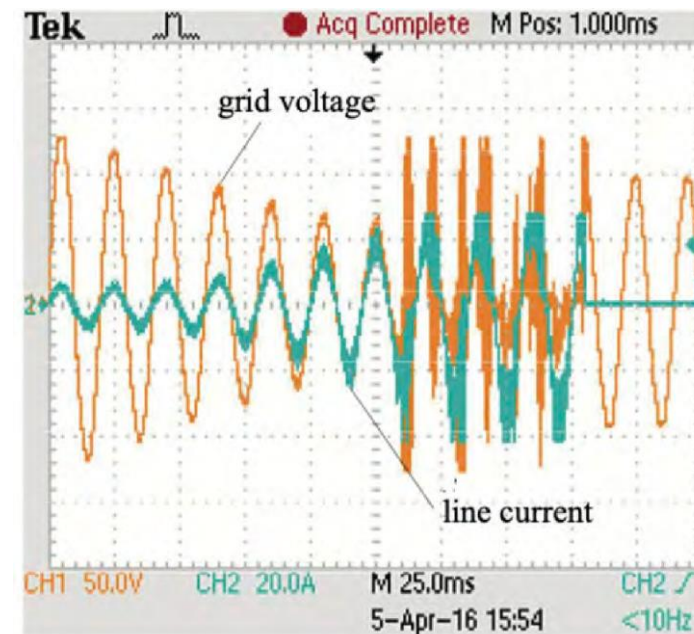
Examples of bifurcation or loss of stability



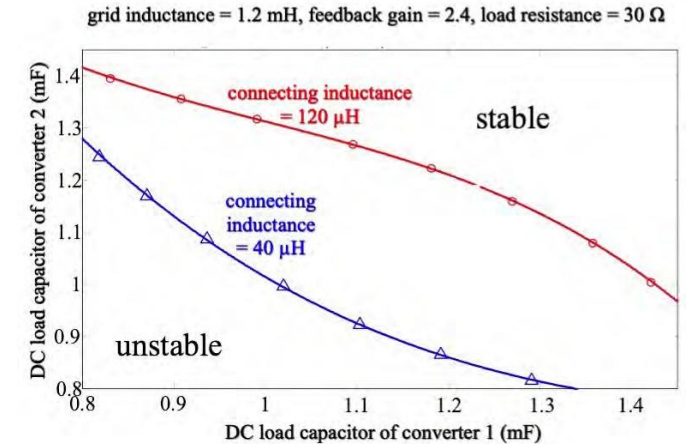
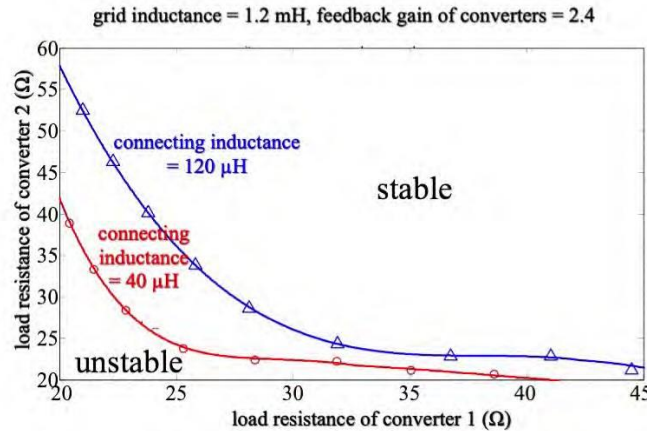
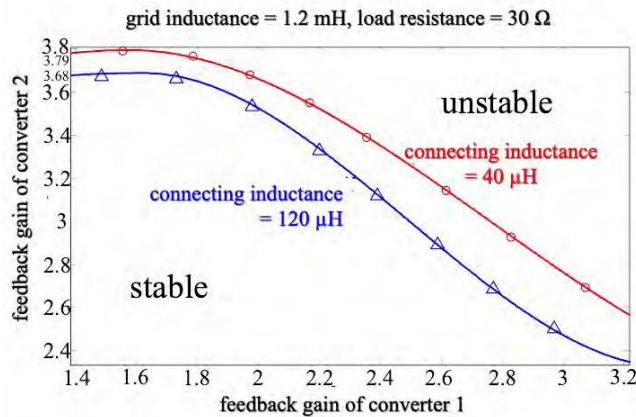
Hopf bifurcation in three-phase **grid-connected voltage source converter** showing high harmonic contents in grid voltage and line current, and AC coupled load voltage, as the load current increases to a certain value.

Bifurcation due to Saturating Nonlinearity

Measured line current and grid voltage from grid-connected three-phase voltage source converter showing irreversible large-signal instability. The system fails to return to stable operation even after reversing the parameter change (reducing the reference current).



design-oriented bifurcation analysis



Bifurcation Analysis

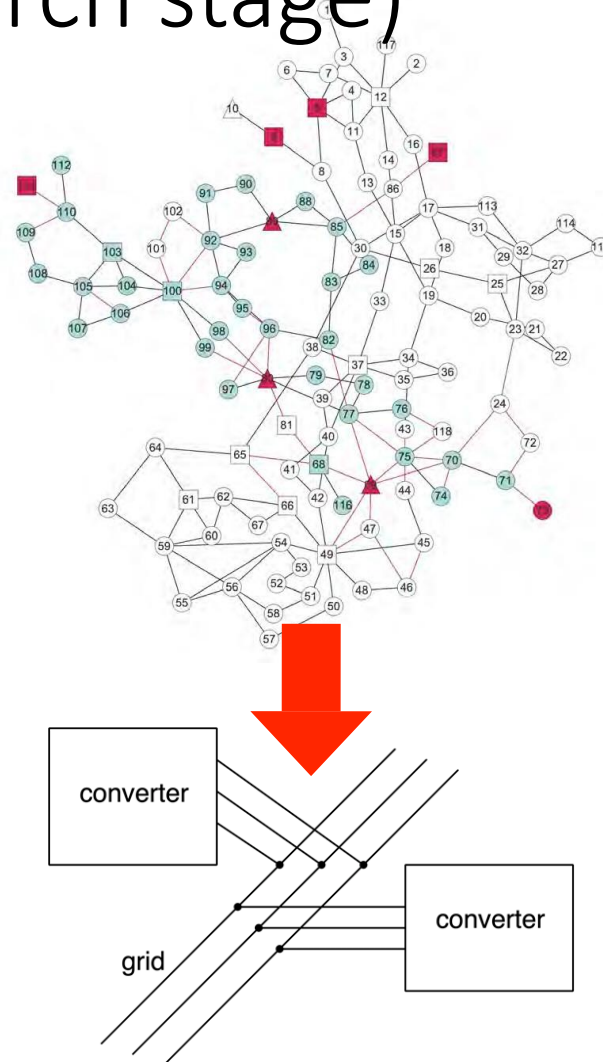
— Stability analysis of local linearized models, but MOVING operating point.
It is thus NOT a linear method strictly speaking, though at each operating point, it is!

Regions of different operating regimes in parameter space

Location of stable / unstable operation boundaries

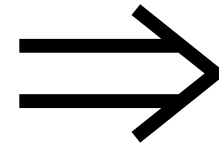
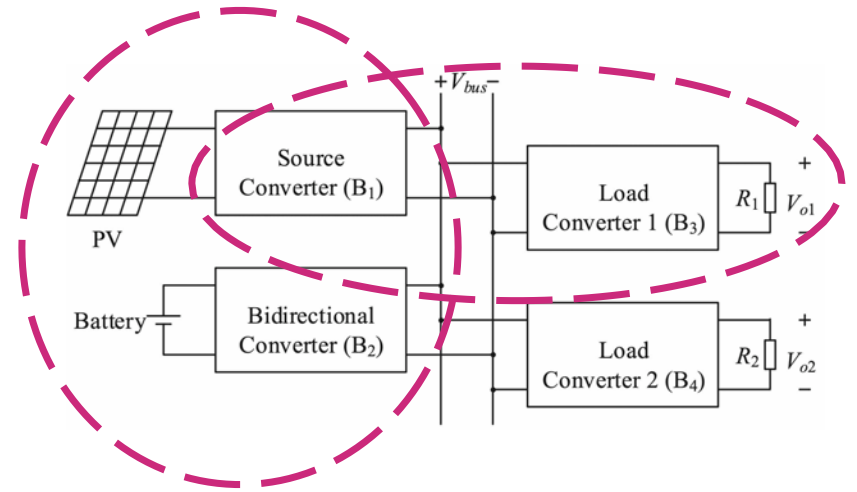
Identification of affecting parameters, e.g., connecting inductance

Preview of Top-Down Approach (immature research stage)



The need for global view

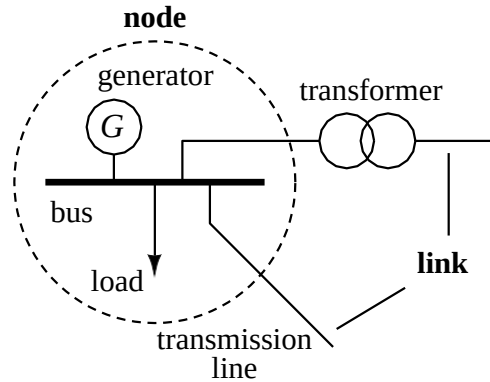
- Analysis under the local or bottom-up perspective can be extended to cover a group of equipment surrounding the point of common coupling, or even groups of equipment interacting via a few points of common coupling.
- However, if we continue to take a bottom-up approach, we **will soon be stuck** by the *escalating complexity of carrying out circuit analysis when the number of interacting devices becomes large or the area of interaction widens.*



GLOBAL PERSPECTIVE looks at the system as a whole and identifies key properties and their relationships with system parameters and network structure.

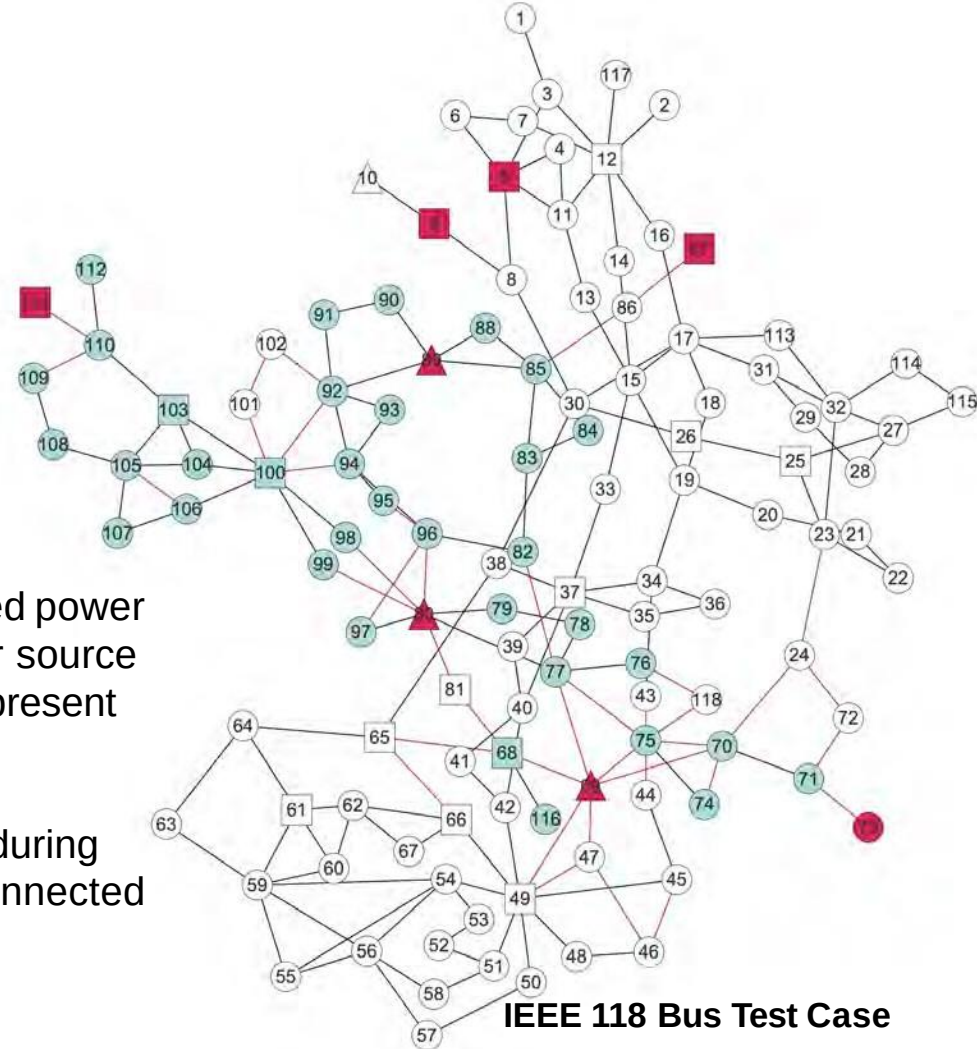
Network model

NETWORK: NODES LINKS



Rectangles represent synchronous generator-based power source nodes; triangles are converter-based power source nodes; circles represent consumer nodes; links represent transmission lines or transformers.

Red nodes and links are overloaded and tripped during the cascading failure process; **blue ones** are disconnected from the power sources and deprived of power.

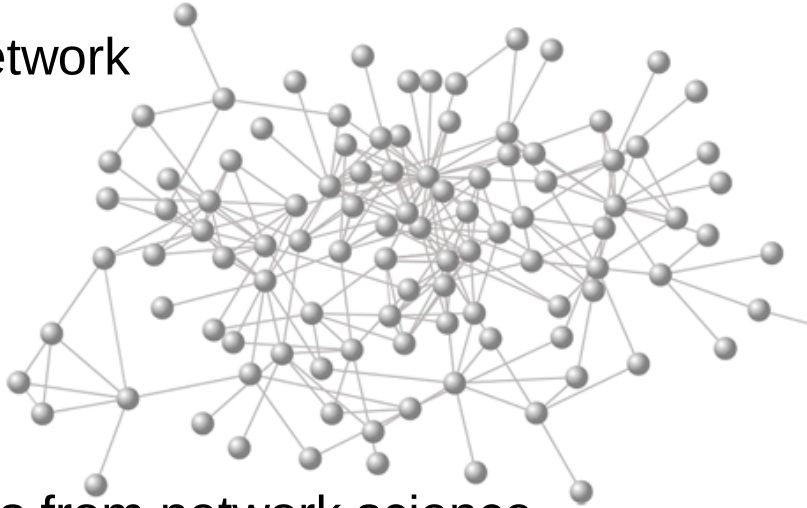


IEEE 118 Bus Test Case

Network model

Complex network

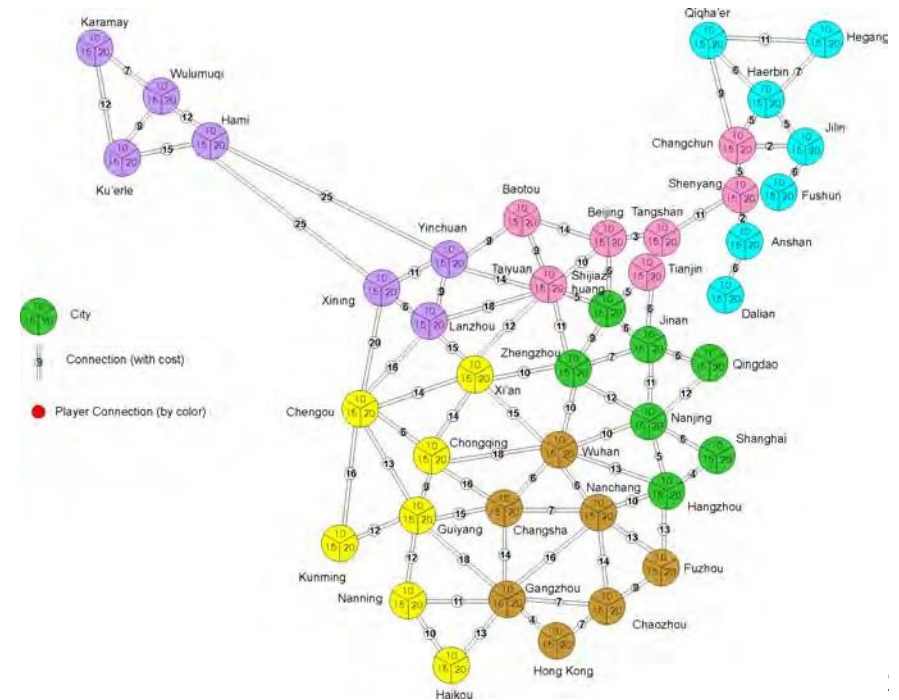
- nodes
- links



- Rich results from network science
 - characterisations: degree, distance, betweenness, clustering, ...
 - impact of structures
 - efficiency of information transfer
 - routing, etc.

Power grid

- generators, transformers, loads
- transmission lines



Prior work in applying complex network results

Check carefully the CASCADING failure sequences!!!!

Study of networks coupling in theoretical sense and impact on cascading failure.

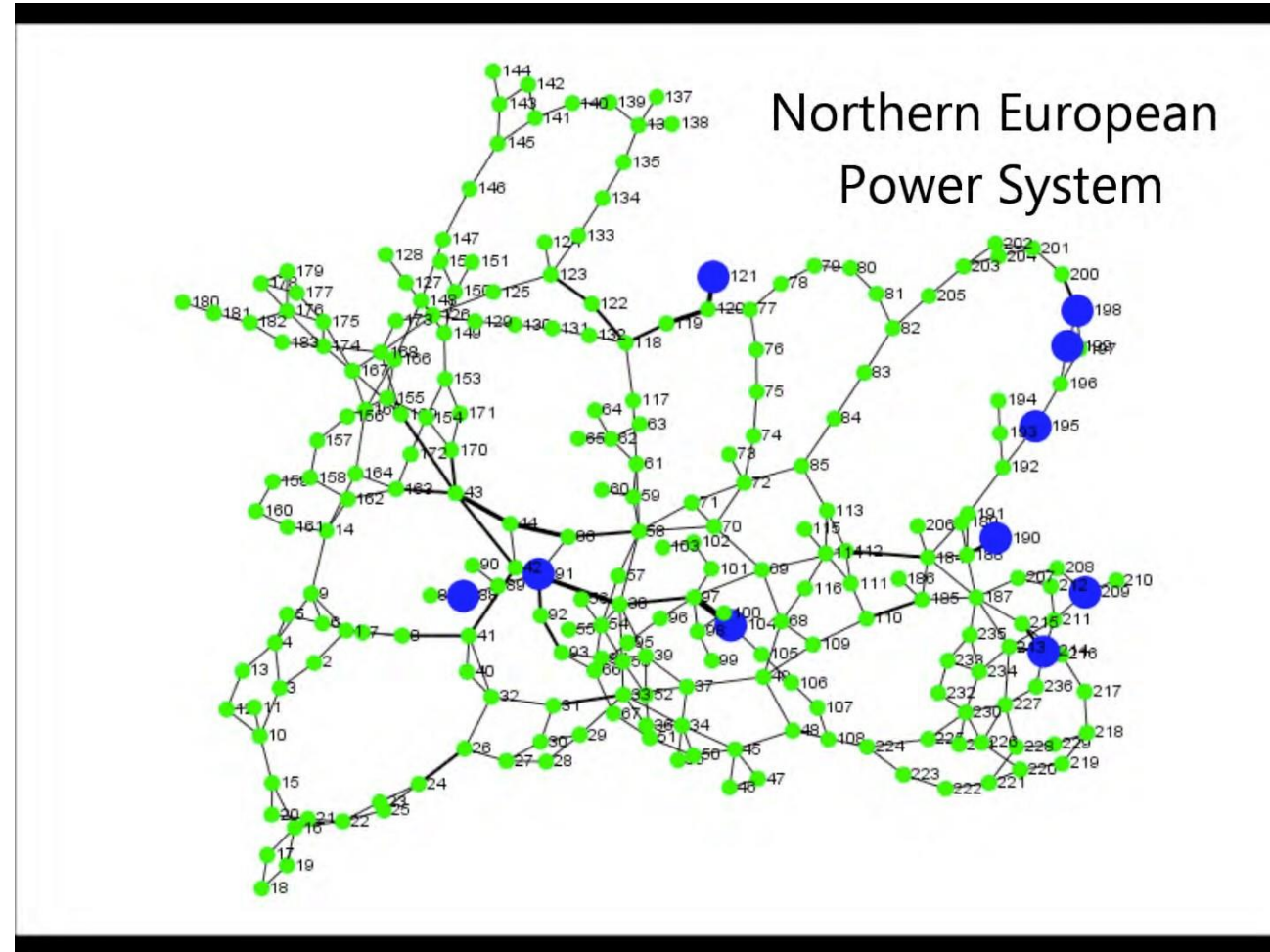
Electrical network operation simplified, and in most cases, not consistent with physical laws:

- Power flow re-distributes according to shortest paths
- Current flows to low degree nodes
- Failures get transmitted like disease transmission

Giving

- **Inconsistent results**
- **Conflicting conclusions**
- **Serious discrepancies**

Unable to reproduce the failure profile.

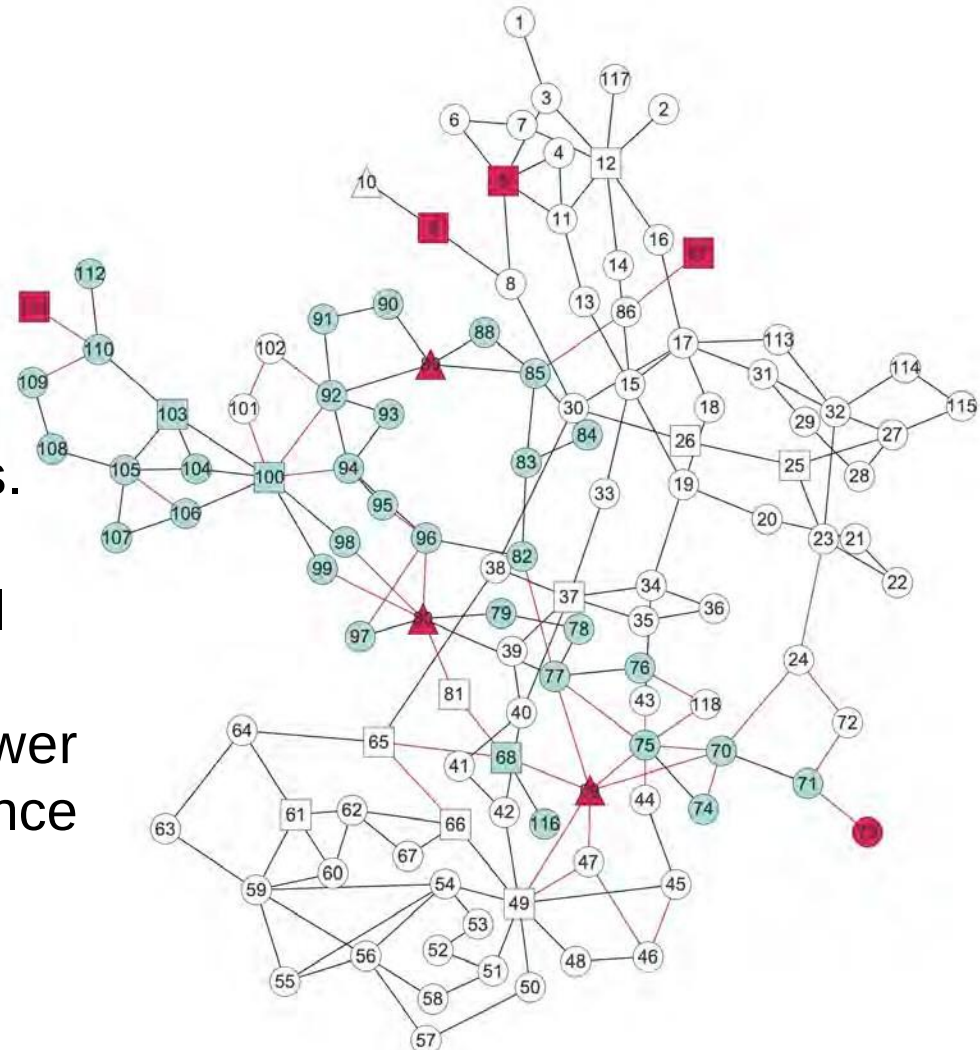


Key remedies

Physical process must be considered.

Power flow according to Kirchhoff's laws and electrical properties of the components.

The Oak Ridge-PSEERC-Alaska (OPA) model (2007) and Zhang-Tse model (2015) use the DC power flow calculation to determine power distribution after each failure event, and hence accurately track the overloading nodes (components).



I. Dobson, B. A. Carreras, V.E. Lynch, and D. E. Newman, "Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization," *Chaos Interdiscipl. J. Nonlinear Sci.*, vol. 17, no. 2, 2007, Art. no. 026103.

X. Zhang and C. K. Tse, "Assessment of robustness of power systems from a network perspective," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 5, no. 3, pp. 456–464, Sep. 2015.

Key remedies

Actual times between successive failures must be considered.

A stochastic process can be applied to provide very *consistent* estimates of the successive failure time points, as shown in Zhang-Zhan-Tse (2017).

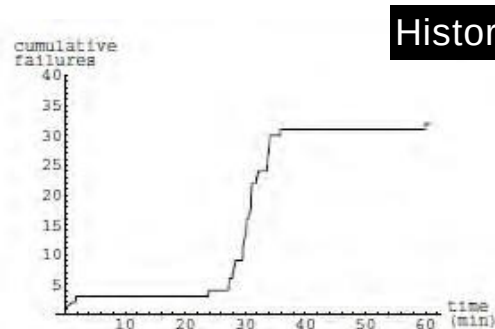


Figure 1. Cumulative line trips in WSCC July 1996 blackout. Time scale is minutes after 14:00 MDT.

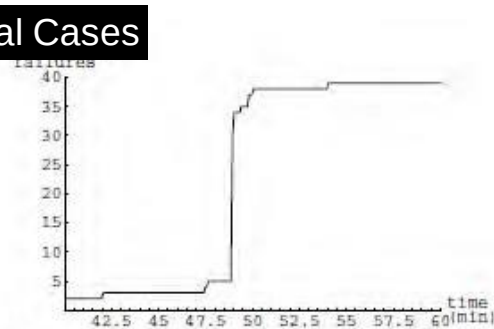
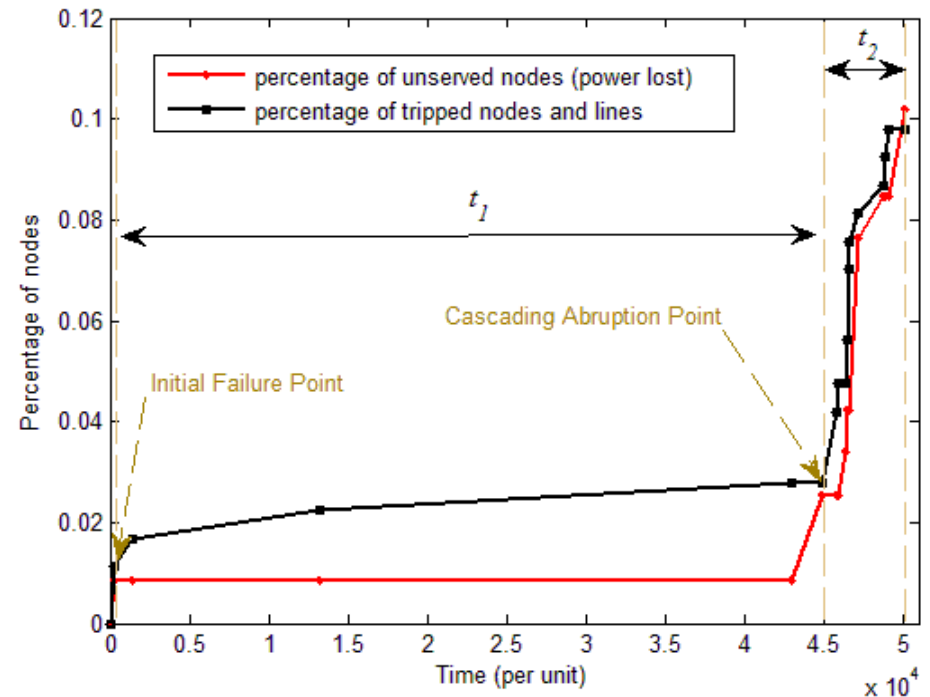
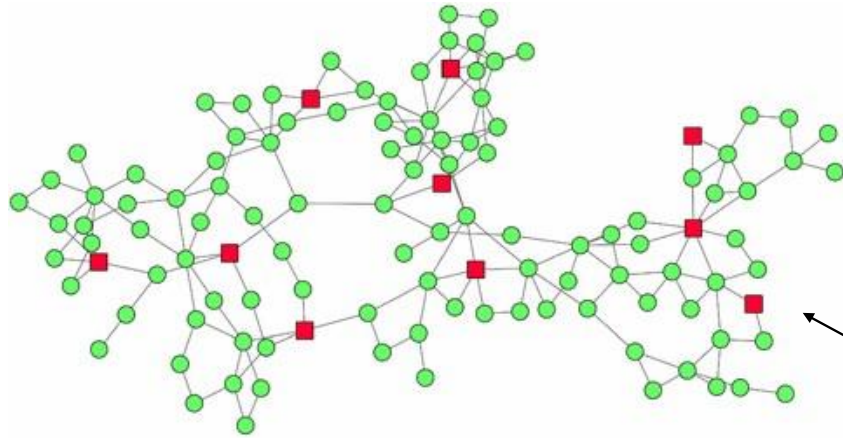


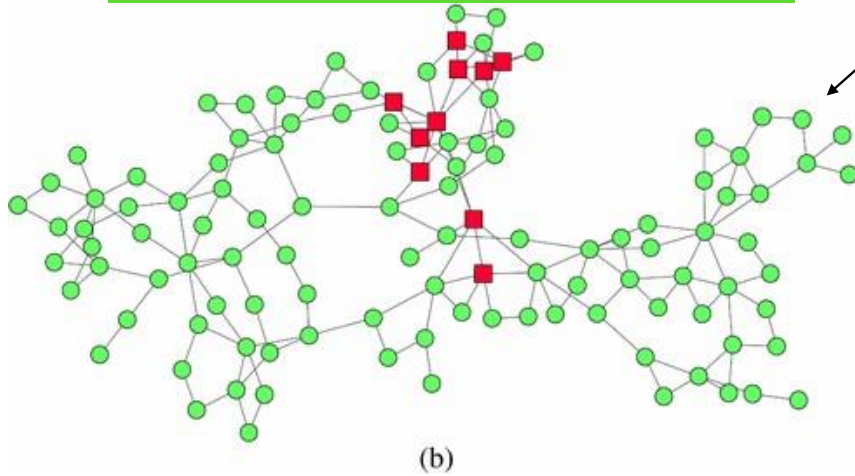
Figure 3. Cumulative line trips in WSCC August 1996 blackout. Time scale is minutes after 15:00 PDT.



Up to this point



Decentralization of power accessibility



(b)

- We have a network model for assessing cascading failure. Applications have been attempted in
 - Robustness assessment
 - Prediction of outage coverage
 - Comparison of network structures
 - Restoration strategies
- The grid is, however, still evolving, and increasing use of power electronics means that
 - *failure mechanisms of PE nodes* must be re-examined
 - effects of PE nodes on *failure of other non-PE nodes* should be studied.

The Challenge:

Penetration of Power Electronics

Modeling the increasing number of PE nodes for assessment of risk and robustness.

Developing control strategies that balance the grid-following function and grid-forming support.

Re-iteration of Key Features

Fundamental difference in dynamics of synchronous machines (slow mechanical power) and power electronics (fast electromagnetic power redistribution).

Synchronous machines:

$$P_m - P_e = T_J \frac{d\omega}{dt}$$

mechanical power electromagnetic power inertia Frequency

- Frequency variation indicates deviation from normal operation - control method derived as explained before
- Inertia resists frequency variation - PE has zero inertia

EFFECTS OF POWER ELECTRONICS

Grid-following inverters inject current to grid with a PLL and do not help control the frequency!

Thus, more PE will make the overall K_G smaller, and the control of frequency less effective!

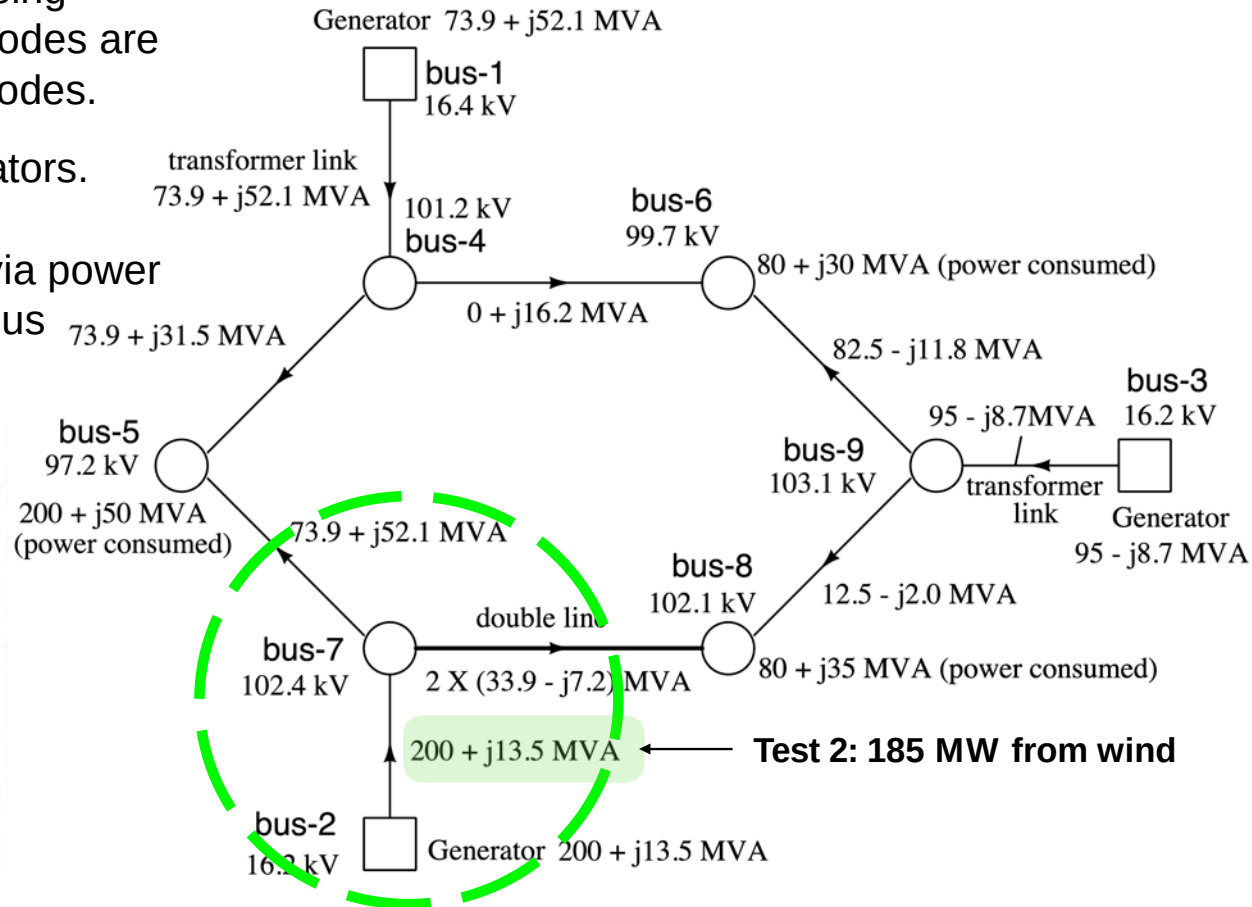
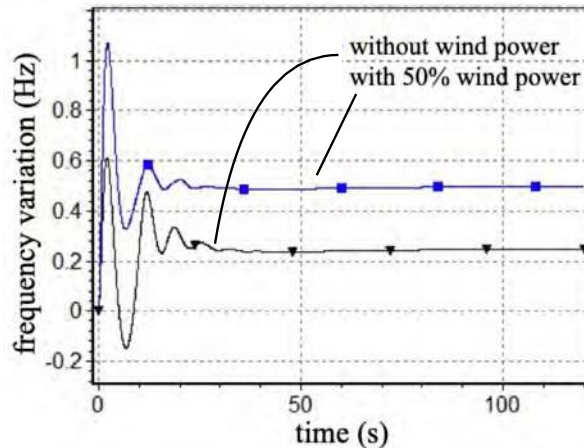
$$\Rightarrow P_G = P_{G0} + K_G \Delta\omega$$

Simple tests

IEEE 9-Bus test case with all 3 generators being synchronous generators. Complex power at nodes are power consumed by loads connected to the nodes.

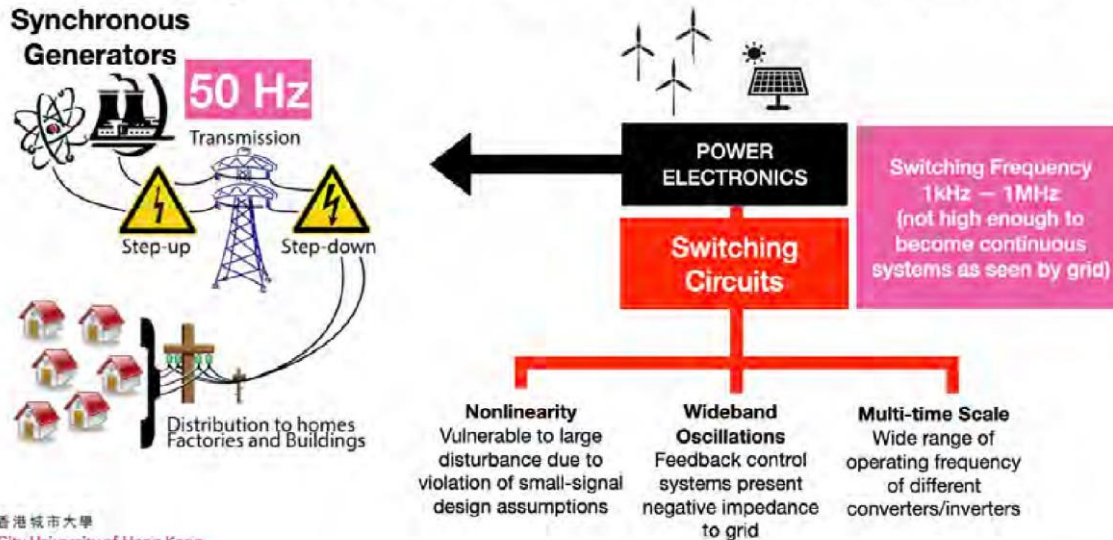
Test 1: all generators are synchronous generators.

Test 2: bus 7 takes 185 MVA from wind farm via power electronics and $15 + j13.5$ MVA from synchronous generator, *i.e., 50% wind power overall!*



Re-iteration of key features

Power Systems vs Power Electronics



Basic Issues

- LARGE DISTURBANCE
 - Nonlinear systems linearized for small-signal design
 - Violation of small-signal assumption leads to design inconsistency
- OSCILLATION (INSTABILITY)
 - Power converters are control systems with feedback to optimize performance. High performance needs high-gain and wideband loop, presenting to grid as **negative impedance!**
- MULTI-TIME SCALE
 - Variety of operating switching frequencies. Analysis is not scalable!

Challenges: how to incorporate power electronics nodes in the network model and to effectively describe all failure events

Challenges

Challenge 1: Multi-Timing

Mix of dynamical systems of different time scales:

- high performance PE
- slow sync machines
- daily fluctuations
- Seasonal fluctuations

Challenge 2: Diversified Dynamical Behavior

Systems with different dynamical features:

- zero inertia PE at different switching frequencies
- tightly PE regulated loads
- high inertia machines
- battery storage

Challenge 3: Defining Appropriate Measures

Identification of effective measures:

- assessing stability
- assessing robustness
 - risk of cascading failure
- outage extent vs the level of PE penetration

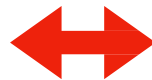
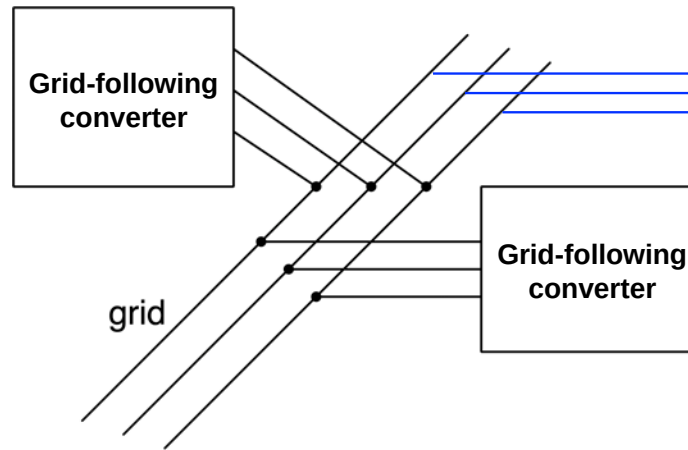
Challenges

Challenge 4: Control Design and Conflicts

Grid-following converters

- pump current to grid from renewable sources or as current loads
- do not participate in grid frequency control

- *actually rely on the grid's stiff frequency and voltage!*



The grid gets less stiff as the percentage of synchronous machines drops!

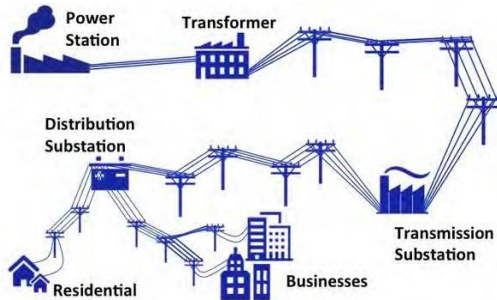
GRID-FORMING
CONVERTER

Supports the grid by participating in grid frequency and voltage control, typically via a droop strategy.

But then, we are still trying to preserve the old grid control environment!

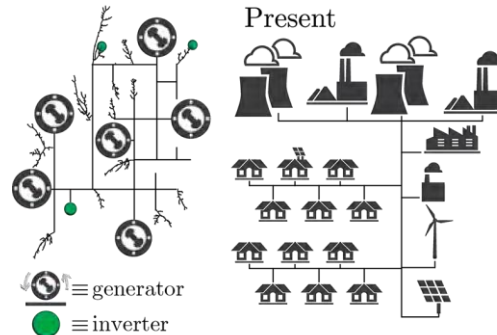
Can the grid control be completely changed?

Dilemma - when will we abandon it?



If PE penetration is still shallow,

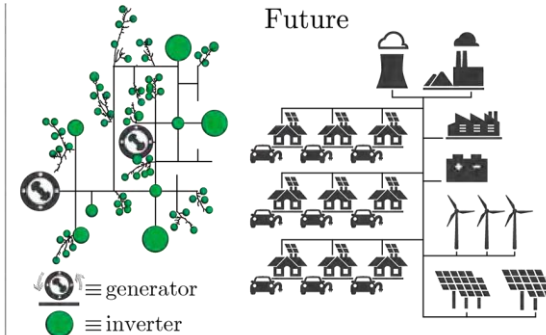
just following the grid, assuming the grid promises its frequency and stiff voltage! That means converters are designed with the grid as a pretty good AC voltage source.



If PE penetration gets deeper,

the grid weakens as sync machines get a lesser share; hence, voltage and frequency no longer as stiff!

Apply grid-forming to restore stiffness or even *fake* the grid, so that the grid following devices continue to work!



If PE eventually dominates, the grid's old properties are maintained artificially, if we continued along the same path (???)

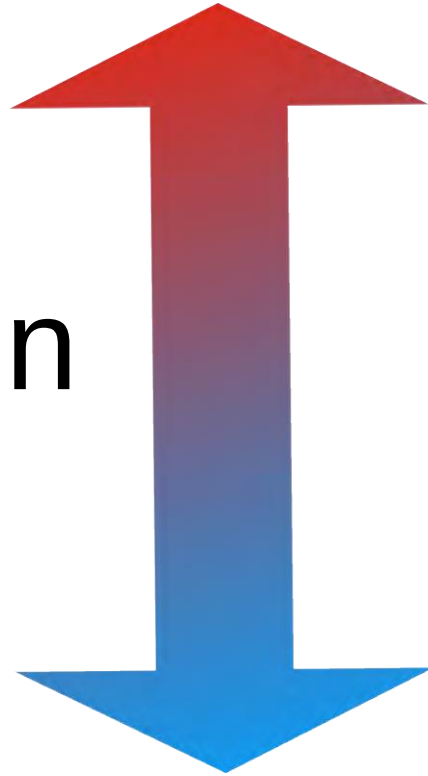
The PE-dominated grid is not the same grid, then why still fake the same old properties?

Eventually, we will have to make a real change!

Top-Down Approach

(immature research stage)

Conclusion



Through combining the top-down and bottom-up approaches, we hope to be able to build better models that can incorporate increasing PE devices into the grid model, hence providing realistic assessments of the risk and robustness of the grid.

To develop relevant system planning and construction strategies for power companies to avoid detrimental stability problems that may emerge in the continuous development of the power system.

In the transition process, we have to balance between

- *PE current sources — Grid following control*
- *PE voltage sources — Grid supporting control*

Bottom-Up Approach

(relatively more mature)

References

C. K. Tse, M. Huang, X. Zhang, D. Liu and X. L. Li, “Circuits and systems issues in power electronics penetrated power grid,” *IEEE Open Journal of Circuits and Systems*, vol. 1, pp. 140–156, Sep. 2020.

X. Zhang, C. Zhan, and C. K. Tse, “Modeling the dynamics of cascading failures in power systems,” *IEEE Journal of Emerging and Selected Topics in Circuits and Systems*, vol. 6, no. 2, pp. 192–204, Jun. 2017.

C. Wan, M. Huang, C. K. Tse, and X. Ruan, “Effects of interaction of power converters coupled via power grid: A design-oriented study,” *IEEE Transactions on Power Electronics*, vol. 30, no. 7, pp. 3589–3600, Jul. 2015. (BEST PAPER AWARD)

Circuits and Systems Issues in Power Electronics Penetrated Power Grid

CHI K. TSE¹ (Fellow, IEEE), MENG HUANG² (Member, IEEE), XI ZHANG³ (Member, IEEE),
DONG LIU¹ (Member, IEEE), AND XIAOLU LUCIA LI¹ (Member, IEEE)

¹Department of Electrical Engineering, City University of Hong Kong, Hong Kong

²School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China

³School of Automation, Beijing Institute of Technology, Beijing 100811, China

This article was recommended by Associate Editor G. Orti.

CORRESPONDING AUTHOR: C. K. TSE (e-mail: chitse@cityu.edu.hk)

This work was supported by Hong Kong Research Grant Council under Grant GRF 15215019E.

ABSTRACT The penetration of power electronics into power generation and distribution systems has deepened in recent years, as prompted by the increasing use of renewable sources, the quest for higher performance in the control of power conversion, as well as the increasing influence of economic plans that necessitate power trading among different regions or clusters of power distribution. As a result of the increased use of power electronics for controlling power flows in power systems, interactions of power electronics systems and conventional synchronous machines' dynamics would inevitably cause stability and robustness concerns, which can be readily understood by the coupling effects among interacting dynamical systems of varying stability margins (or transient performances). In this article, we present the various problems of power electronics penetration into power grids and the implications on the stability and robustness of power networks. We specifically attempt to bring together two distinct perspectives, namely, bottom-up (local) and top-down (global) perspectives, and examine the current progress and future direction of research in power systems amidst the extensive deployment of power electronics.

INDEX TERMS Power grid, power electronics, grid-connected power electronics, robustness, stability.

I. INTRODUCTION

SINCE the inception of the first power system at Godalming, England, in 1881, the power distribution network has grown rapidly in different parts of the world and has been playing an increasingly important role in many developed and developing economies. For the past Century and until now, the power distribution network has mainly been composed of a suite of conventional alternating current (AC) equipment [1]. Much of the electrical power has been generated and pumped into the grid by synchronous generators, and the magnitudes of voltage at different locations are transformed by AC transformers. Moreover, the power consumed by the conventional loads has predominantly been determined by electrical components connected to the grid, such as motors, incandescent light bulbs, and so on. The stability issue of the conventional power system has been relatively well studied and understood by researchers

and electrical engineers. Typical characteristics have been revealed and sound theories have been developed and used for several decades [2].

Today's power systems, however, are undergoing a rapid transformation, featured by the increasing level of utilization of a new kind of equipment—power electronics converters [3], [4]. In terms of power generation, transmission and consumption, power electronics devices have been extensively used in place of their conventional counterparts. The electricity generated from renewable energy sources (e.g., wind turbines and photovoltaic panels) that interface with the power grid through power electronics converters continues to increase [5]. The HVDC (High Voltage DC) electricity transmission, with mandatory interface via power electronics equipment, has gained increasing popularity for large-scale and remote power delivery and trading [6]. For the load sides, power electronics adapters are widely used for electric power

Acknowledgement

Grateful thanks to

Prof. C. K. Michael Tse, City University of Hong Kong

Prof. Meng Huang, Professor, Wuhan University

Dr Xiaolu Lucia Li, Postdoc, City University of Hong Kong

Dr Dong Liu, Postdoc, City University of Hong Kong

Prof. Xi Zhang, Assistant Professor, Beijing Institute of Technology

Thank you!