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Power Grids in the Midst of Rapidly Increasing Penetration of Power Electronics

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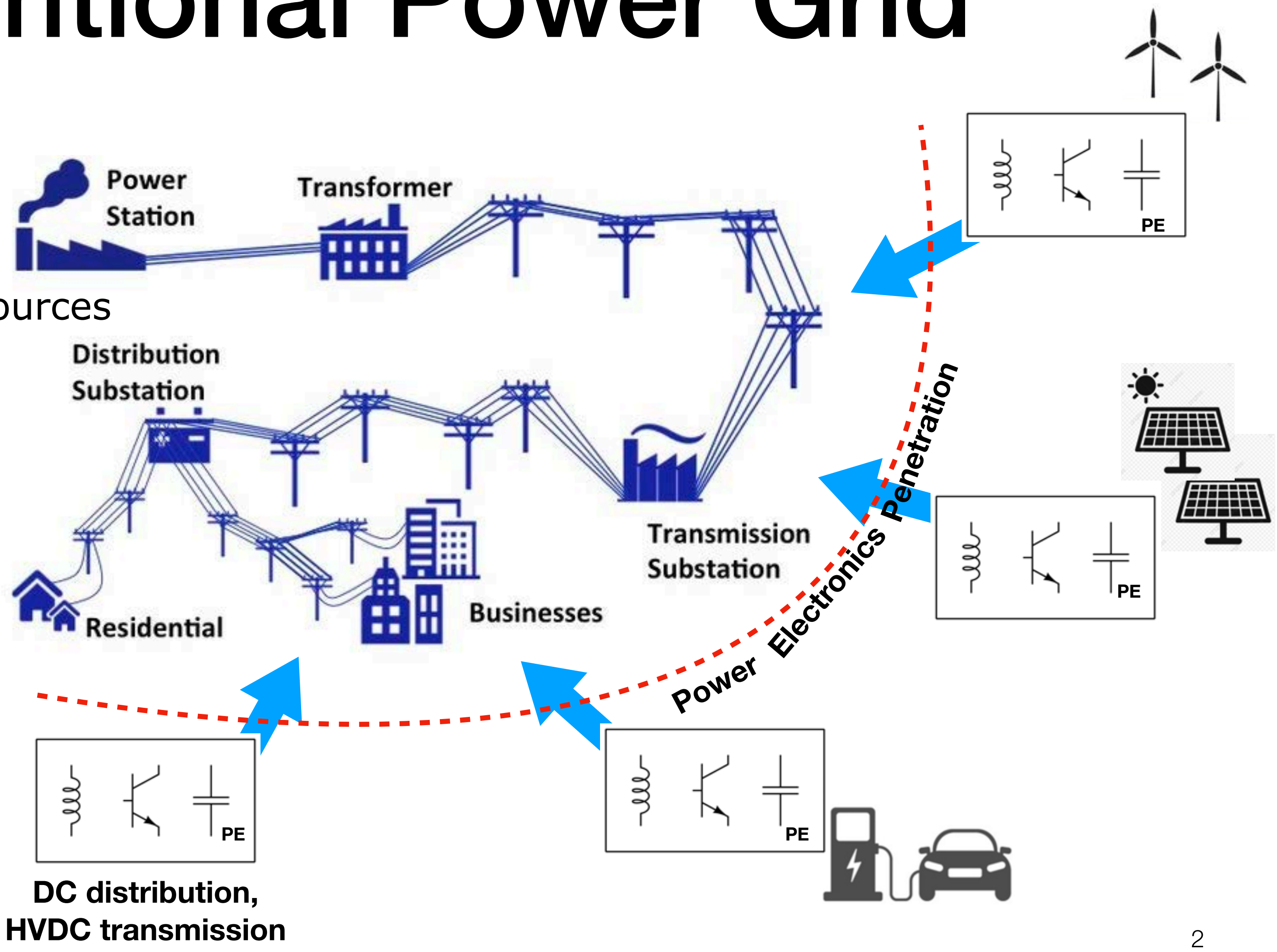
Conventional Power Grid

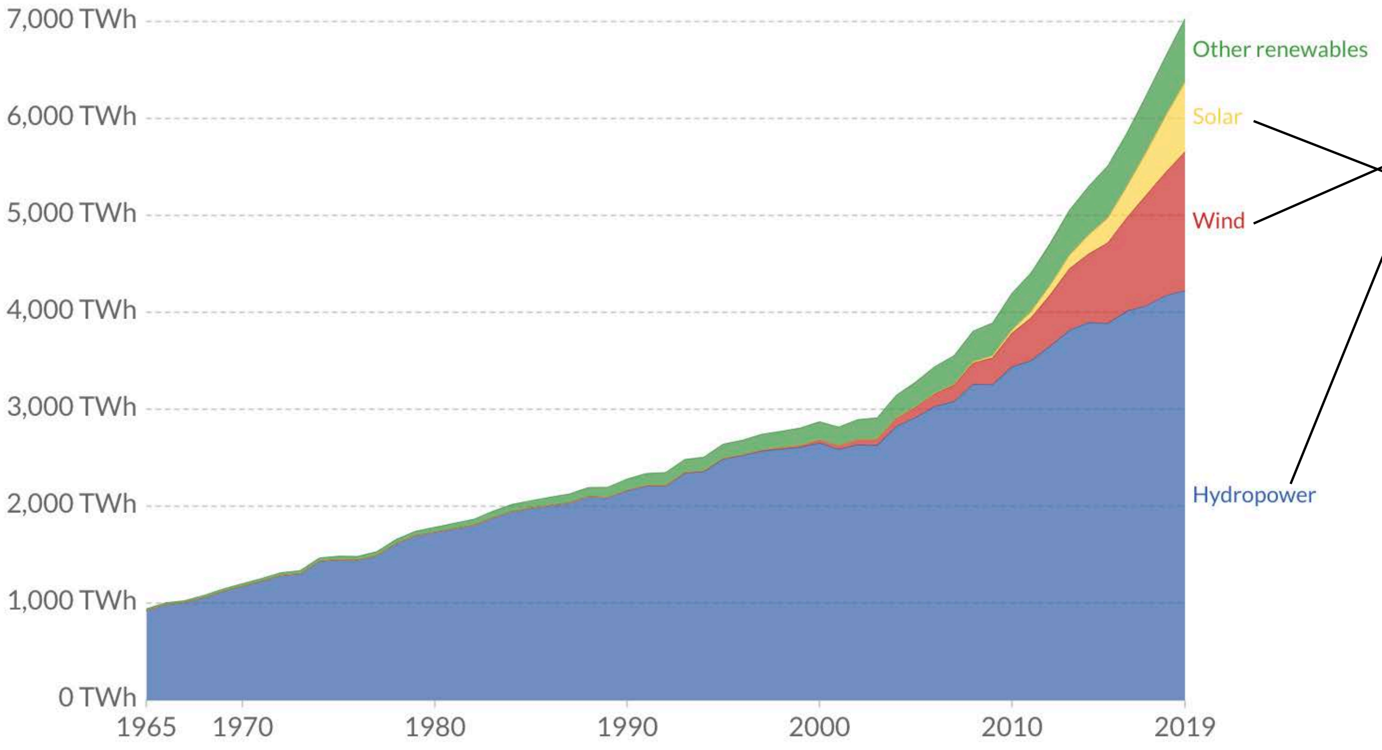
Power Generation
- Power plants (coal, nuclear)
  - Synchronous generators
- Small number of renewable sources

Distribution
- Transmission
- Transformation

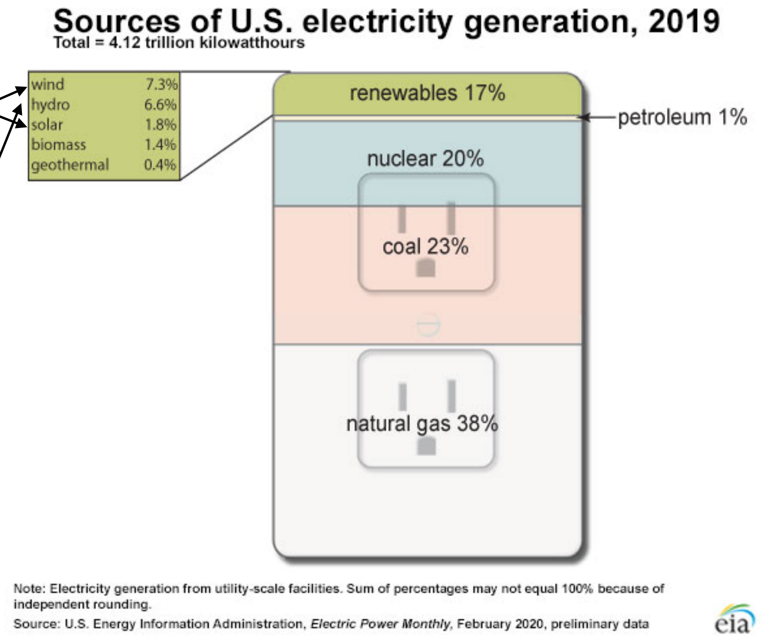
Concumption
- Loads
- Active regulated loads



Renewable Energy Trends

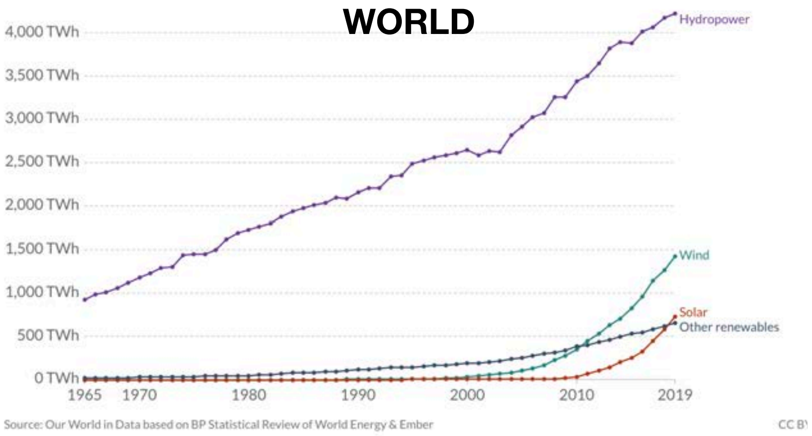


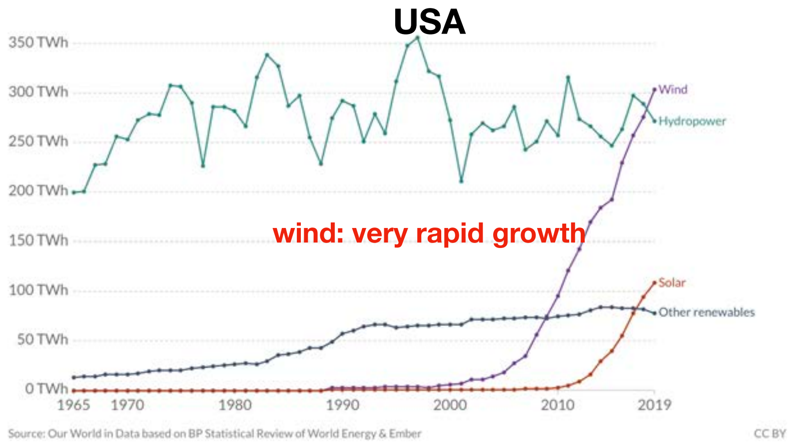
Source: BP Statistical Review of Global Energy
Note: 'Other renewables' refers to renewable sources including geothermal, biomass, waste, wave and tidal. Traditional biomass is not included.

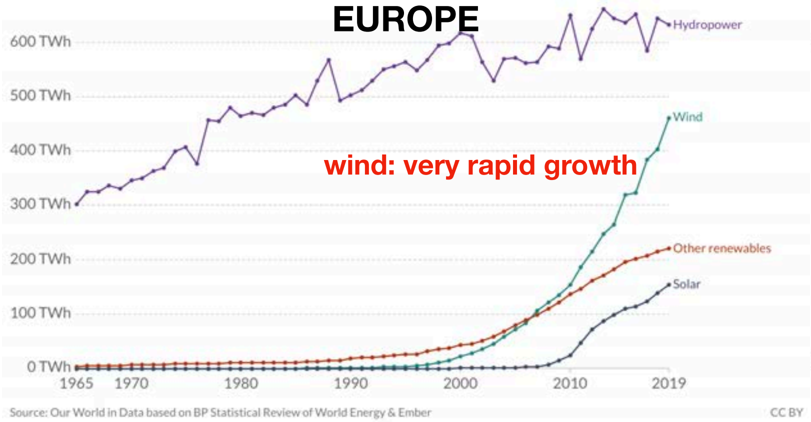


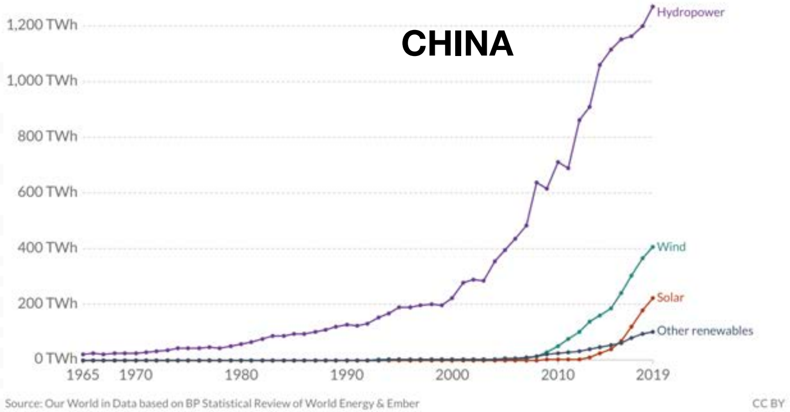
https://ourworldindata.org/renewable-energy

Renewable Energy Generation by Source









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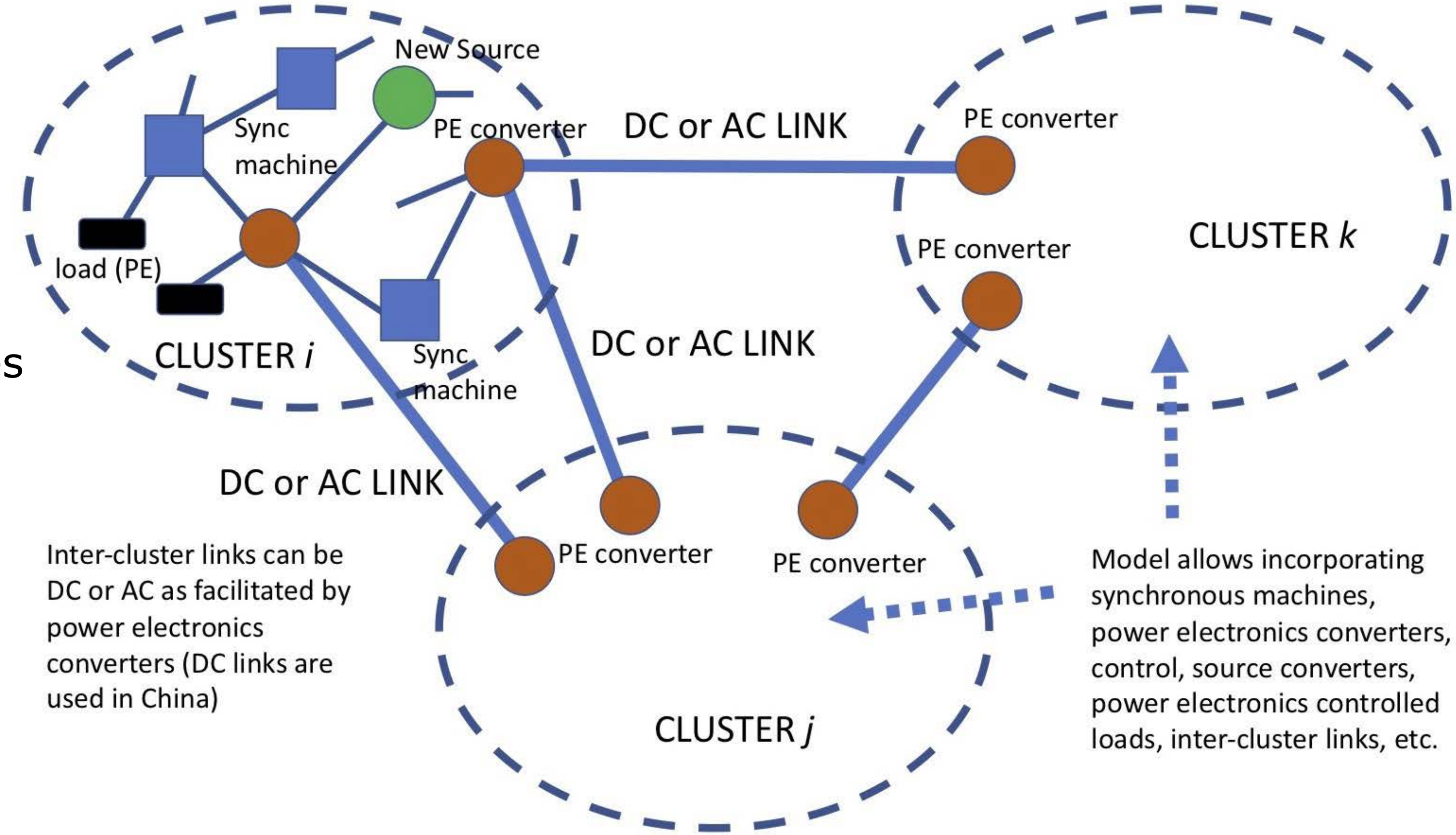
Modern Grid

Features

Clustering
  Intercluster connections

Generators
  Sync power generators
  Renewable power sources

Loads
  Conventional loads
  Active regulated loads



Driving Factors

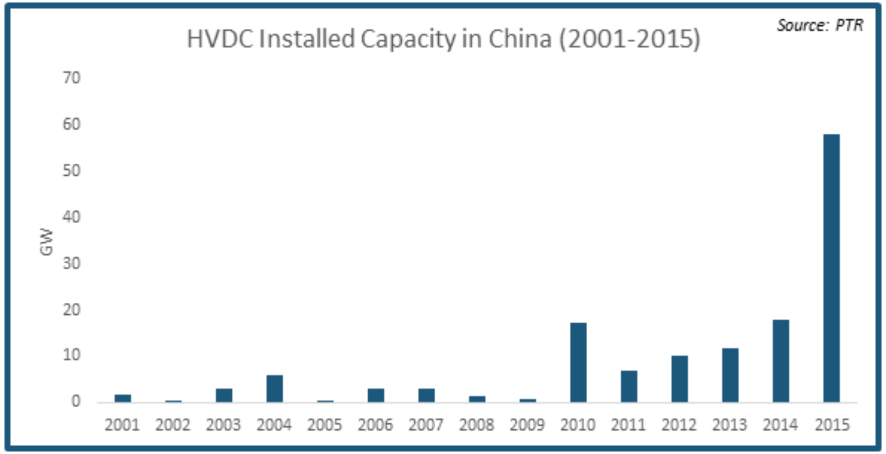
Towards use of power electronics

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

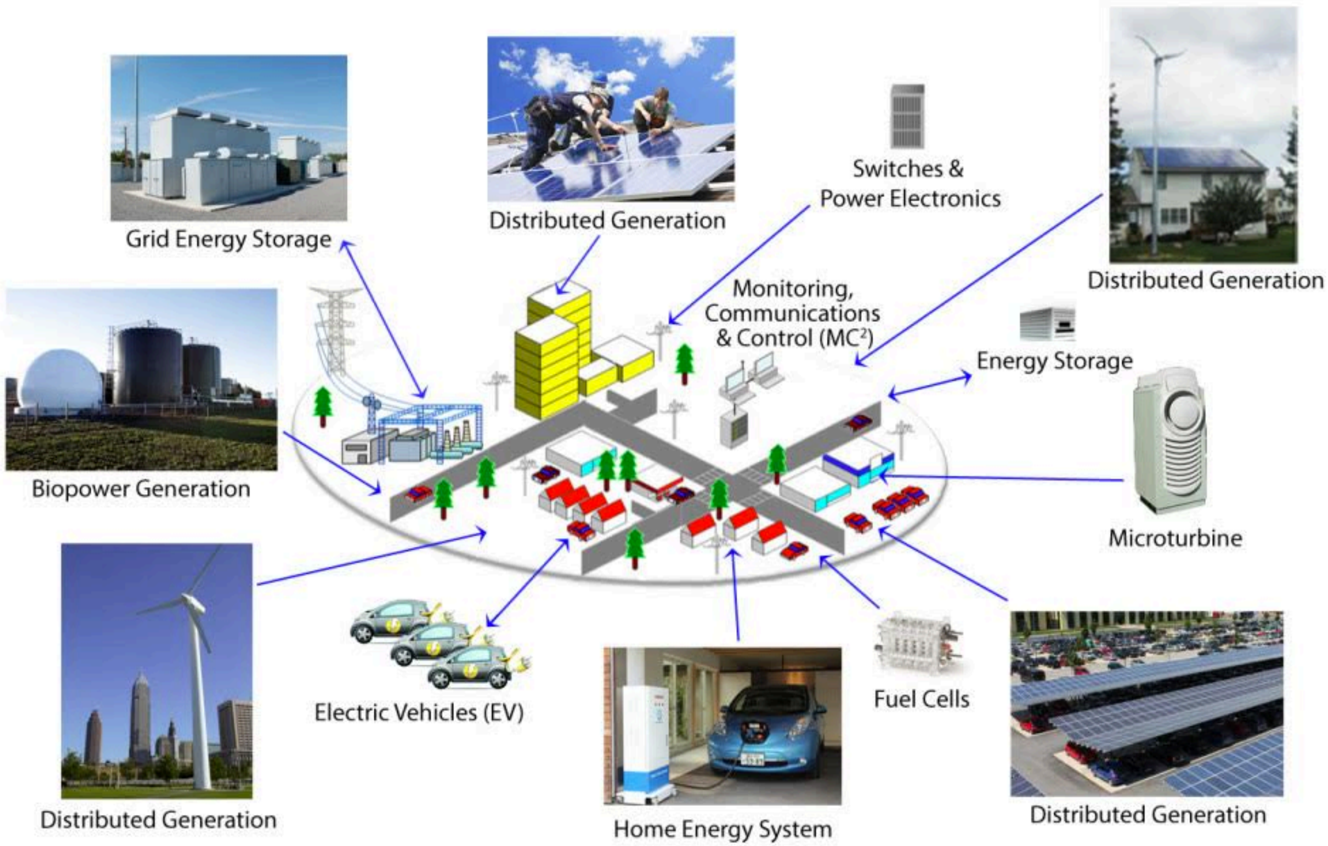
Energy Trading

Bulk power transmission due to uneven source distribution

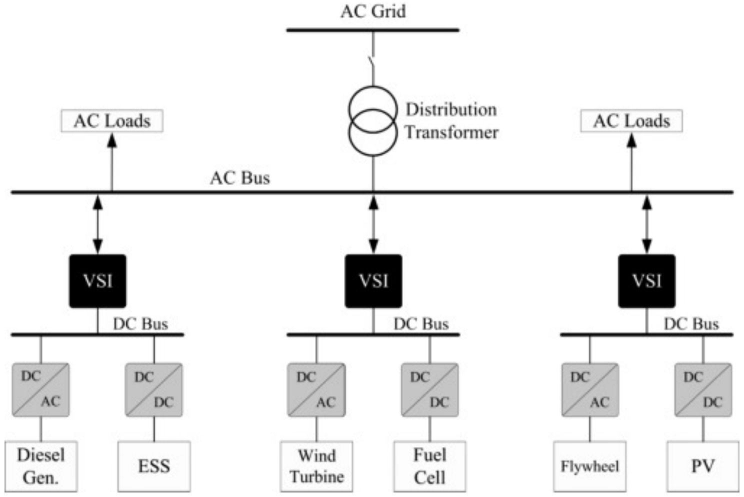


Roughly 60% of the HVDC projects installed after 2010 were 3GW or more in China. State Grid of China (SGCC) plans to spend roughly $90B just in UHVDC interconnections from 2009 to 2020, and it aims to make more than 20 UHVDC transmission links operational by 2030. The Changji-Guquan UHVDC link, which is expected to be commissioned by 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



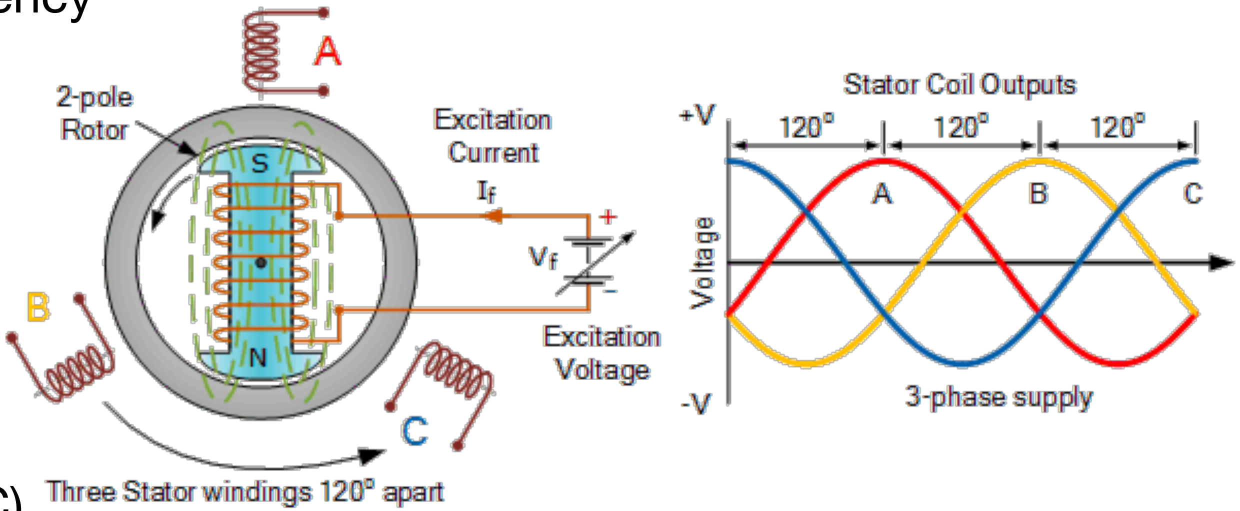
Extensive use of power electronics for power control
In generation, distribution and end-user management.



What’s the impact?

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 ← shaft torque
  - Output voltage ← 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

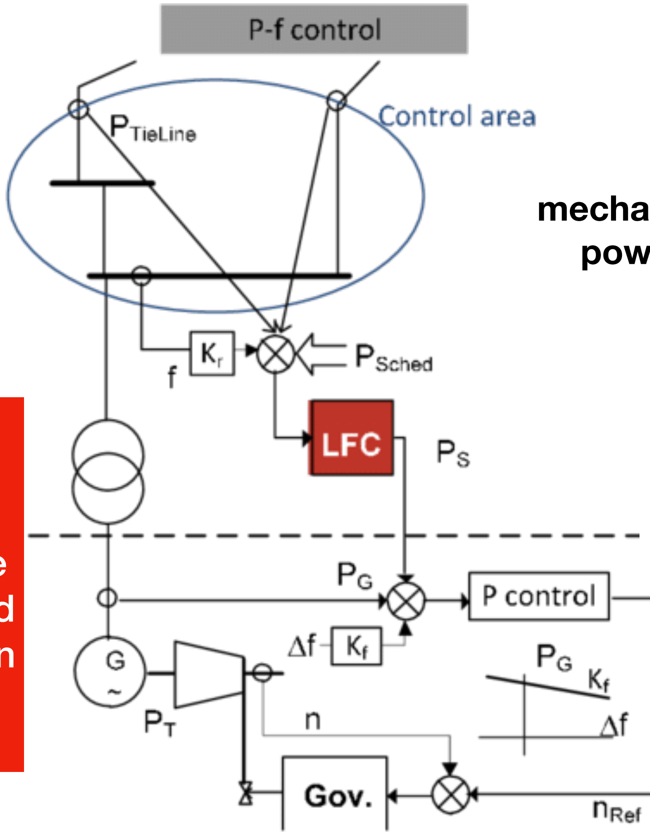


Figure Source: K. Máslo and Z. Hruška, J Energy Power Sources 2(3), 2015

Frequency-Power Control

Detects change in frequency and adjusts torque in rotating shaft

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

mechanical power — **electromagnetic power** — **inertia** — **Frequency**

Purpose

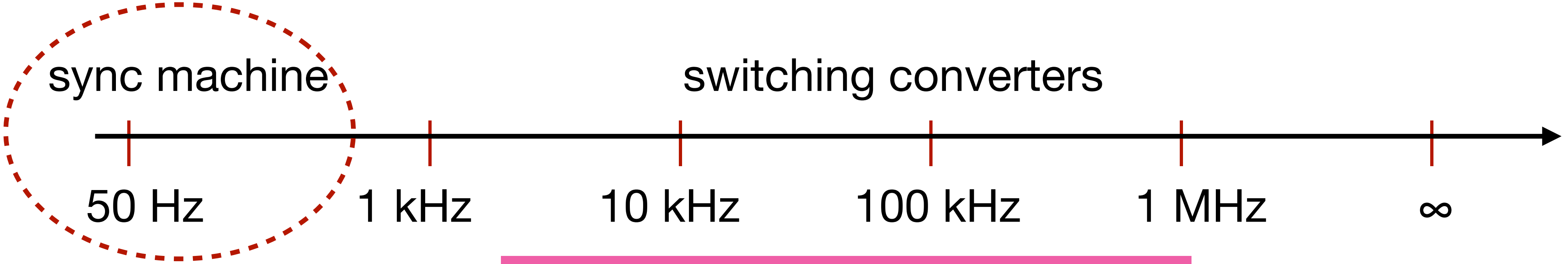
Maintain a stiff grid with stable frequency and voltage

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 sychronous machines!

Power Electronics - What's the difference?

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!*



LOW-FREQUENCY CONTINUOUS SYSTEM

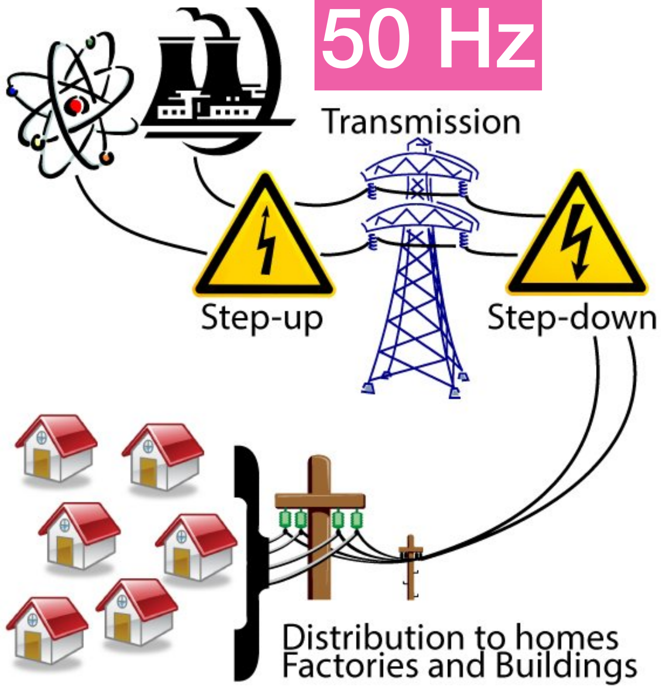
NONLINEAR HYBRID SWITCHING CONTINUOUS SYSTEM

AVERAGED SMOOTH CONTINUOUS SYSTEM

Power Systems vs Power Electronics

Synchronous Generators

50 Hz



POWER ELECTRONICS

Switching Circuits

Switching Frequency 1kHz — 1MHz (not high enough to become continuous systems as seen by grid)

Nonlinearity
Vulnerable to large disturbance due to violation of small-signal design assumptions

Wideband Oscillations
Feedback control systems present negative impedance to grid

Multi-time Scale
Wide range of operating frequency of different converters/inverters

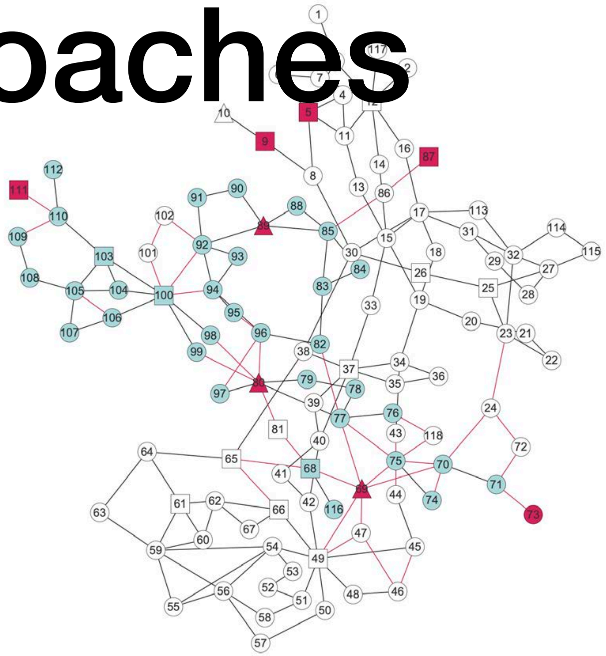
Basic Issues

- 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!***

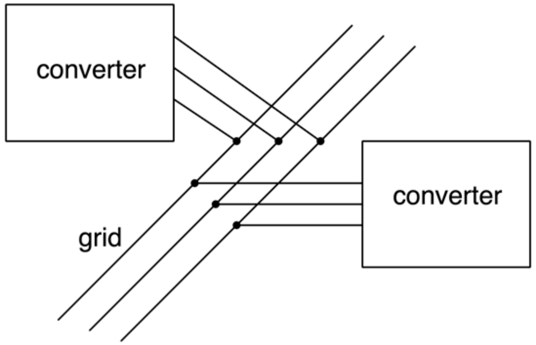
- MULTI-TIME SCALE
  - Variety of operating switching frequencies. Analysis is not scalable!

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.]

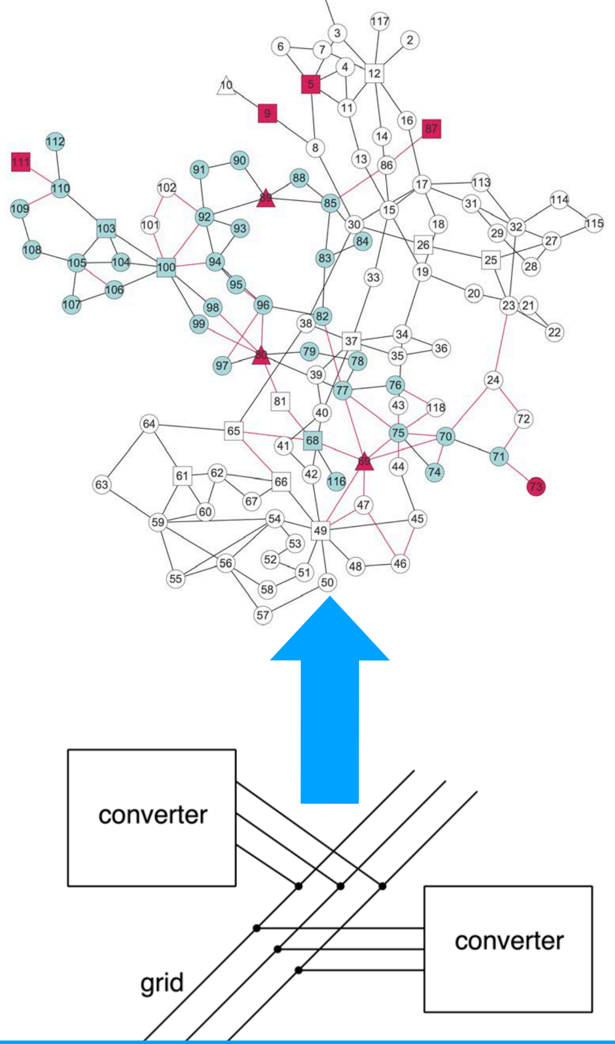
Samples of methods

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 - Synchroniz-ation 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

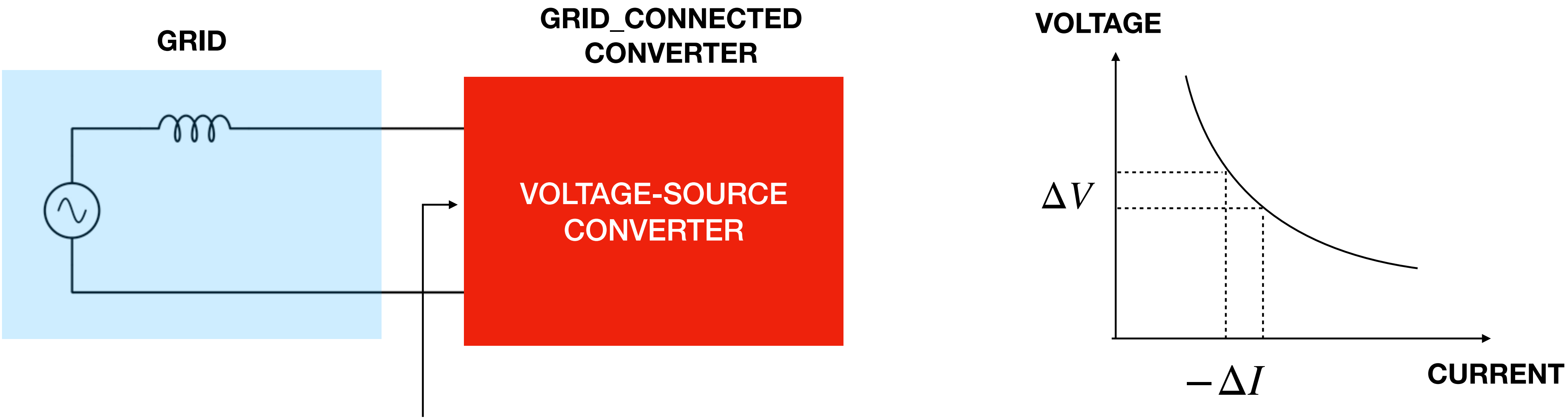


*R*eview of Bottom-Up Approach

(relatively more mature)

Conventional Methods

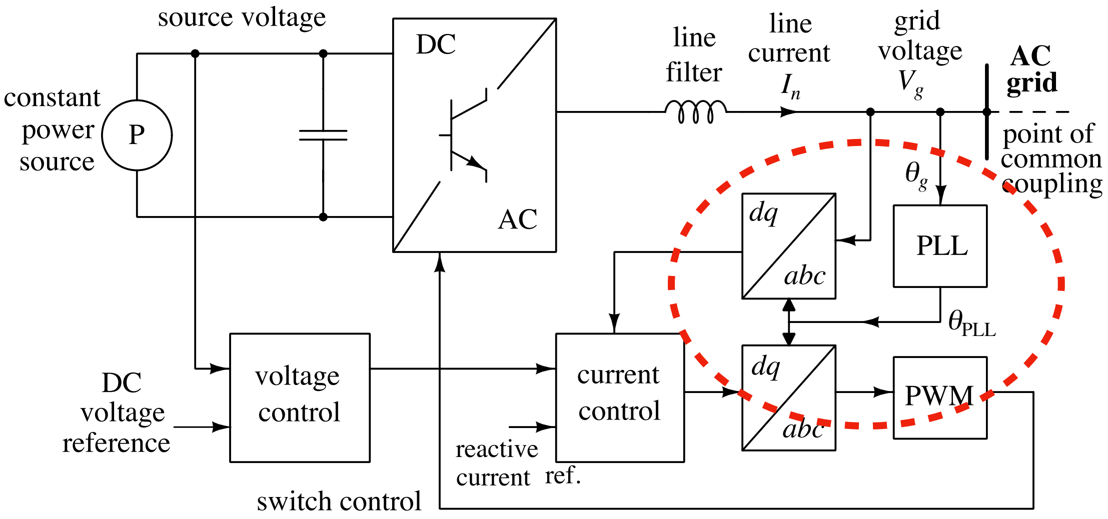
- Traditional small-signal models and linearized analysis
- Impedance based stability criteria (e.g., Middlebrook's criterion, Nyguist, …)



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 = Vg / In Zs**

grid voltage
line current
source impedance of grid

- **Unstable operation as damping weakens**

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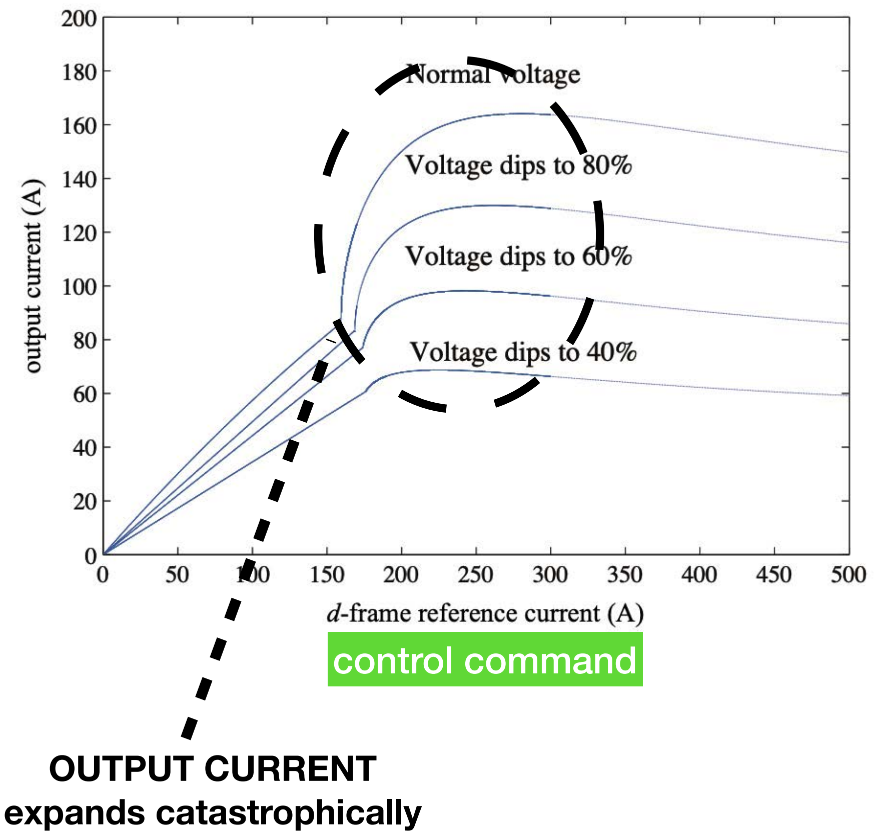

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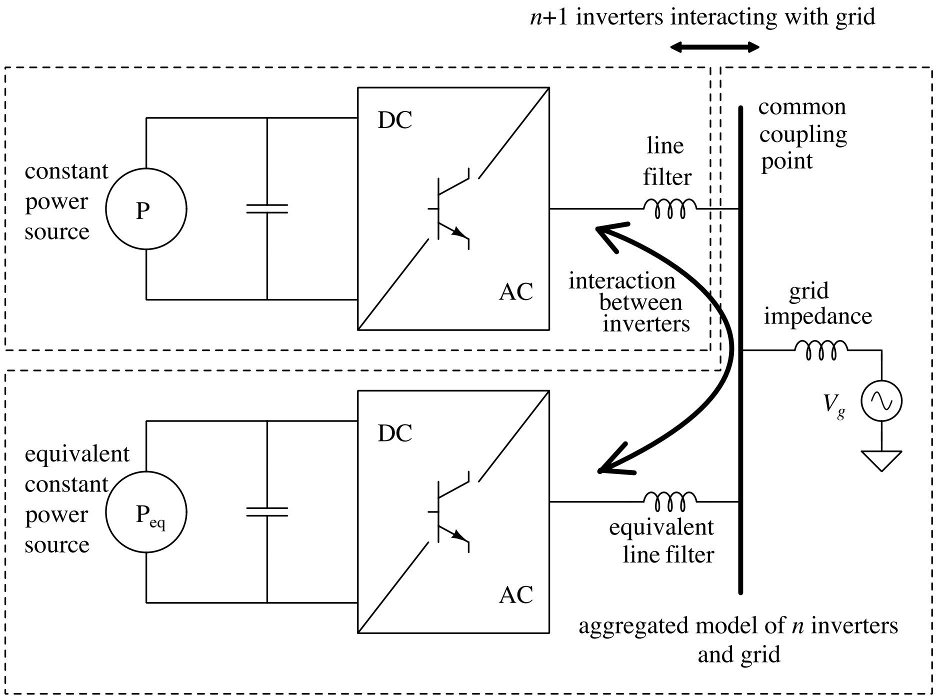
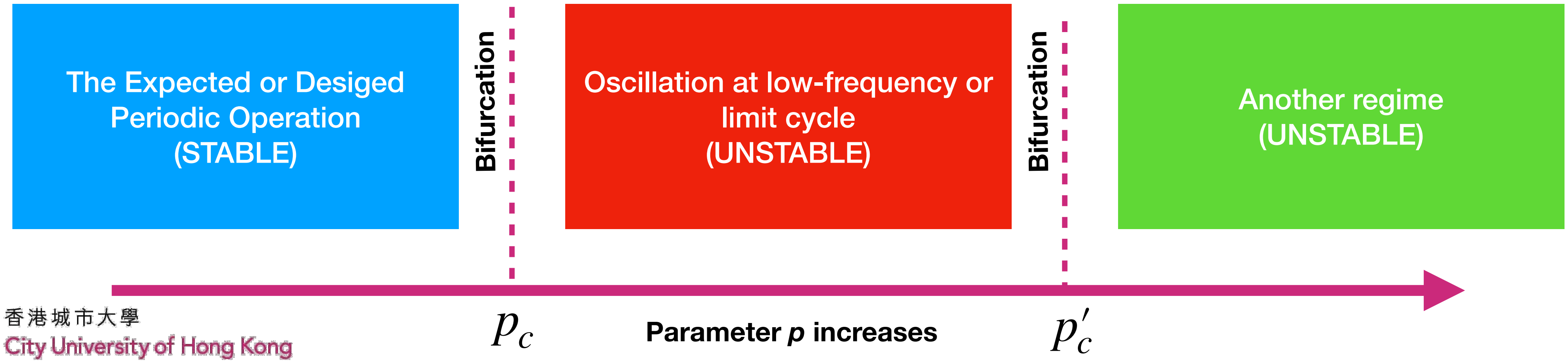
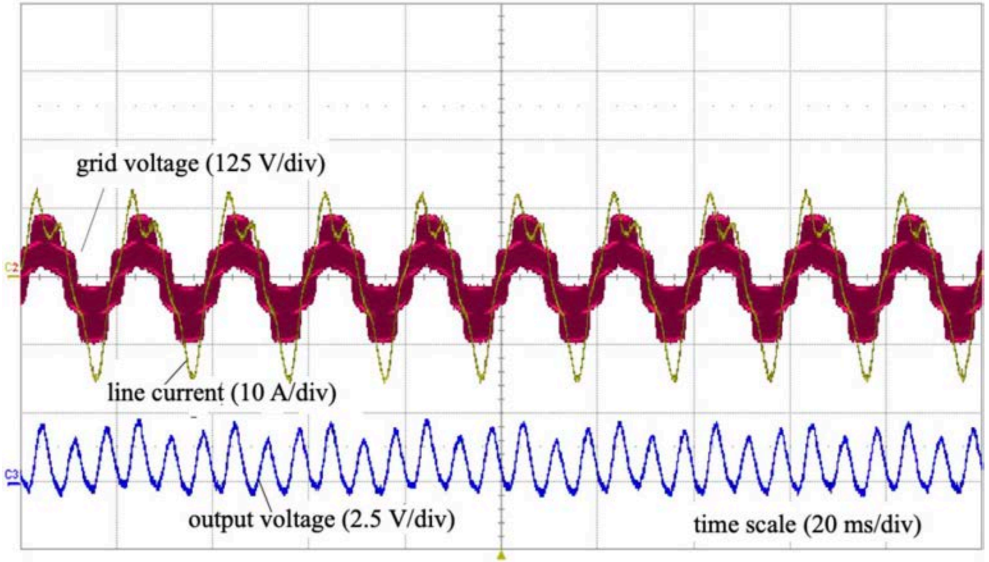


Bifurcation Analysis

- 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 stabilty analysis extended to MORE THAN one operating regimes.



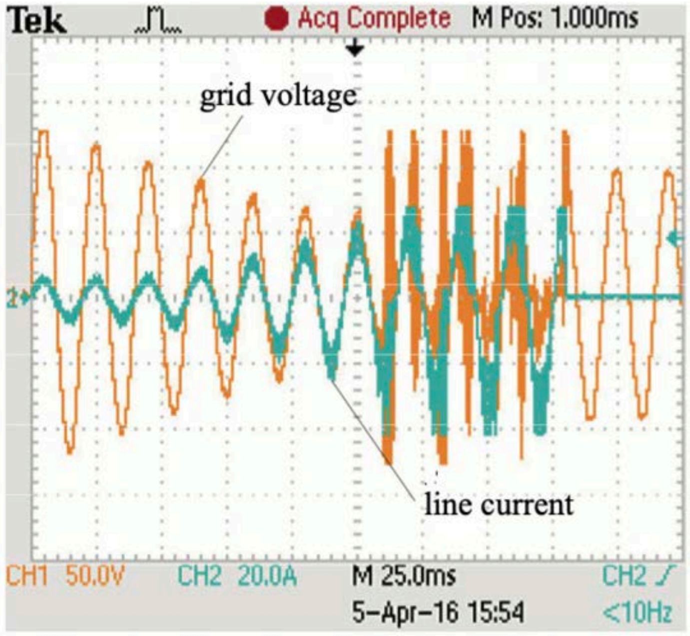
Examples of Bifurcation or Loss of Stability



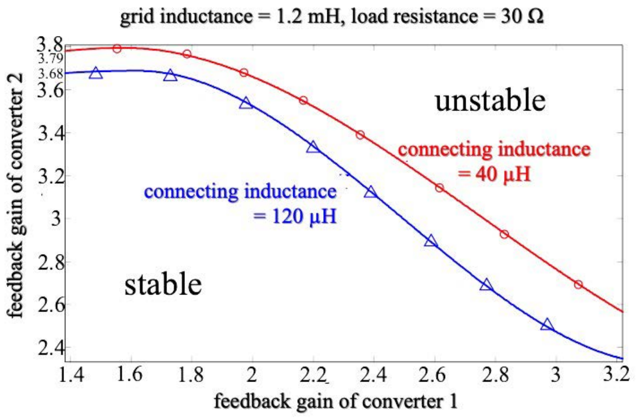
Hopf bifurcation in three-phase ***grid-connected voltage source converter*** showing high harmonic contents in grid voltage and line current, and AC coupled load voltage, as the load current increases to a certain value.

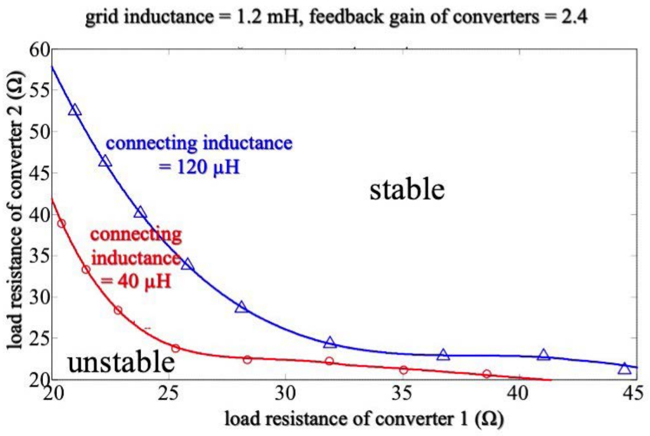
Bifurcation due to Saturating Nonlinearity

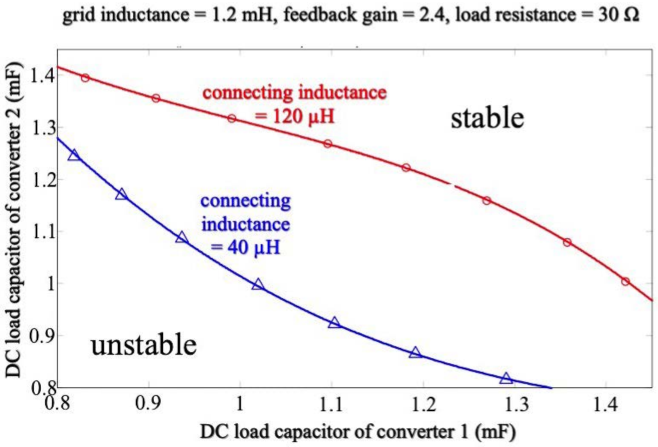
Measured line current and grid voltage from grid-connected three-phase voltage source converter showing irreversible large-signal instability. The system fails to return to stable operation even after reversing the parameter change (reducing the reference current).



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

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City University of Hong Kong
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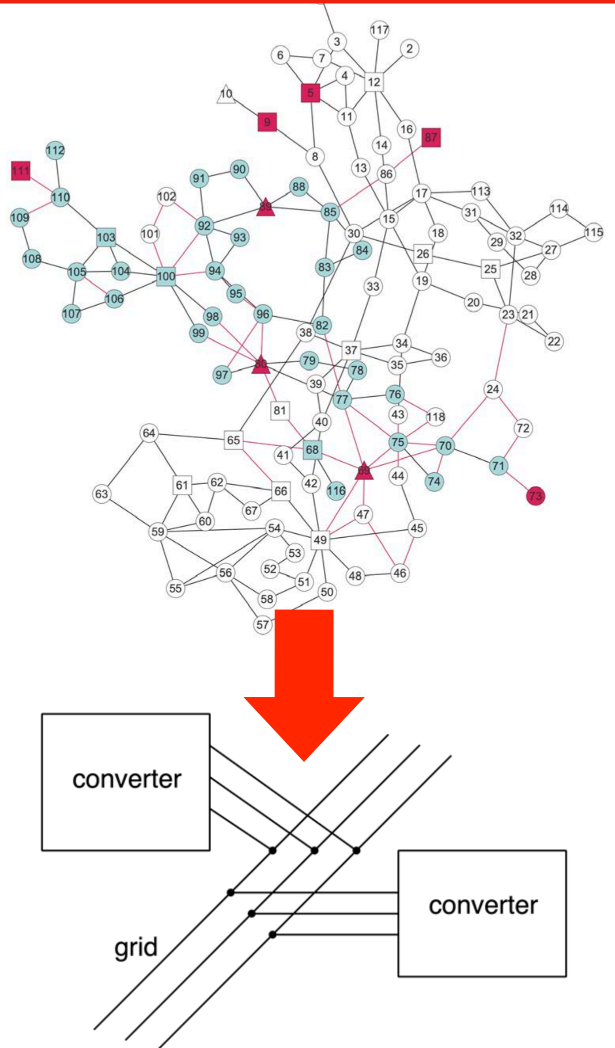
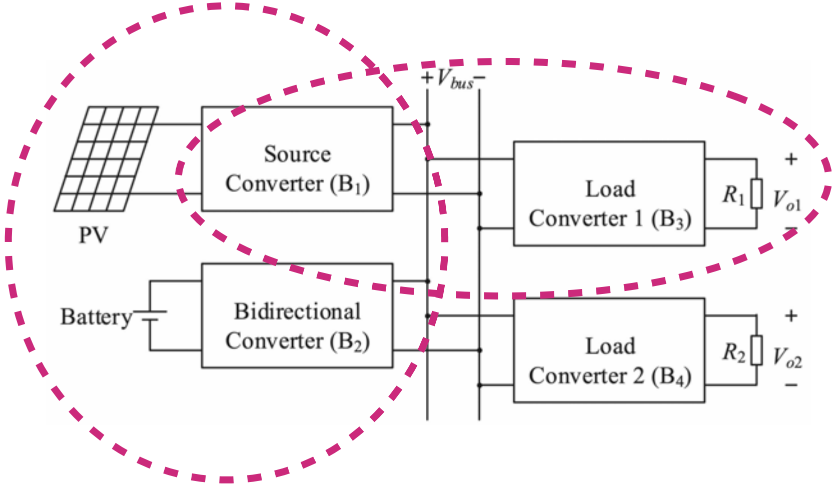
*Pre*view of Top-Down Approach

(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.*



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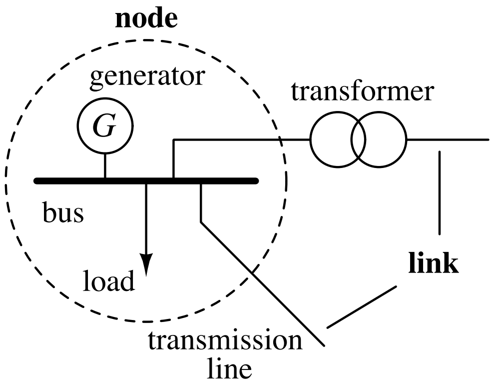
GLOBAL PERSPECTIVE looks at the system as a whole and identifies key properties and their relationships with system parameters and network structure.

Network Model

NETWORK:

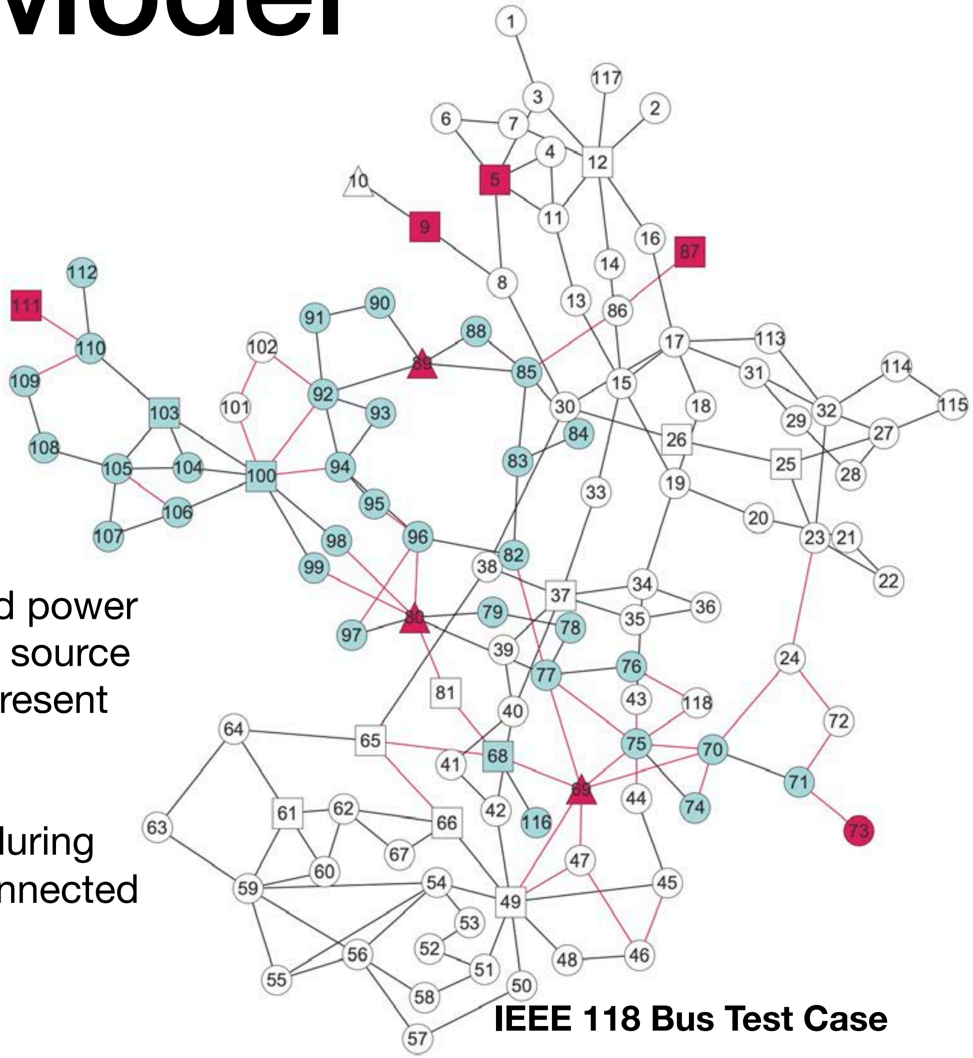
NODES

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.

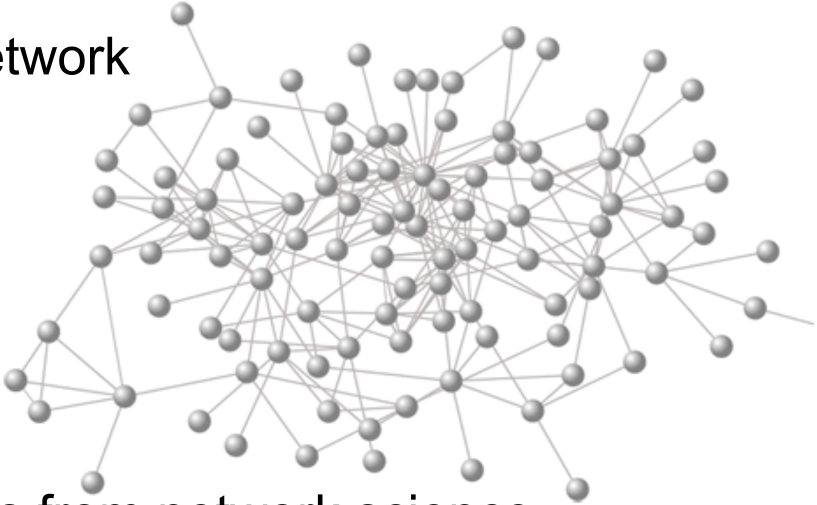
Red nodes and links are overloaded and tripped during the cascading failure process; **blue ones** are disconnected from the power sources and deprived of power.



IEEE 118 Bus Test Case

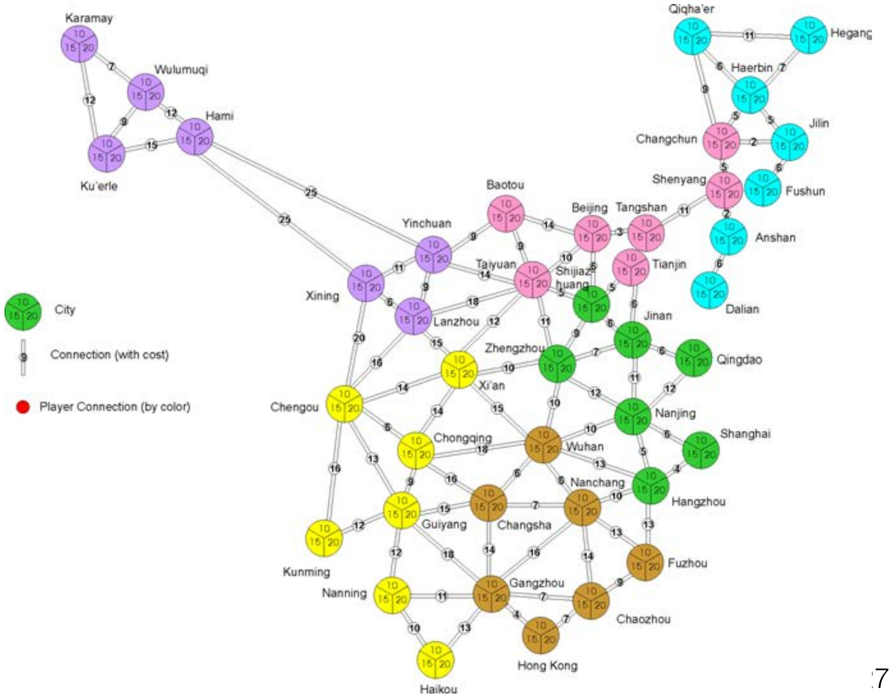
Network Model

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

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:

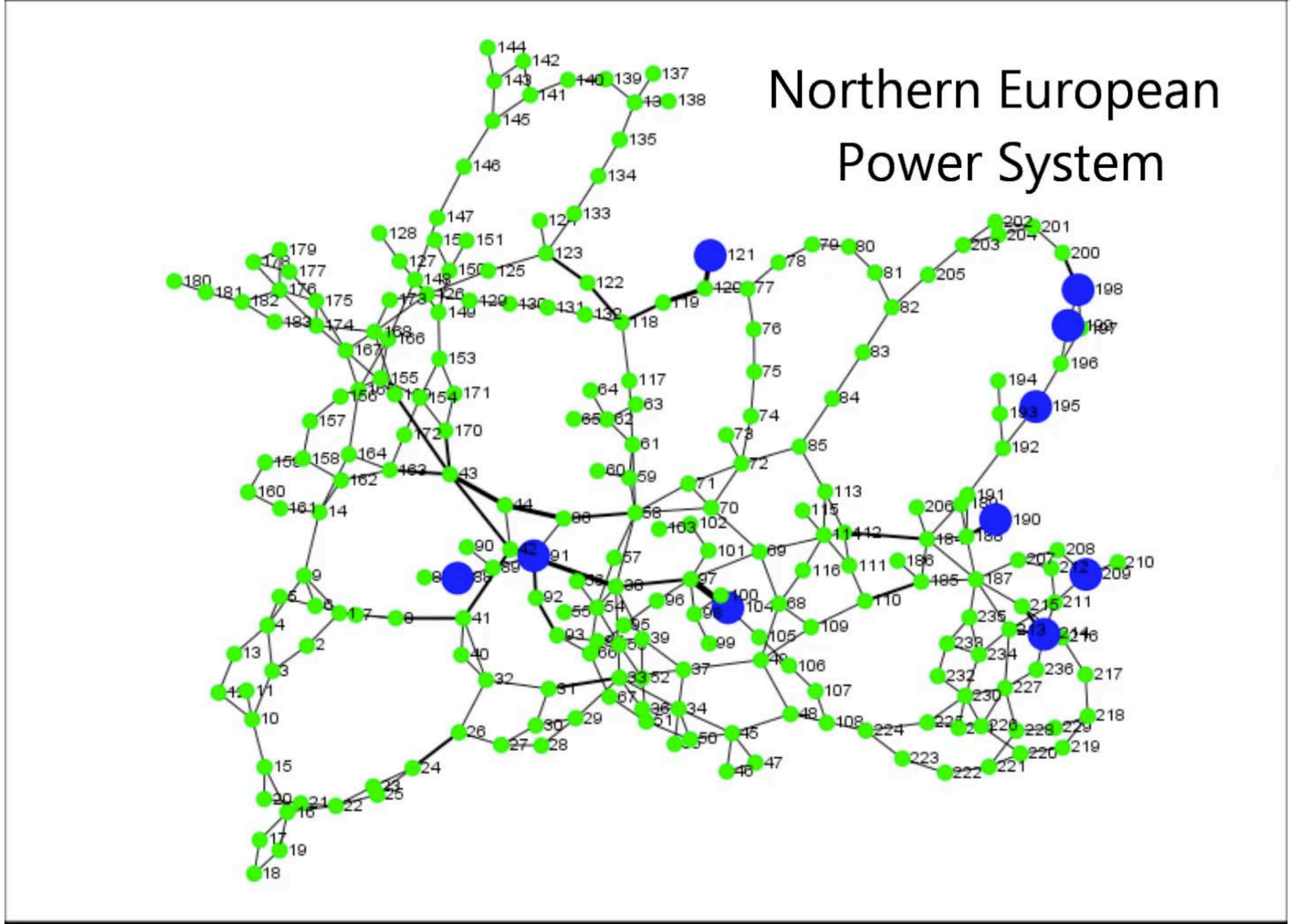
- Power flow re-distributes according to shortest paths
- Current flows to low degree nodes
- Failures get transmitted like disease transmission

Giving

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

Unable to reproduce the failure profile.

Check carefully the CASCADING failure sequences!!!!

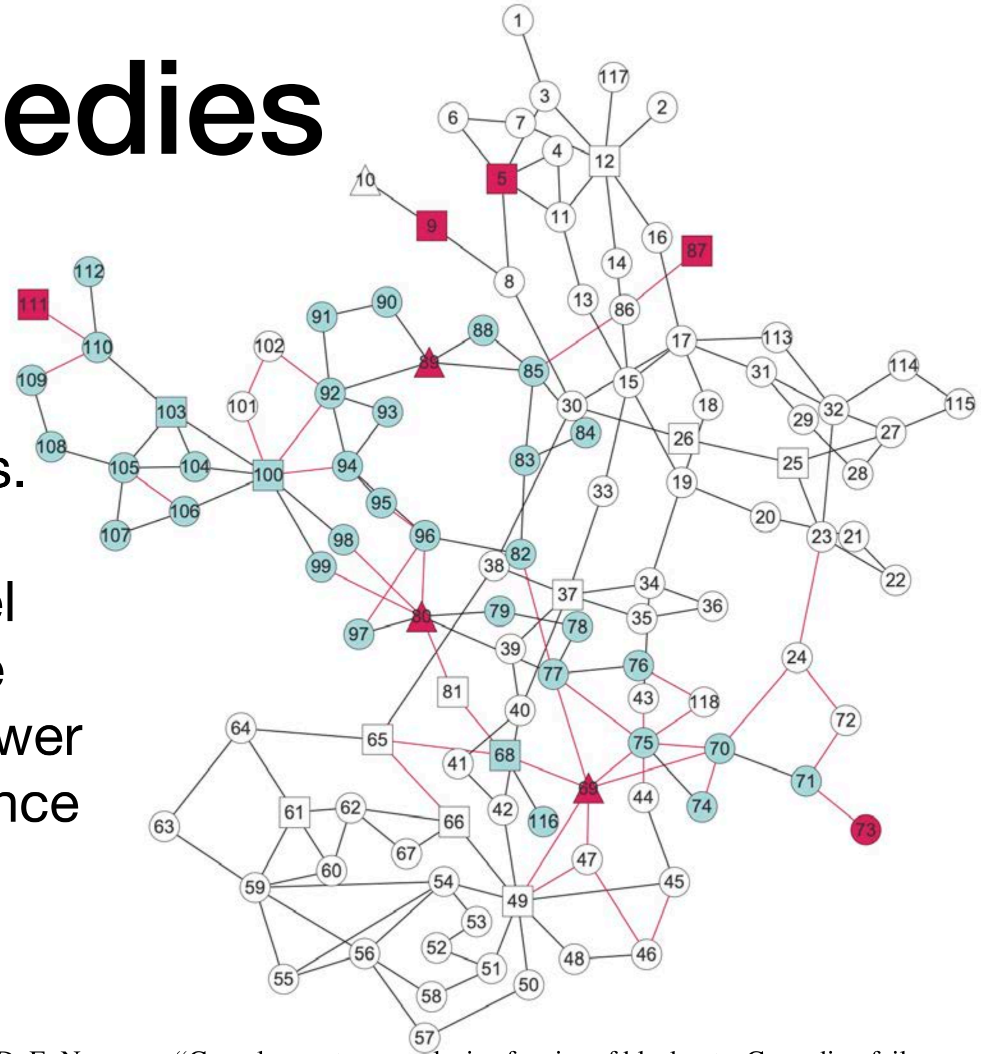


Key Remedies

Physical process must be considered.

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

The Oak Ridge-PSERC-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 faliures 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).

Historical Cases

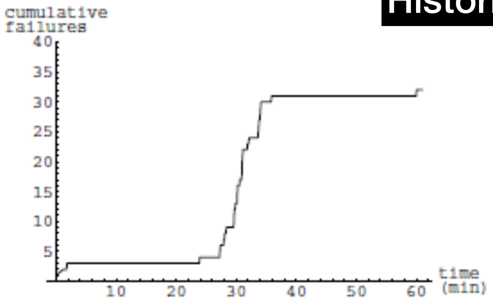


Figure 1. Cumulative line trips in WSCC July 1996 blackout. Time scale is minutes after 14:00 MDT.

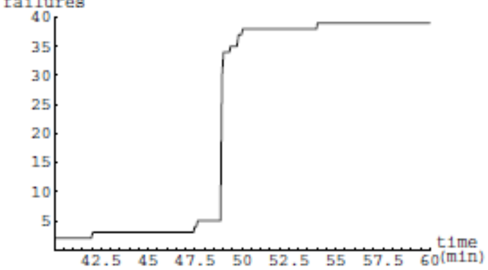
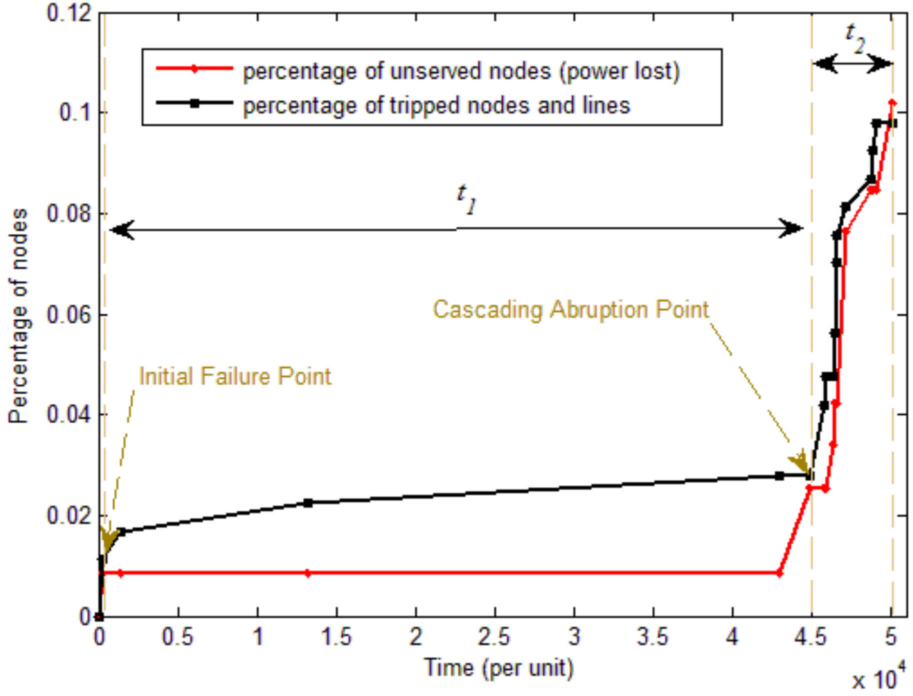
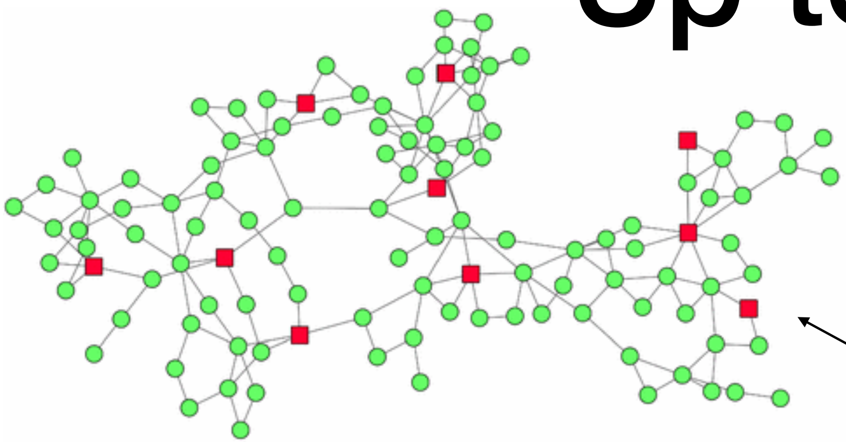


Figure 3. Cumulative line trips in WSCC August 1996 blackout. Time scale is minutes after 15:00 PDT.

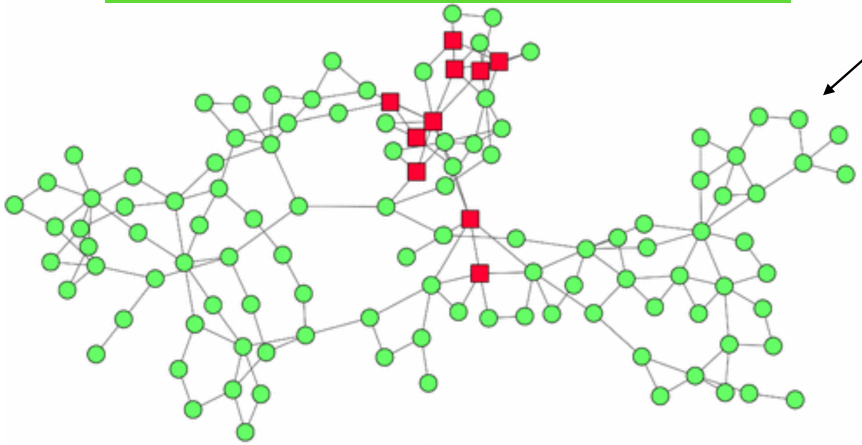


IEEE 118 Bus Test Case simulated by our network model. Results showing consistent features in the profile of cascading failures.

Up to this point



Decentralization of power accessiilibity



(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 (P_m), **electromagnetic power** (P_e), **inertia** (T_J), **Frequency** ($\frac{d\omega}{dt}$)

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!

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

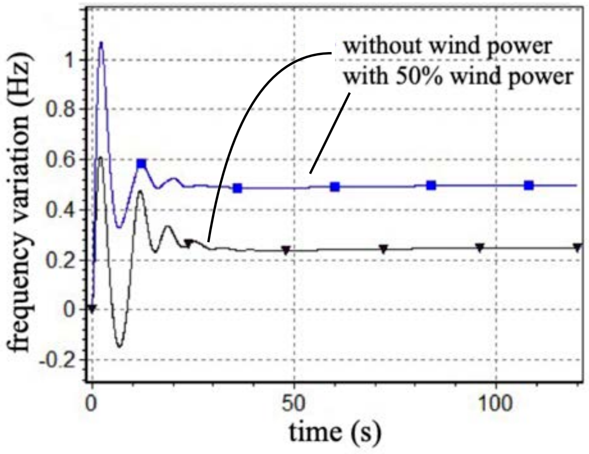
$$\Rightarrow P_G = P_{G0} + K_G \Delta\omega$$

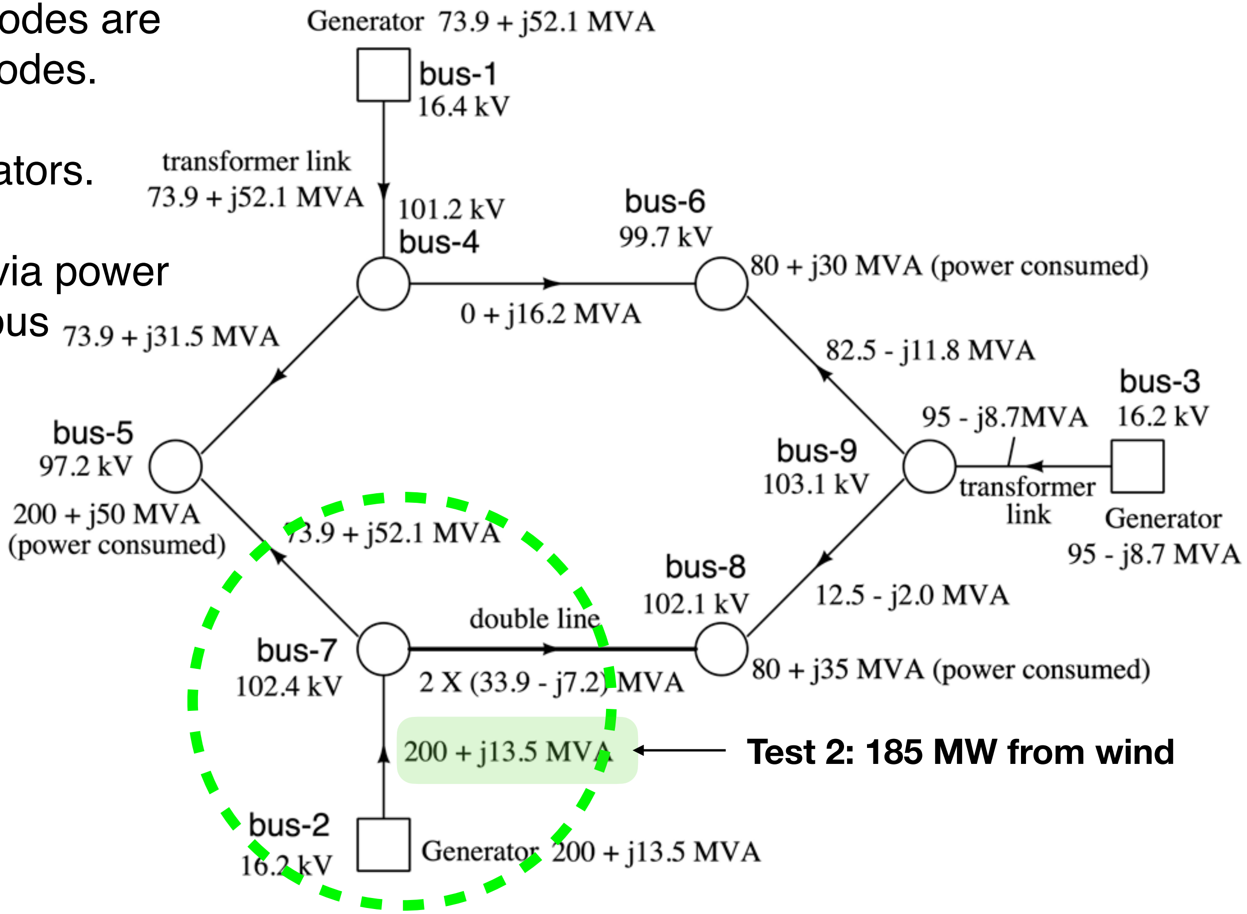
Simple Tests

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.

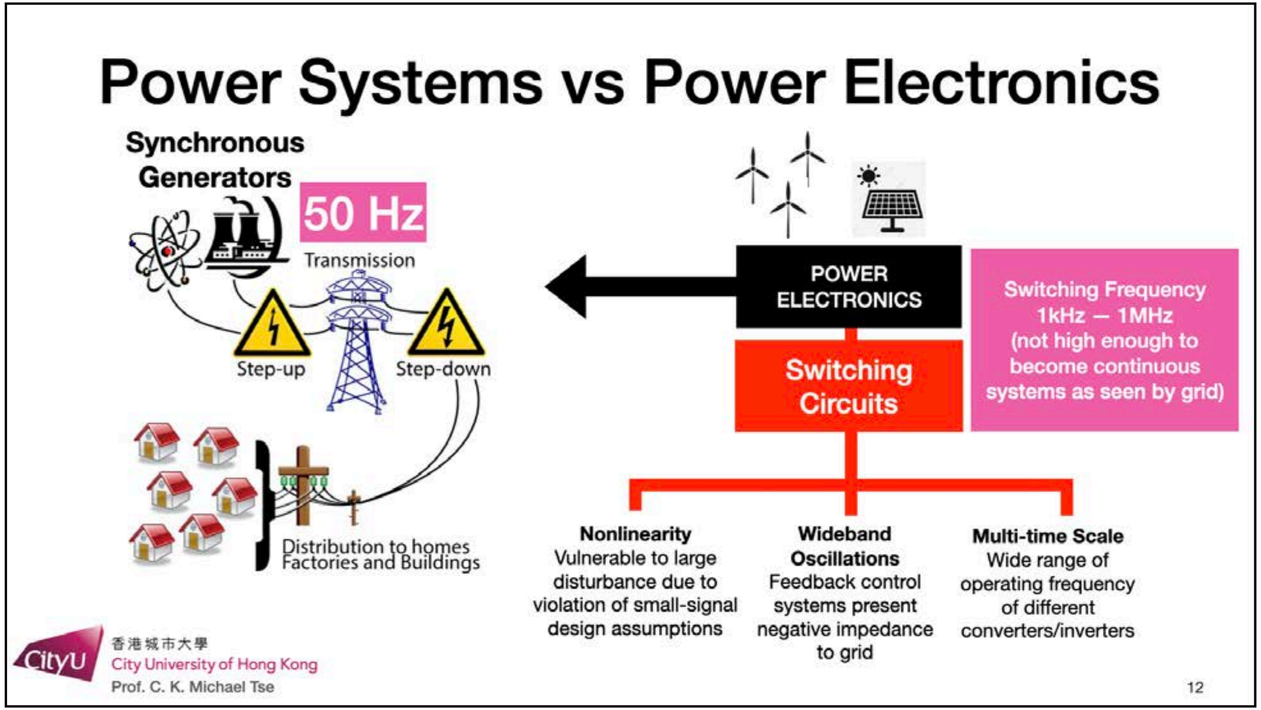
Test 1: all generators are synchronous generators.

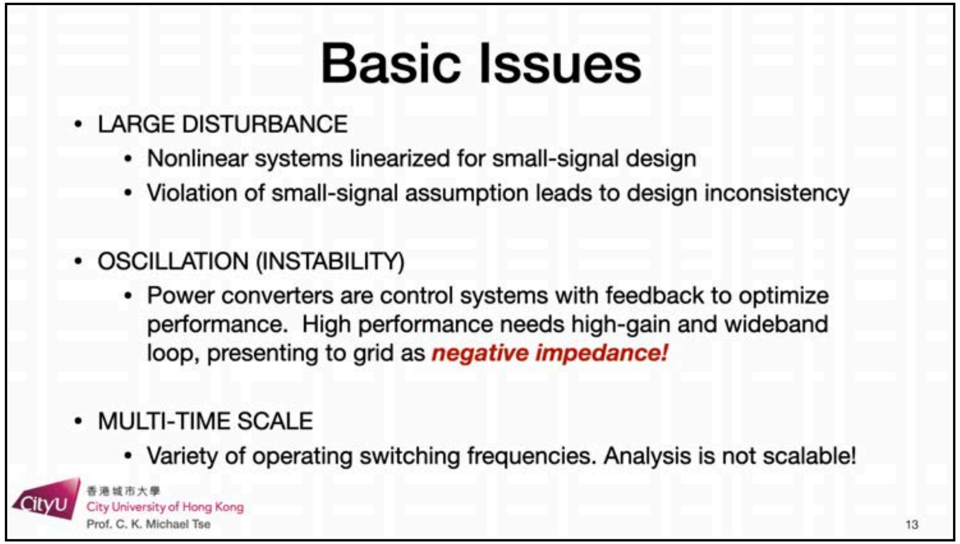
Test 2: bus 7 takes 185 MVA from wind farm via power electronics and 15+j13.5 MVA from synchronous generator, ***i.e., 50% wind power overall!***





Re-iteration of Key Features





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

An Initial Model

Aims

Simulates the cascading failure processing with consideration of power electronics penetration

Combines primary frequency control AND DC power flow, with PE nodes not participating in the frequency control

Algorithm

Step 1: Initialize the electrical parameters and capacities of the power network under test at the start of the simulation, i.e., $t = 0$.

Step 2: Plant an initial failure at $t = 1$.

Step 3: Remove the tripped power components.

Step 4: Update the network topology and find the disconnected subnetworks (islands) N_S.

Step 5: For each subnetwork $s_n (n = 1, 2, \ldots, N_S)$ that contains power sources, apply the primary frequency control to balance the power between the generator and load sides. The steady-state frequency deviation $\Delta f(t)$ after the primary frequency control is calculated according to

$$\Delta f(t) = \frac{\sum_{G_i \in \Omega_{G_{sn}}} P_{G_i}(t-1) - \sum_{D_i \in \Omega_{D_{sn}}} P_{D_i}(t-1)}{\sum_{G_i \in \Omega_{G_{sn}}} K_{G_i} + \sum_{D_i \in \Omega_{D_{sn}}} K_{D_i}}$$

where $P_{G_i}(t-1)$ is the power output of generator G_i and $P_{D_i}(t-1)$ is the power consumed by load D_i; $\Omega_{G_{sn}}$ and $\Omega_{D_{sn}}$ are sets of the generators and loads in subnetwork s_n; K_{G_i} and K_{D_i} are the frequency coefficients of generator i and load i, and these two constants represent the contribution of generators and loads to the frequency control. Note that the frequency coefficients of PE-based generators are all set to zero as they do not participate in the primary frequency control. The power produced by generator G_i after applying the primary frequency control is

$$P_{G_i}(t) = P_{G_i}(t-1) - K_{G_i} \Delta f(t).$$

Similarly, the power consumed by load D_i after applying primary frequency control is

$$P_{D_i}(t) = P_{D_i}(t-1) + K_{D_i} \Delta f(t).$$

Step 6: Compute the power flow distribution based on the updated $P_{G_i}(t)$ and $P_{G_i}(t)$.

Step 7: Update the power flow, and if there exist overloaded components, go to step 8; otherwise, simulation stops.

Step 8: Trip the overloaded component and update the time $t = t + 1$.

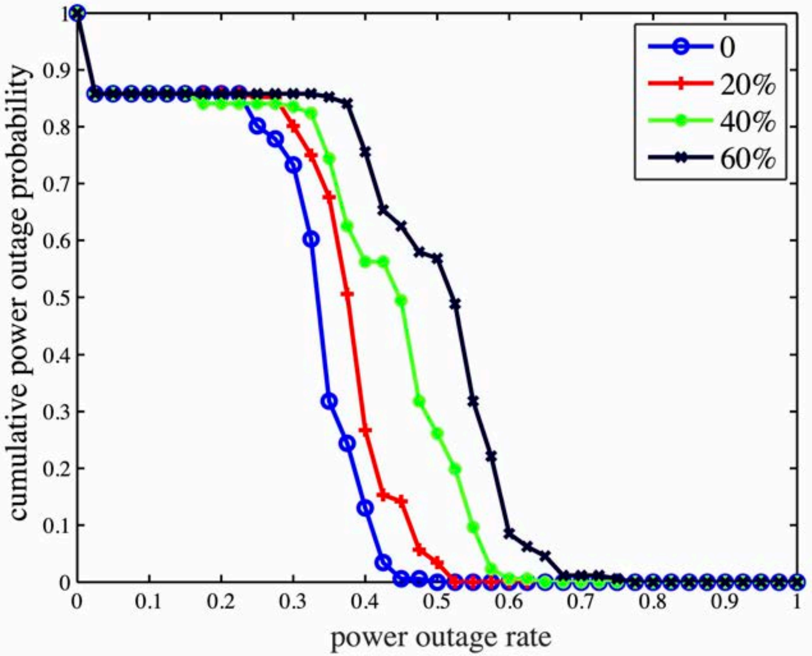
C. K. Tse, M. Huang, X. Zhang, D. Liu and X. L. Li, "Circuits and systems issues in power electronics penetrated power grid," ***IEEE Open Journal of Circuits and Systems,*** vol. 1, pp. 140–156, Sep. 2020.

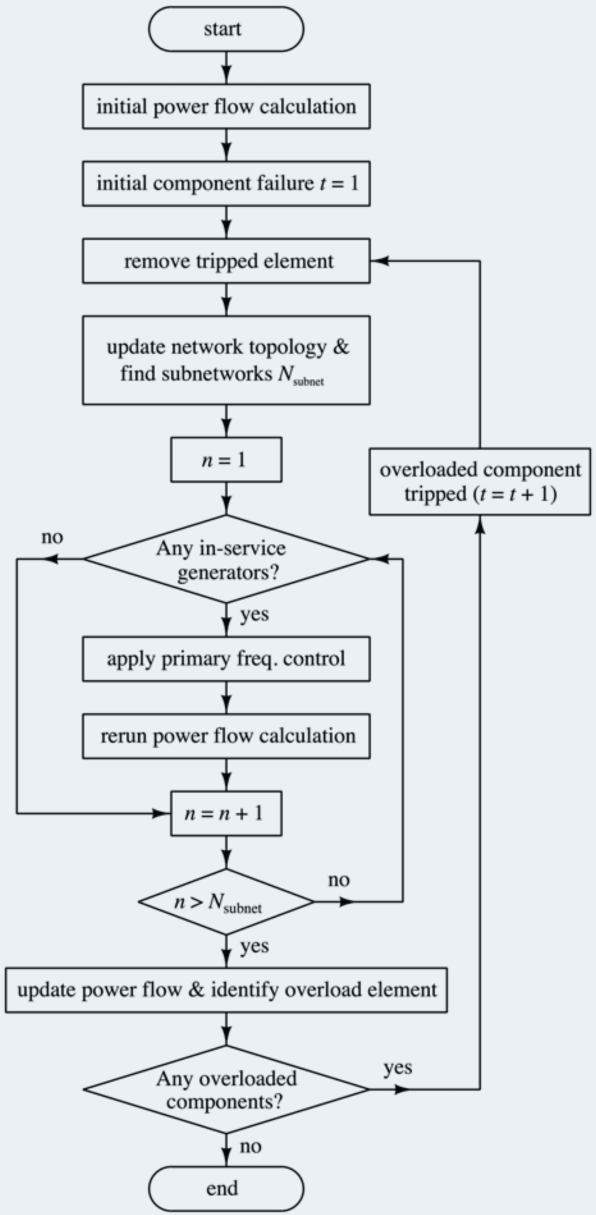
Simulation of IEEE 118-BUS

EFFECTS OF INCREASING PE can be revealed by this model

Power outage rate (x-axis) is the fraction of network without power supply.

As more PE is used, the power outage probability increases, at any given outage rate.

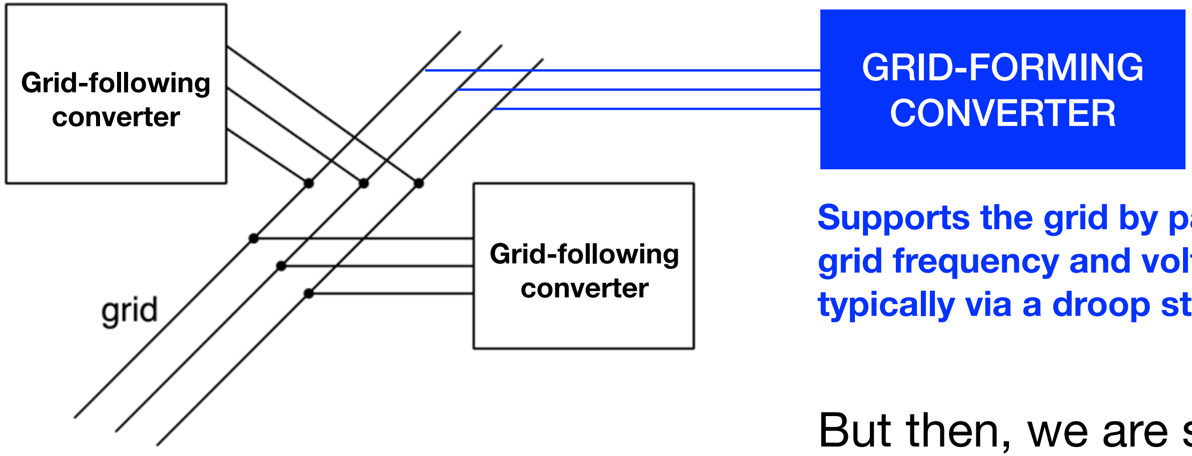




Challenges

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!*



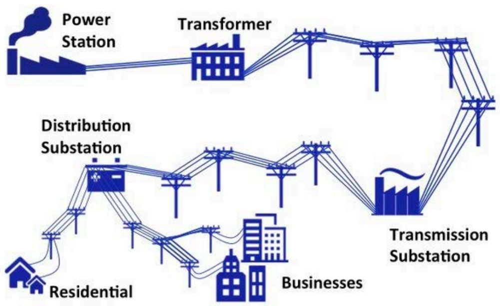
The grid gets less stiff as the percentage of synchronous machines drops!

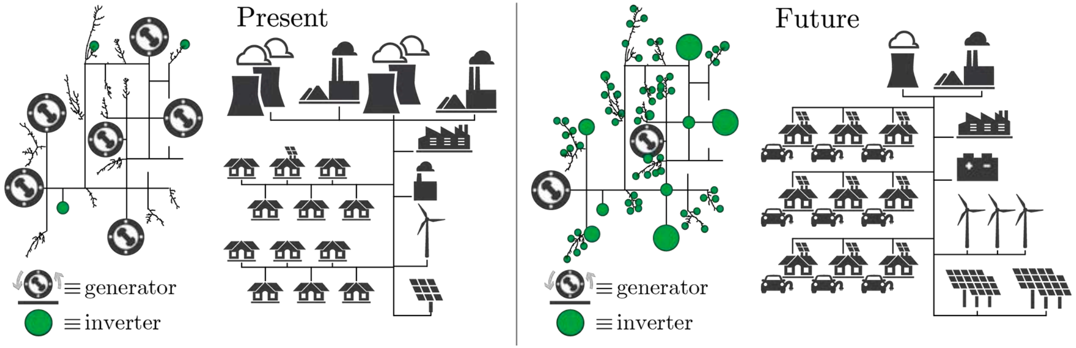
Supports the grid by participating in grid frequency and voltage control, typically via a droop strategy.

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 sycn 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

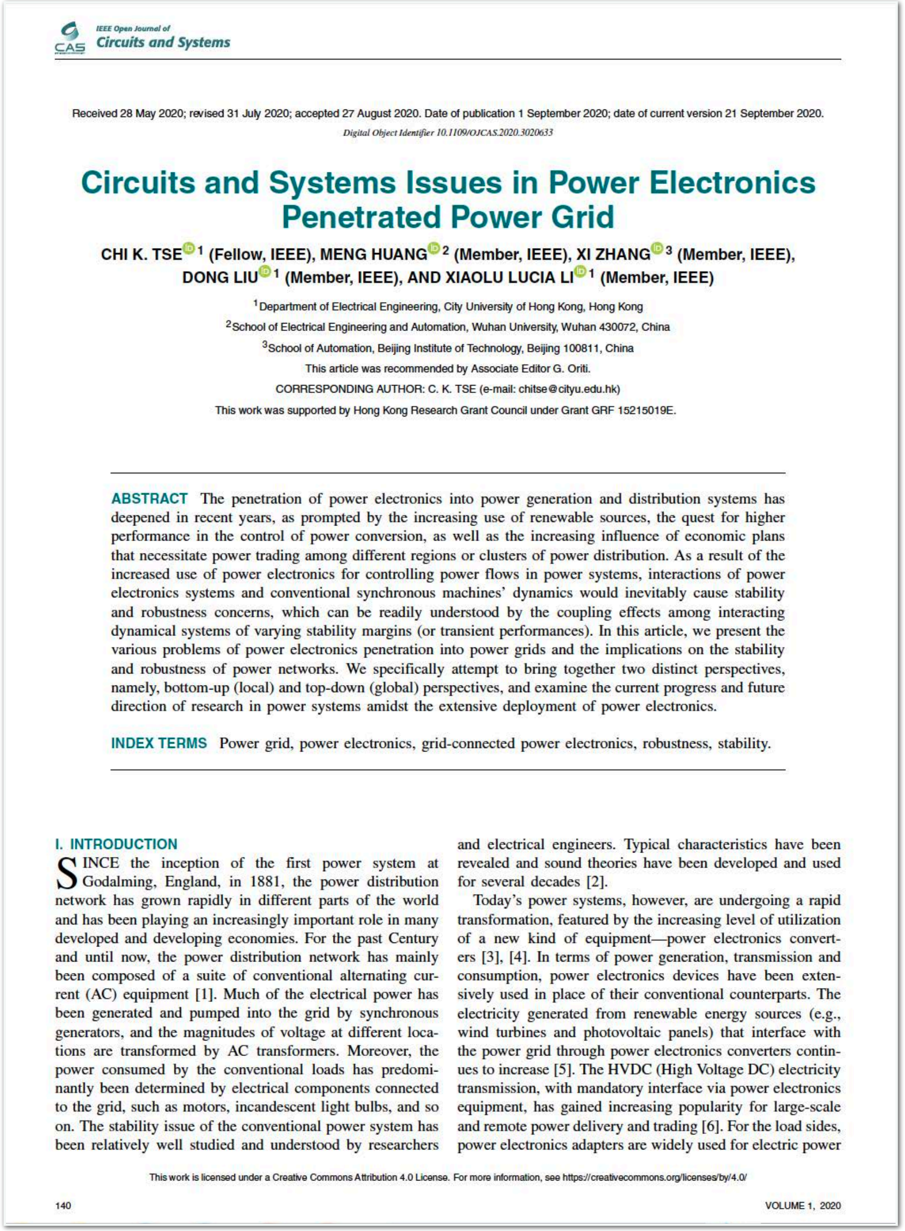
(relatively more mature)

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)



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Circuits and Systems Issues in Power Electronics Penetrated Power Grid

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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

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