香港城市大學
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Hong Kong Institute for Advanced Study

HKIAS Distinguished Lecture Series on Electronics and Photonics

Challenges of Modern Power Grid in the Midst of Deepening Power Electronics Penetration and Increasing Renewable Energy Use

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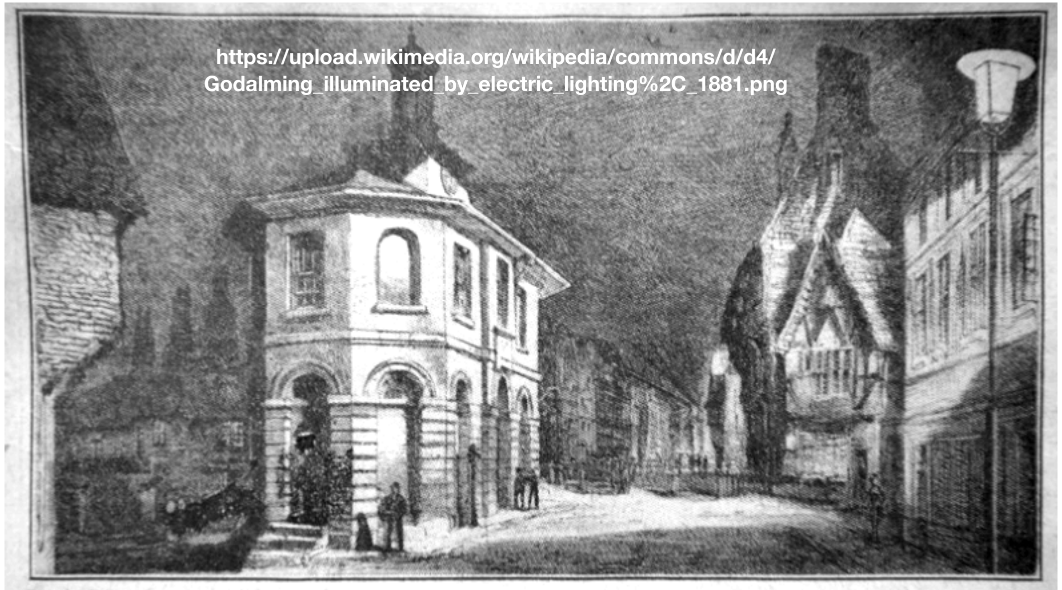
April 12, 2022

The winner was AC!

But as power systems evolve over time, what challenges are we facing?

In the coming decade, how considerations of sustainability will shape the development path of our power supply systems?

First Public Power Supply System



Godalming, England 1888
(~50 km southwest of London)

Waterwheel driving a Siemens **AC Alternator** (dynamo)

Several supply cables, some laid in gutters

Feeding 7 arc **lights** and 34 incandescent **lights**.

hongkong electric 港燈 HK Electric

CLP 中電

Historical note:
AC was found to be more efficient for transmission than DC.
50 Hz is a convenient turbine speed, and no flickers for lights (to human eyes) and yet insignificant skin effect of cables.

The Evolving Power Grid

Power Generation

Power plants (coal, nuclear)

Synchronous generators

Small number of renewable sources

Distribution

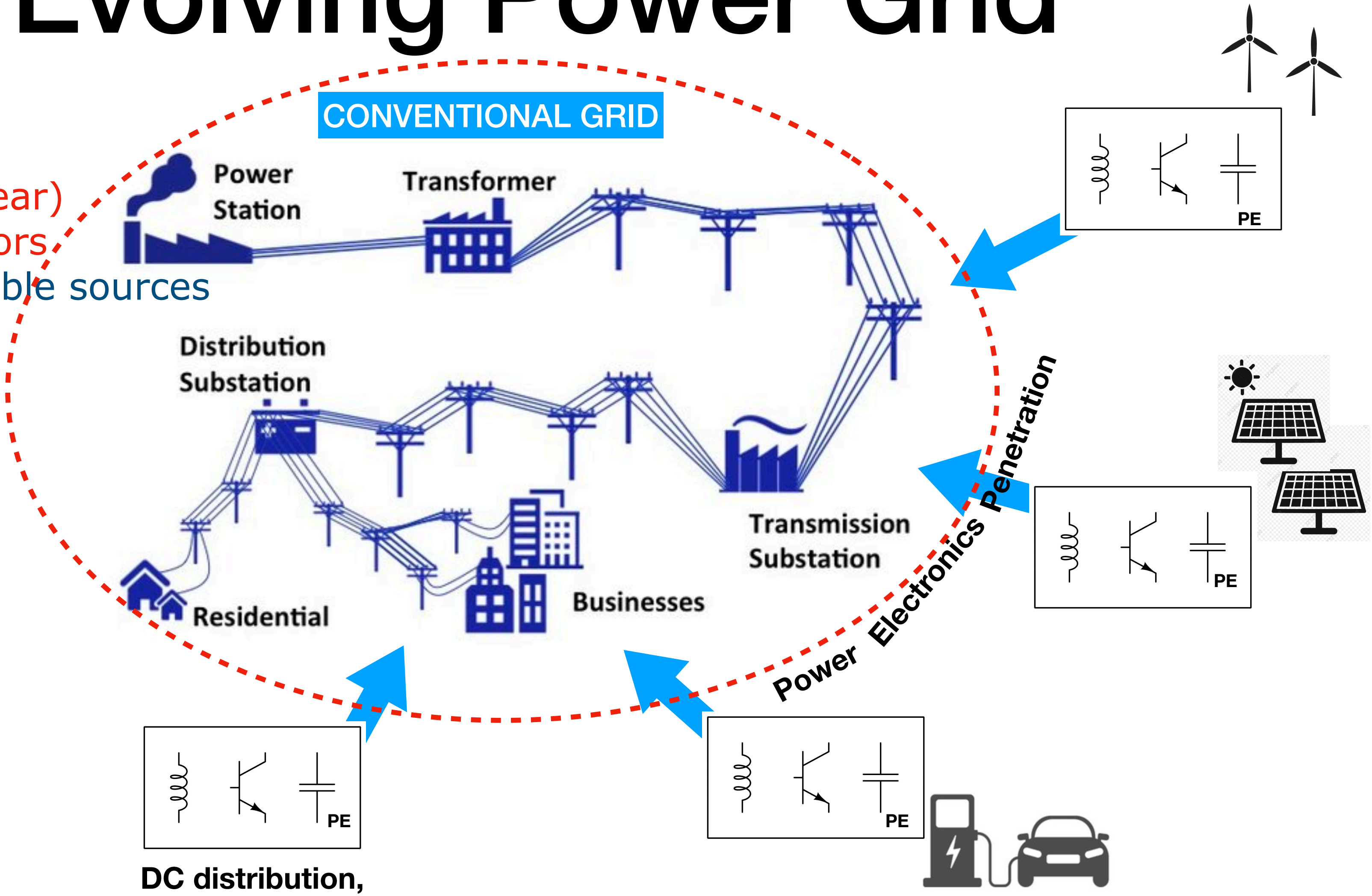
Transmission

Transformation

Consumption

Passive loads

Active regulated loads



DC distribution,
HVDC transmission

Notable Trends

SUPPLY SIDE

- More renewable sources
  - PV
  - Wind

LOAD SIDE

- More active devices
  - Solid-state lighting
  - Regulated loads
    - EV chargers
    - Datacenter power supplies

South China Morning Post

All new cars in Hong Kong could be electric by 2030, five years ahead of schedule, environment official says

- There were nearly 25,000 electric passenger cars on Hong Kong's roads in October, compared to just 180 in 2010
- The government is stepping up policy support to push the adoption of emission-free vehicles, including subsidies for EV purchases and charging infrastructure

Climate change: China aims for 'carbon neutrality by 2060'

By Matt McGrath
Environment correspondent

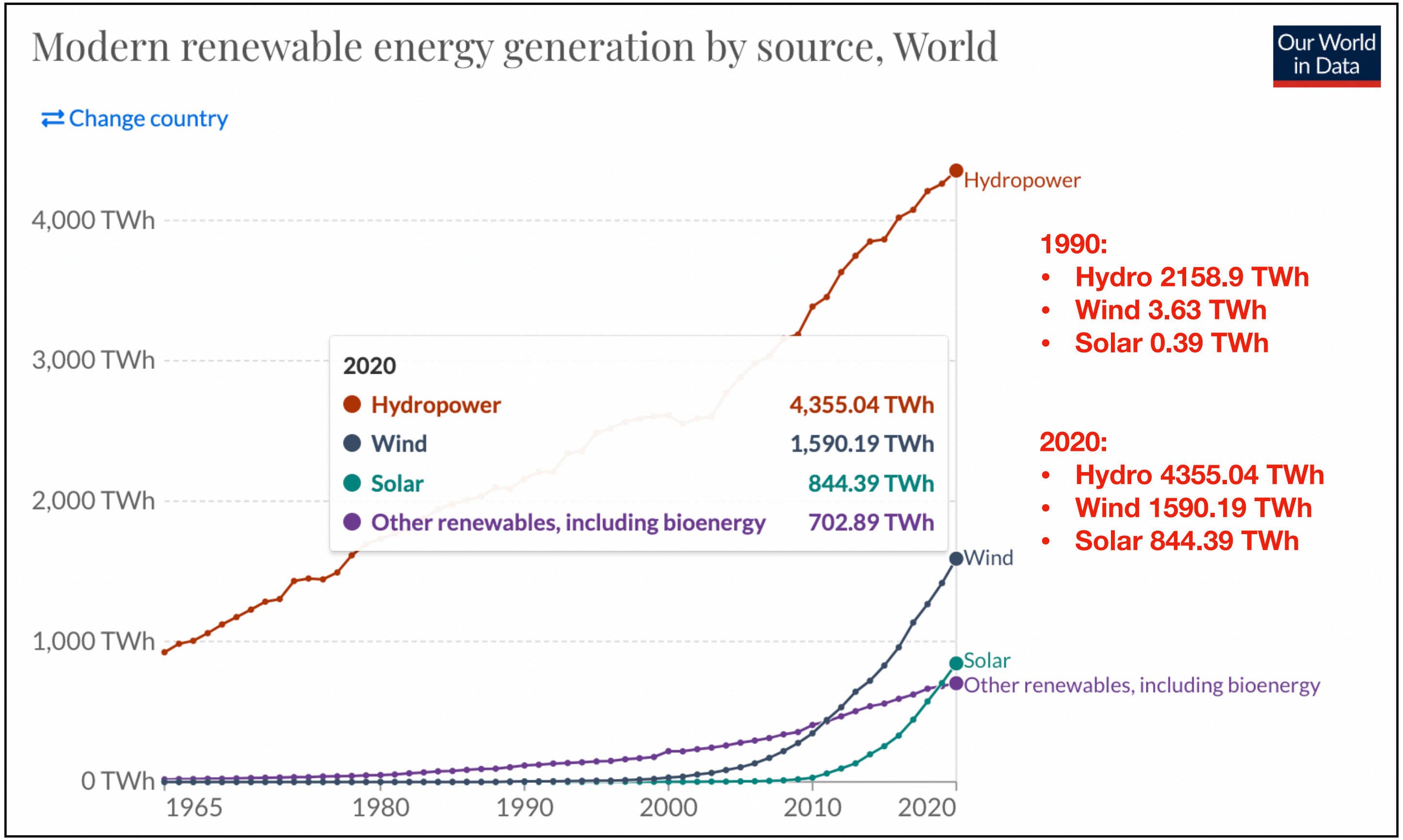
22 September 2020

China's President Xi Jinping addressing the UN via video link

China will aim to hit peak emissions before 2030 and for carbon neutrality by 2060, President Xi Jinping has announced.

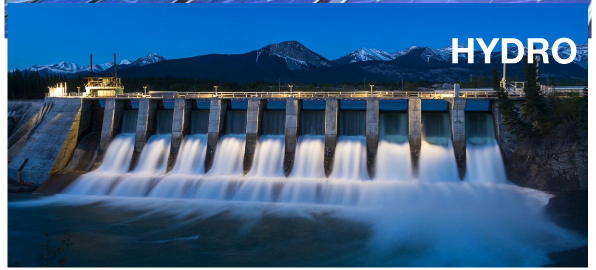
In 2020, Chinese Communist Party general secretary Xi Jinping announced that China aims to peak emissions before 2030 and go carbon-neutral by 2060 in accordance with the Paris climate accord.

Renewable Energy Trends



1990:
- **Hydro 2158.9 TWh**
- **Wind 3.63 TWh**
- **Solar 0.39 TWh**

2020:
- **Hydro 4355.04 TWh**
- **Wind 1590.19 TWh**
- **Solar 844.39 TWh**



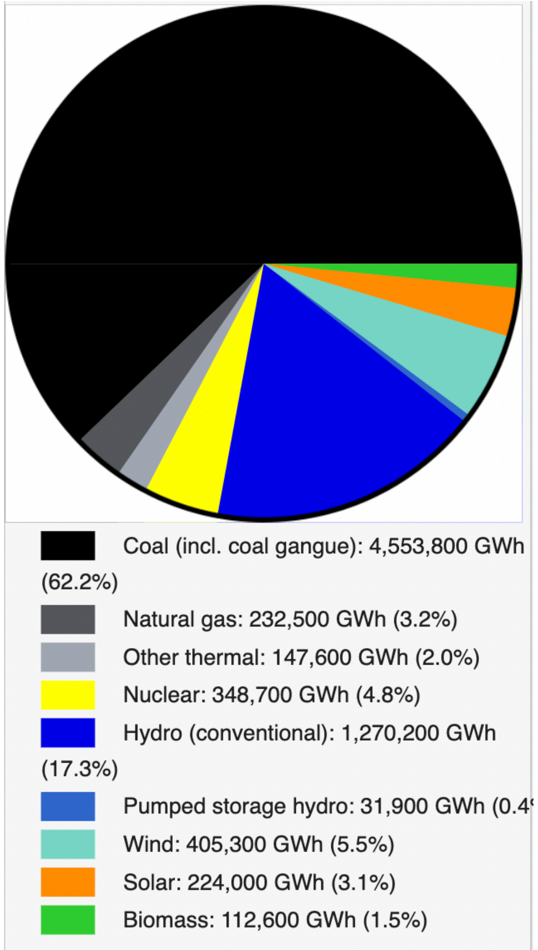
https://ourworldindata.org/renewable-energy

Renewable Trends in China

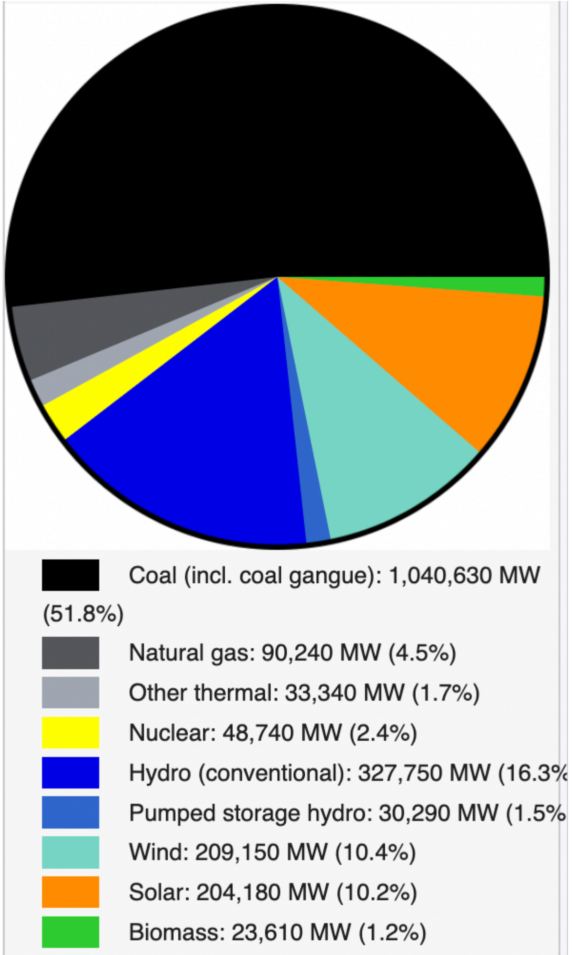
Renewable energy consumption 2020

2,082,800 GWh
(27.32% of total)

ENERGY CONSUMPTION 2019



POWER CAPACITY 2019



Renewable installation capacity 2020

900 GW
[295 GW solar
281 GW wind]

(c.f. 1040 GW coal)

https://en.wikipedia.org/wiki/Electricity_sector_in_China

EVs Growth Trends

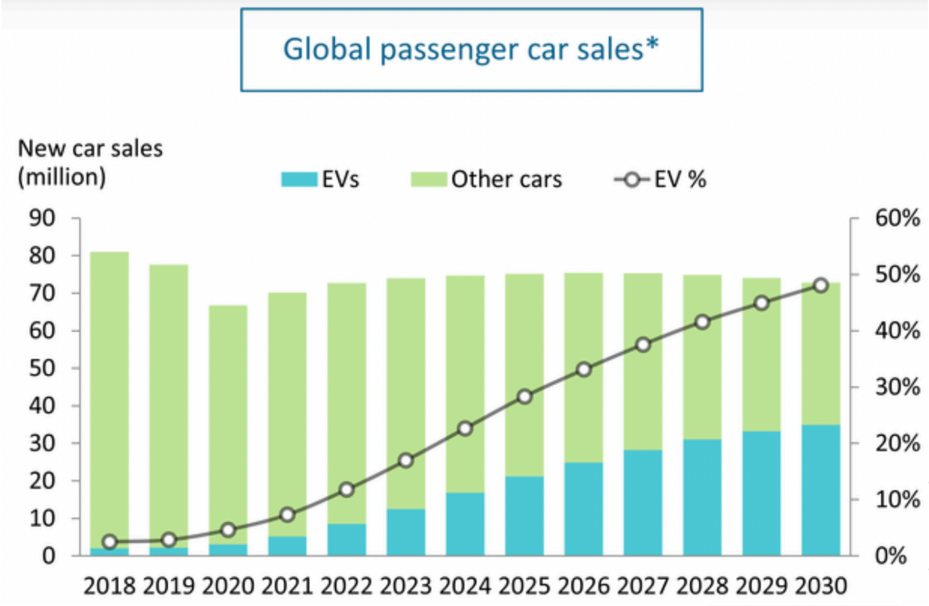
2020

- 3.1M EVs sold (4.7% of new cars sold)

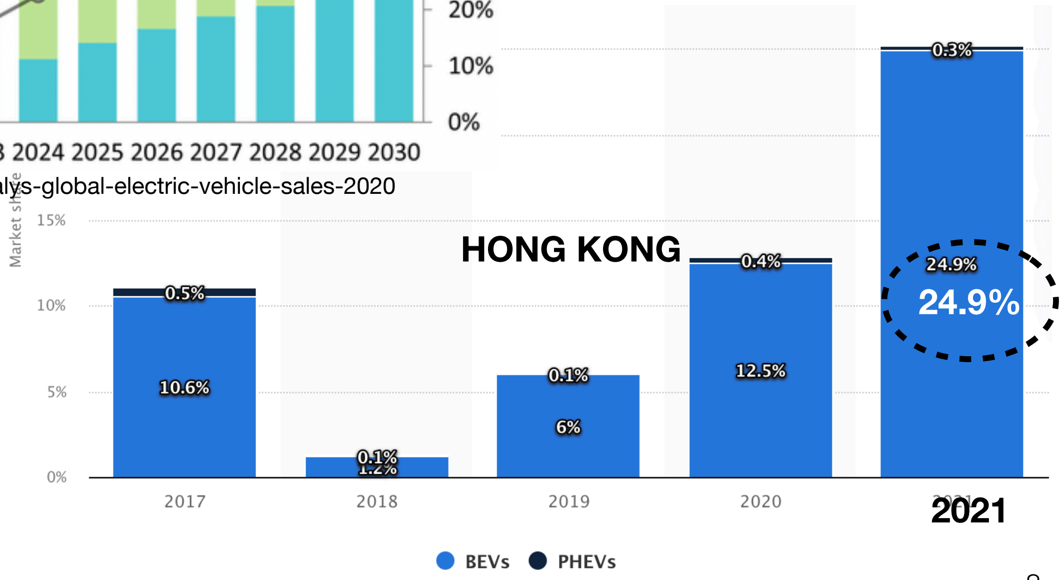
2030

- Projected to increase to 48%

Tremendous demand increase in charging stations and electricity supply infrastructure.



https://canalys.com/newsroom/canalys-global-electric-vehicle-sales-2020

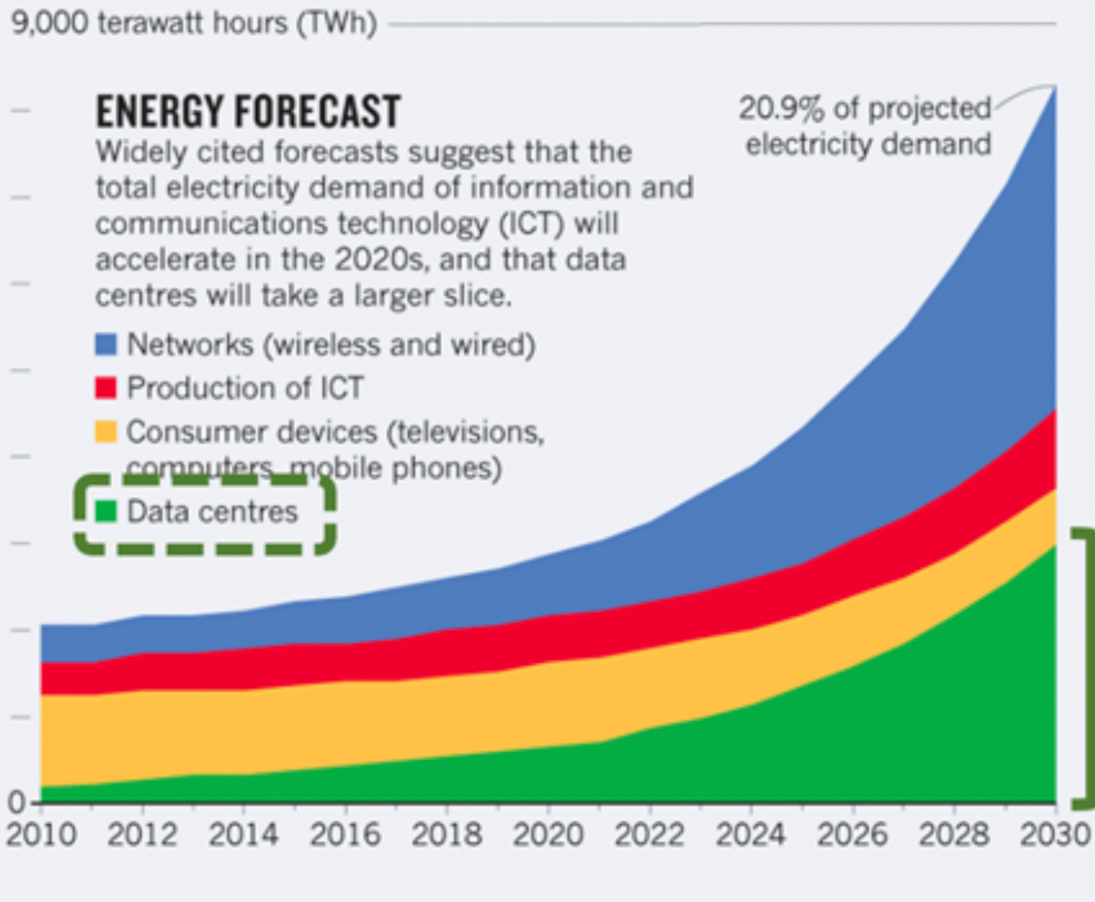


Datacenters Growth Trends

- ICT is expected to account for 21% of global power consumption by 2030
- Networks and Datacenters will be the key consumers

Historical:

Lighting used to take a big share (15-20%). As LED becomes the key technology, lighting no longer takes the largest share of consumption.



The chart above is an 'expected case' projection from Anders Andrae, a specialist in sustainable ICT. In his 'best case' scenario, ICT grows to only 8% of total electricity demand by 2030, rather than to 21%.

Key Driving Forces

SUPPLY SIDE

Conventional sync generators

-Renewable power sources

Load SIDE

Conventional loads

-Active regulated loads

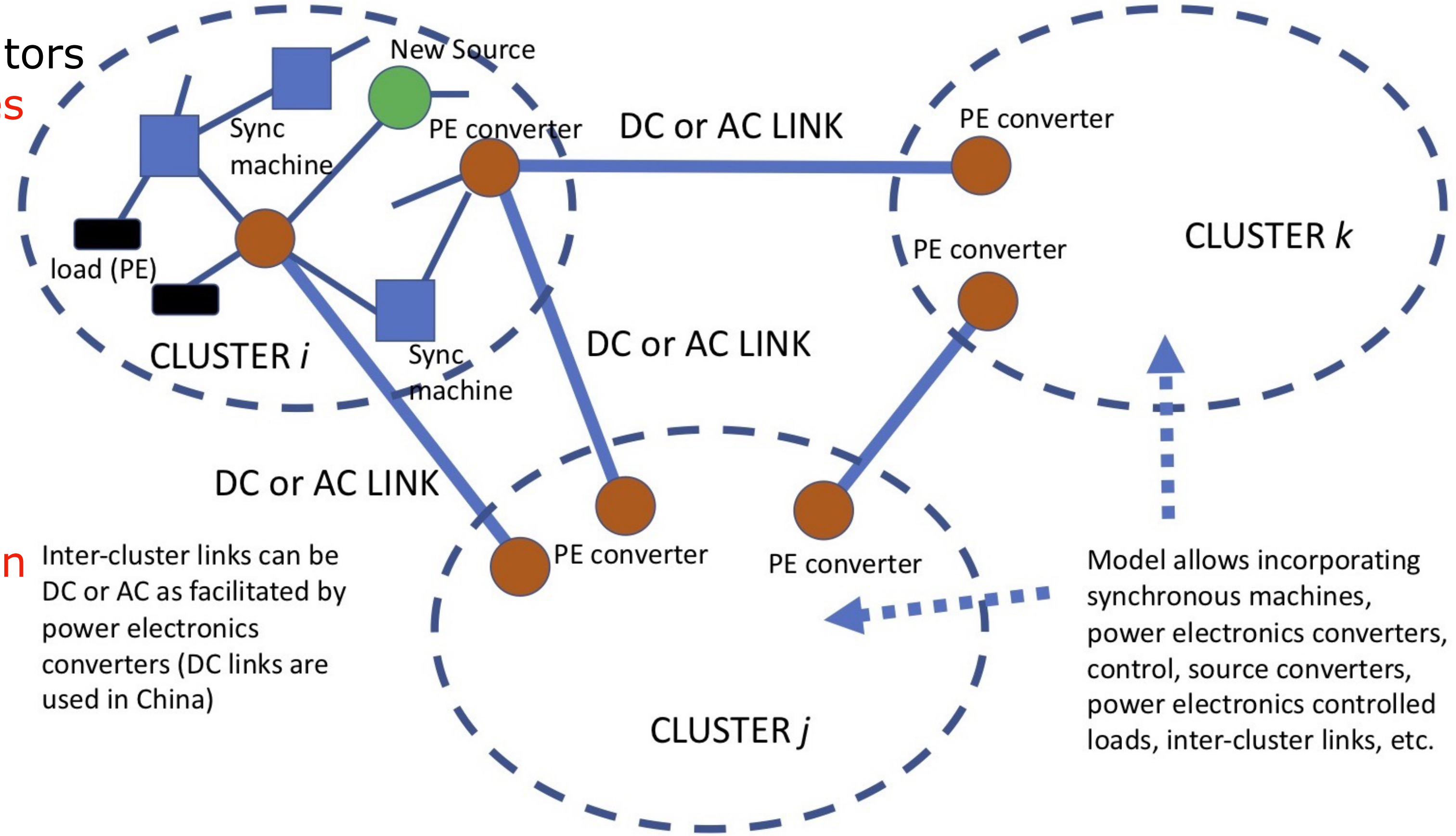
CLUSTERING

Intercluster connections

Power trading

Long distance transmission

AC-DC conversion



And Other Factors

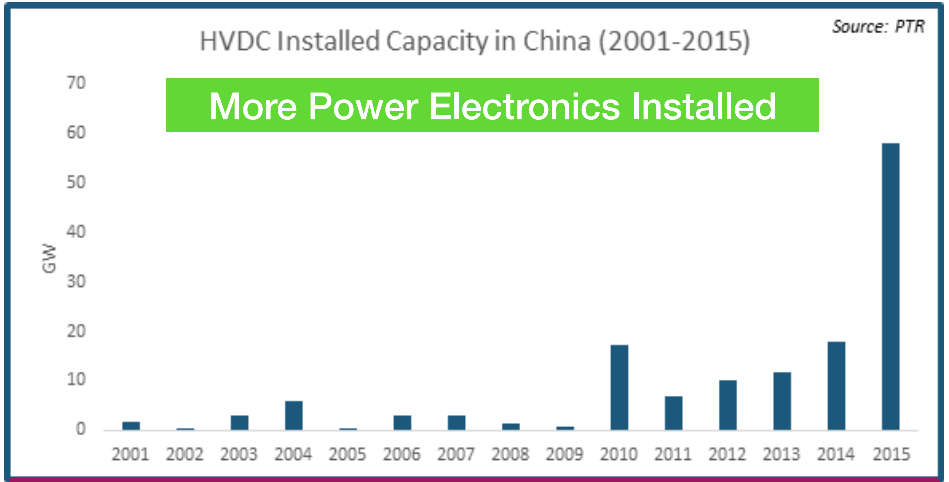
leading to increasing deployment of power electronics

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

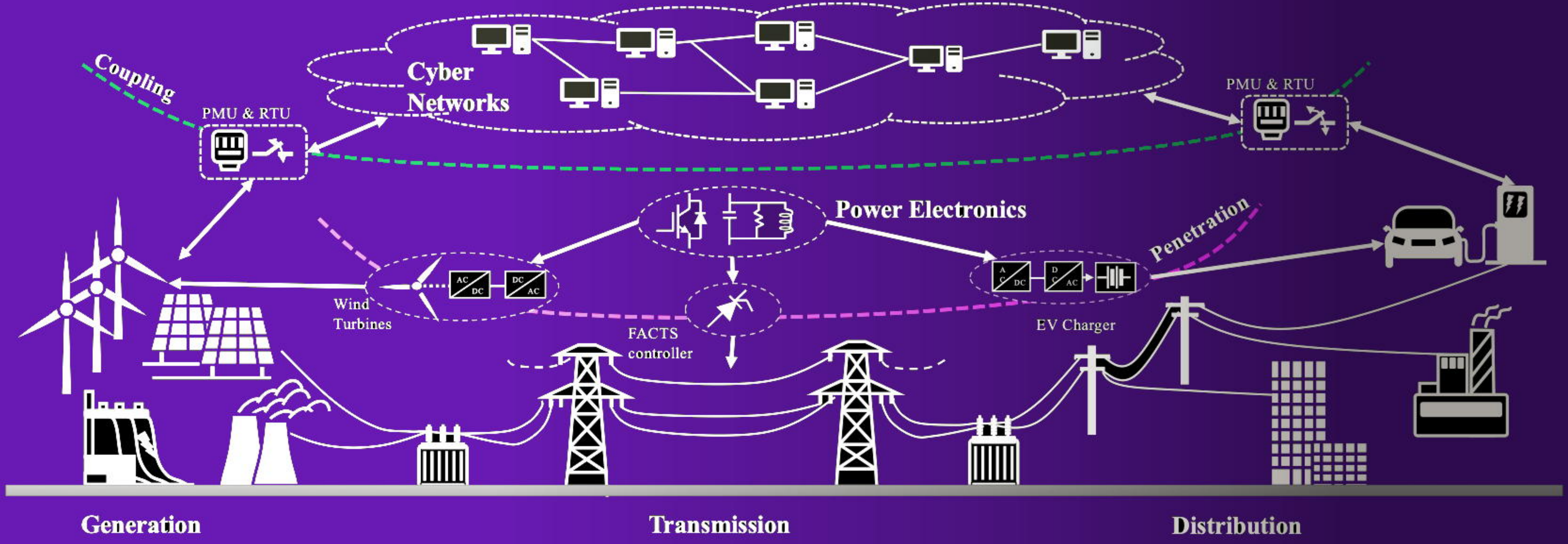
Power electronics substations
Solid state transformers (more compact, smaller)
Control for power quality
Facilitating DC distribution & transmission

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) spent roughly $90B just in UHVDC interconnections from 2009 to 2020 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 (1100 kV) transmission capacity and transmission line length (Xinjiang to Anhui). This 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.



MODERN POWER GRID

FUNDAMENRALLY THE SAME, BUT WITH LOTS OF POWER ELECTRONICS

Questions / (Mis-)expectations

Hong Kong: 1 M vehicles; about 3% being EVs
Suppose EVs increase to **20%**, and each consumes 20 kWh per day.

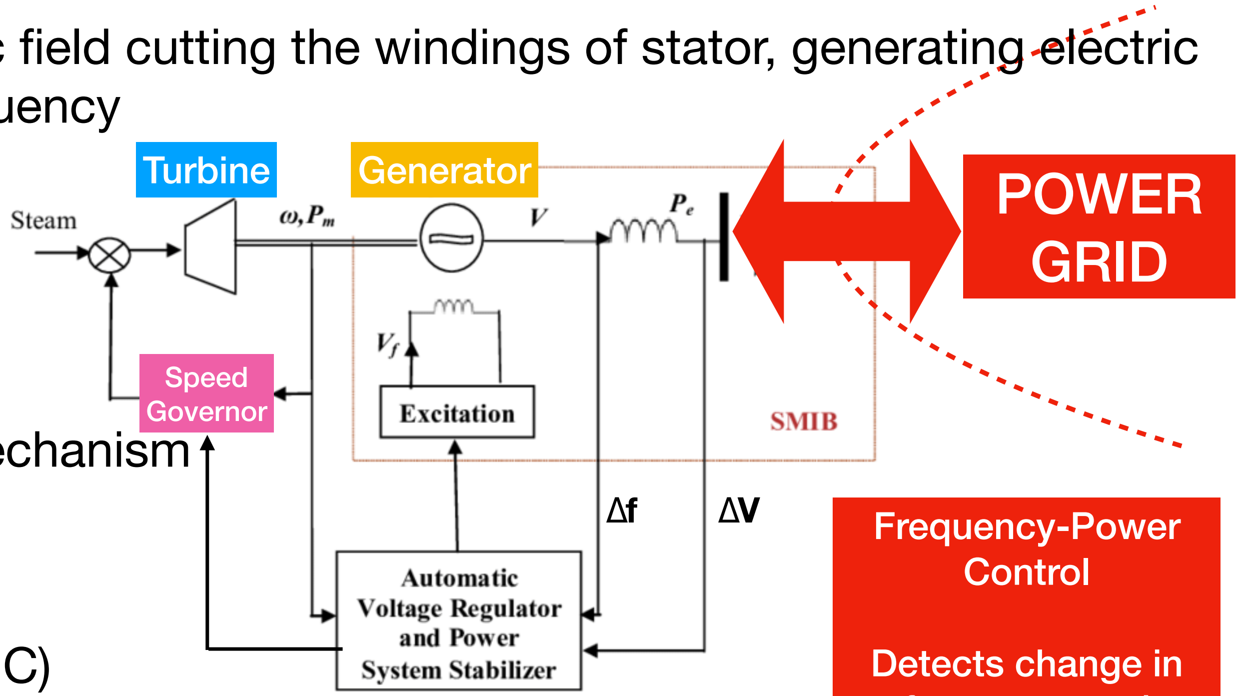
- **EVs need 40 MWh per day!**
- **40,000 charging stations (5 EVs share 1 charger)**
- **1280 MW extra capacity (32 kW charger)**

- More EVs are expected in coming years. We need more charging stations or home EV charging devices. Can we do it?
- We should deploy more PV or wind power. We are able to double or triple the renewable generation. Should we do it?
- We can build high-performance power conversion equipment, like fast-response power supplies, high-efficiency power loads. Should we further optimise performance?

More Power Electronics
What's the impact?

Overview of Grid Control

- Synchronous machine dominated
  - Rotor creates rotating magnetic field cutting the windings of stator, generating electric current at the same rotor's frequency
  - Power balance achieved: ***Mechanical = electrical***

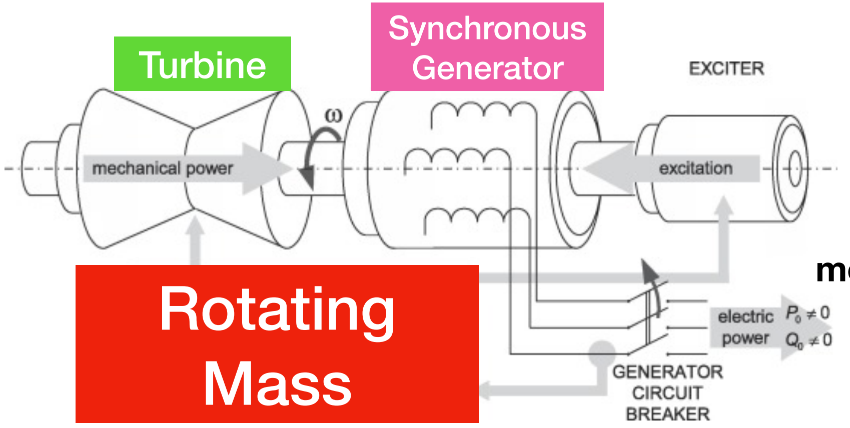


- Conventional Control: Working Mechanism
  - Power ← shaft torque
  - Output voltage ← field current
- Automatic Generation Control (AGC)
  - Detects frequency variation and changes torque to balance power
  - Detects voltage variation and changes excitation of generation

Frequency-Power Control

Detects change in frequency and adjusts torque in rotating shaft

Concept of Inertia



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

Newton's Law

- P_m: mechanical power by turbine
- P_e: electric power produced and to be used
- T_J: inertia
- ω: frequency

Inertia : the key to stability

Tendency to keep rotating due to the energy stored in the rotating masses. Inertia in the power system is provided by the synchronous generators that dominate the power generation in the system.

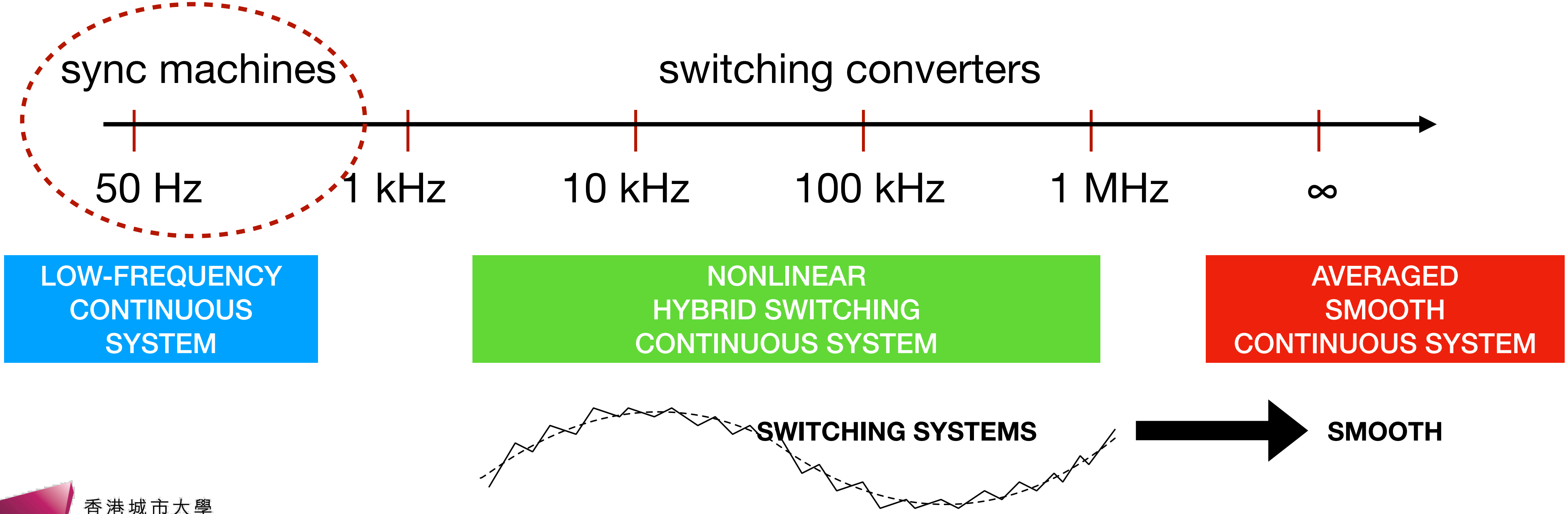
Power electronics have no inertia!

When a power converter plugs on to the grid, it assumes the grid being a voltage source in order to work properly. Such converters are **grid-following.**

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

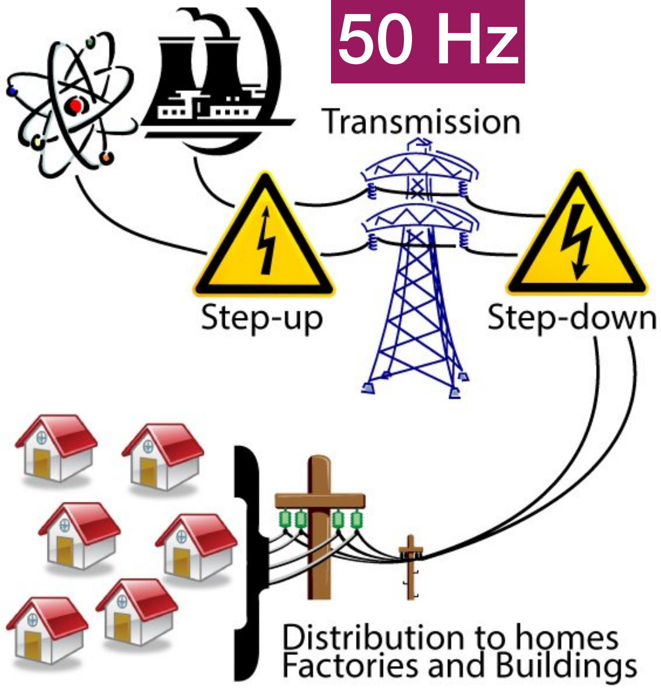
Power Electronics - What's the difference?

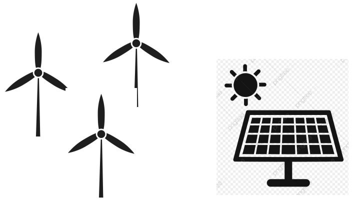
Power converters work in switching mode, i.e., toggling of two or more circuit topologies to modulate power flow, but there is *NO STANDARD switching frequency!*



Power Systems with Power Electronics

Synchronous Generators





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 Chaos
Feedback control systems present negative impedance to grid

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

Basic Issues - Problems Already Emerged

- **LARGE DISTURBANCE**
  - Nonlinear systems linearized for small-signal design
  - **Violation of small-signal assumption** leads to design inconsistency

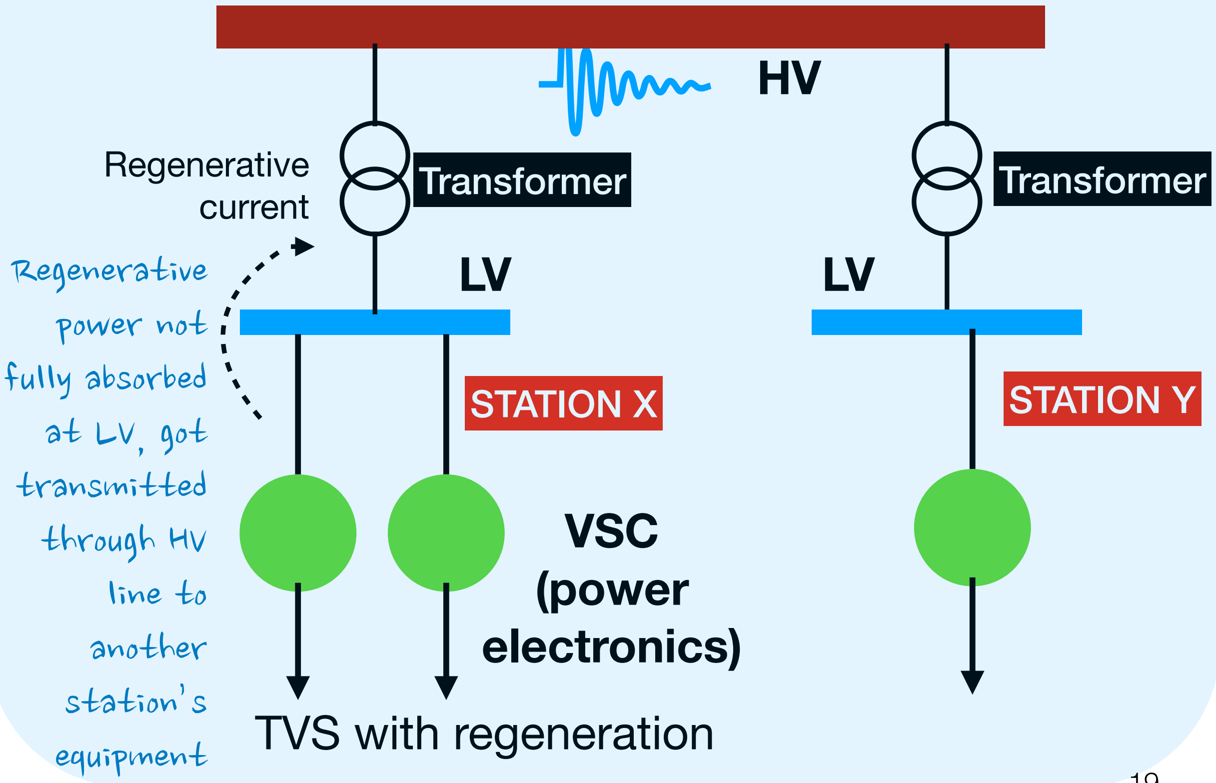
- **OSCILLATION & CHAOS (INTERACTIVE)**
  - Power converters are control systems with feedback to optimize performance. High performance needs high-gain and wideband loop, presenting to grid as ***negative impedance!***

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

Real-life Example I

Railway System

usual oscillation transmitted through HV link



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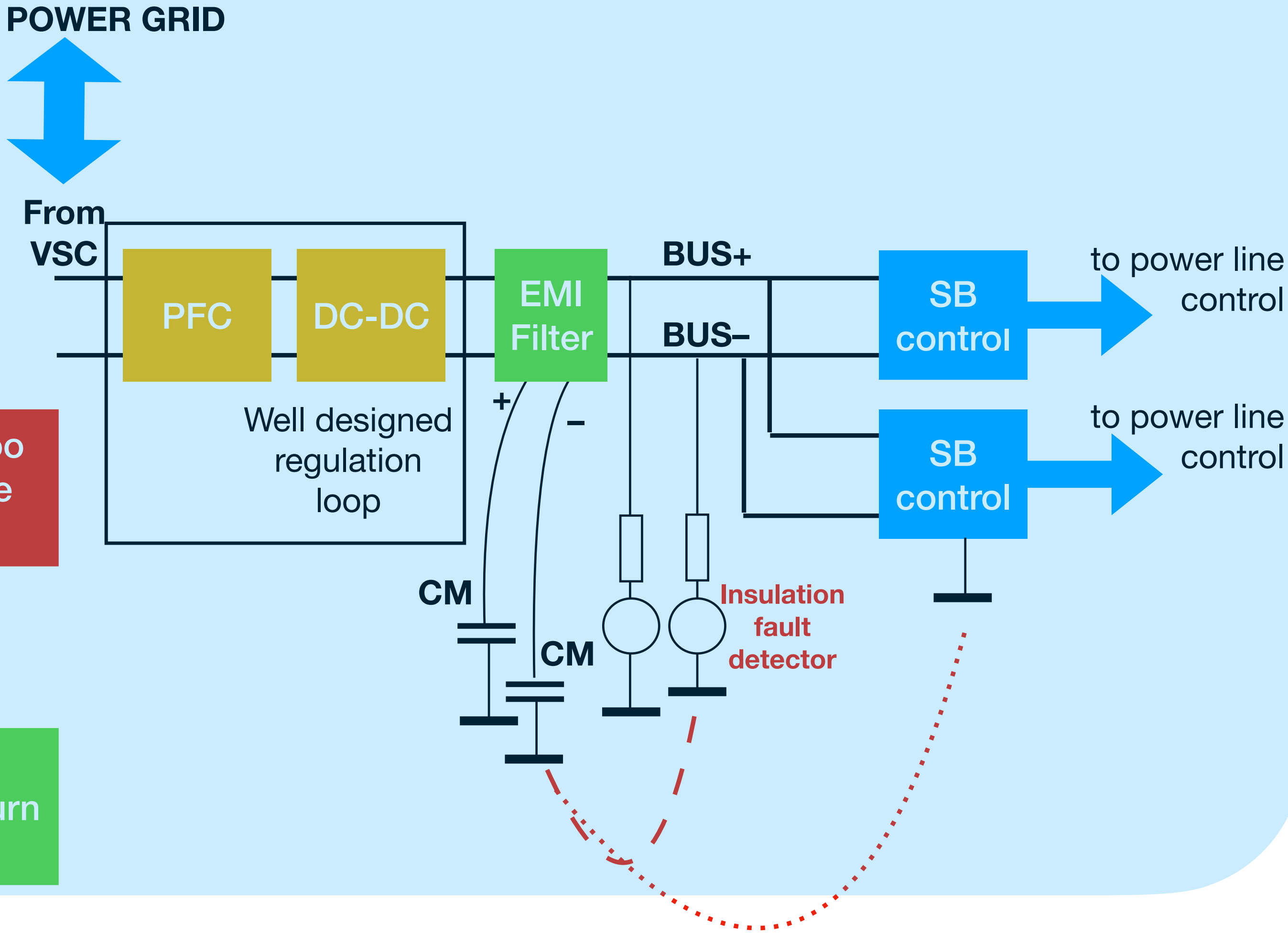
Real-life Example 2

- Power Supply System to switchboard controllers in railway system
  - DC Bus oscillation

? DC-DC converter loop too tight, presenting negative impedance to the bus

  - Insulation leakage at BUS– terminal

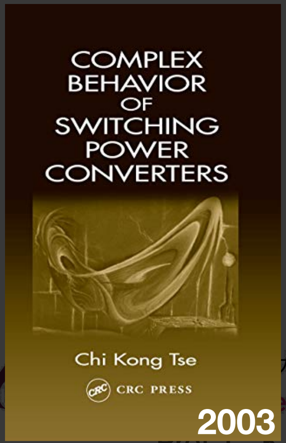
? Insulation fault detector could have recorded return noise current



At load side, devices are coupled via grid

IEEE Transactions on Power Electronics
Best Paper Award 2015

The moral is:
Converters too well designed aren't good for others!



2003

We started research on power converter's nonlinear dynamics back in 1992.
We were the first extending the study to interactive grid-connected converters back in 2012.

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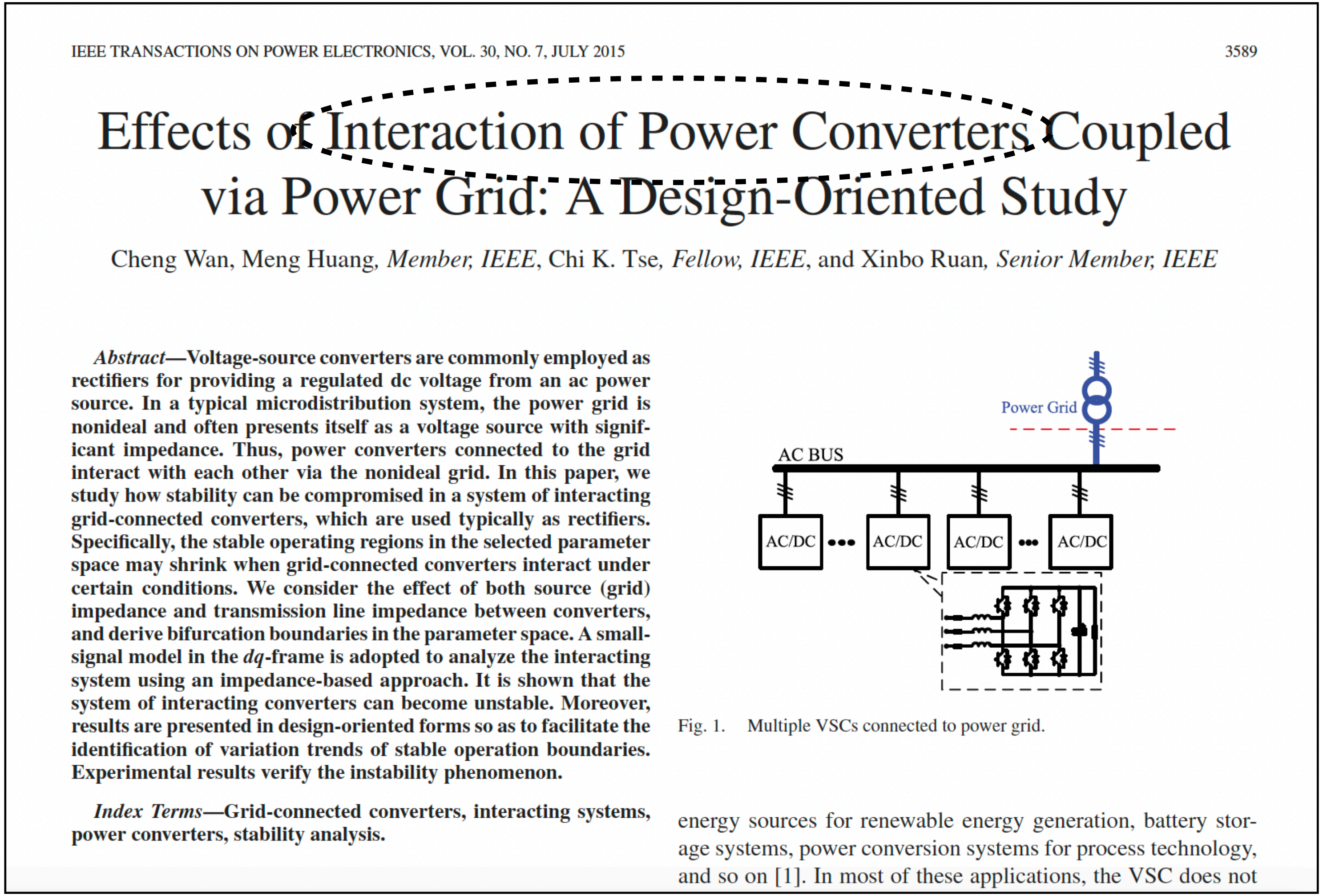


IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 30, NO. 7, JULY 2015 3589

Effects of Interaction of Power Converters Coupled via Power Grid: A Design-Oriented Study

Cheng Wan, Meng Huang, *Member, IEEE*, Chi K. Tse, *Fellow, IEEE*, and Xinbo Ruan, *Senior Member, IEEE*

***Abstract*—Voltage-source converters are commonly employed as rectifiers for providing a regulated dc voltage from an ac power source. In a typical microdistribution system, the power grid is nonideal and often presents itself as a voltage source with significant impedance. Thus, power converters connected to the grid interact with each other via the nonideal grid. In this paper, we study how stability can be compromised in a system of interacting grid-connected converters, which are used typically as rectifiers. Specifically, the stable operating regions in the selected parameter space may shrink when grid-connected converters interact under certain conditions. We consider the effect of both source (grid) impedance and transmission line impedance between converters, and derive bifurcation boundaries in the parameter space. A small-signal model in the *dq*-frame is adopted to analyze the interacting system using an impedance-based approach. It is shown that the system of interacting converters can become unstable. Moreover, results are presented in design-oriented forms so as to facilitate the identification of variation trends of stable operation boundaries. Experimental results verify the instability phenomenon.**

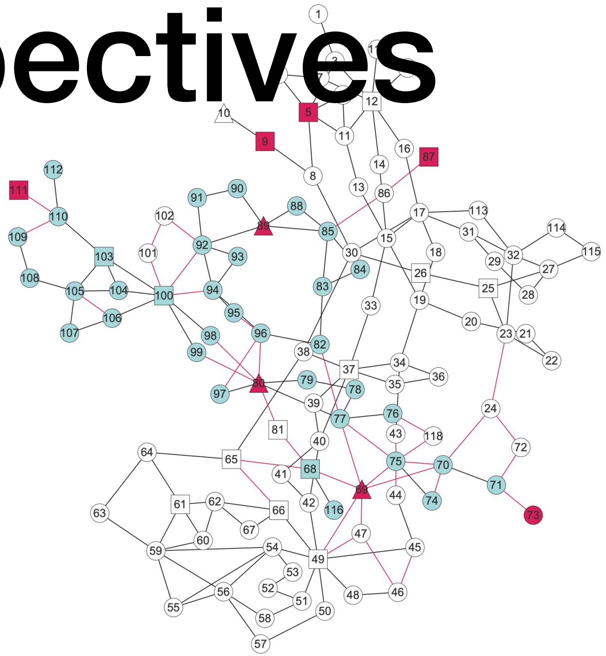
***Index Terms*—Grid-connected converters, interacting systems, power converters, stability analysis.**

Fig. 1. Multiple VSCs connected to power grid.

energy sources for renewable energy generation, battery storage systems, power conversion systems for process technology, and so on [1]. In most of these applications, the VSC does not

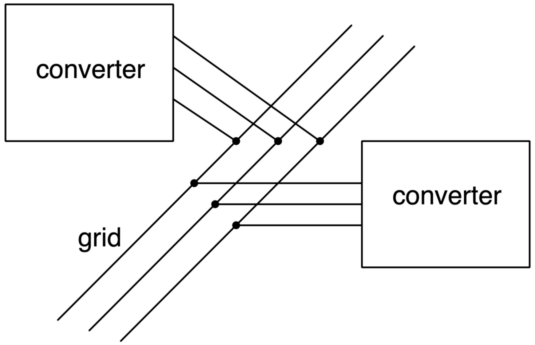
Analytical Methods

Two Distinct Perspectives



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

COMPLEXITY RESEARCH

BOTTOM-UP (LOCAL)

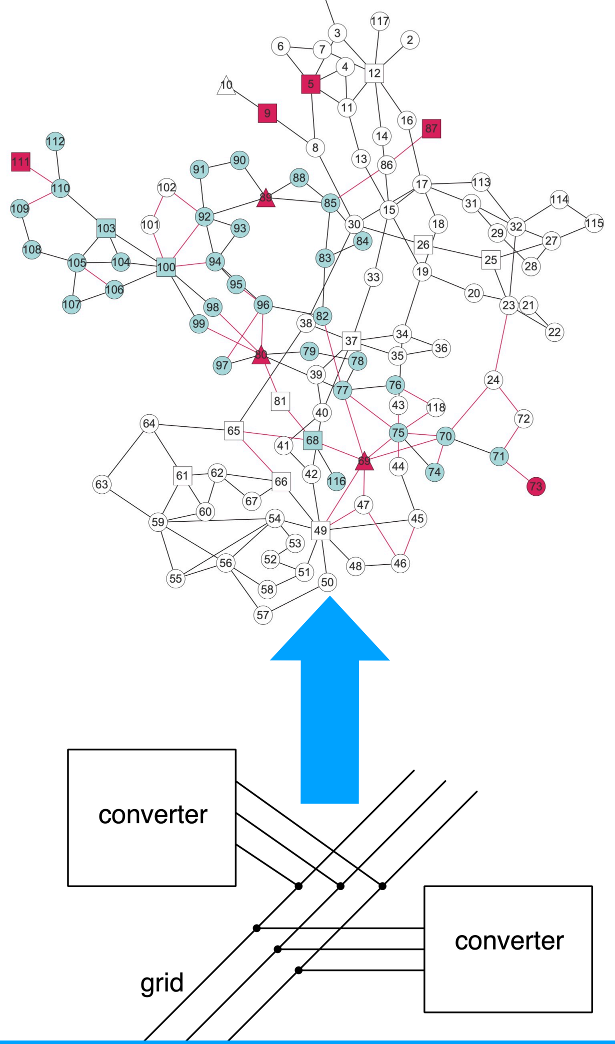
Approaches	Perspectives	Sample Issues	Sample Methods
Bottom-up	Local	Stability - Oscillation - Bifurcation - Operating boundaries - Effects of parameter changes - Mutual interactions	Small-signal model Impedance method Large-signal model Circuit theory Differential equation Frequency-domain method Switching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

Nonlinear dynamics and complex behavior

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

Complex networks and robustness behavior

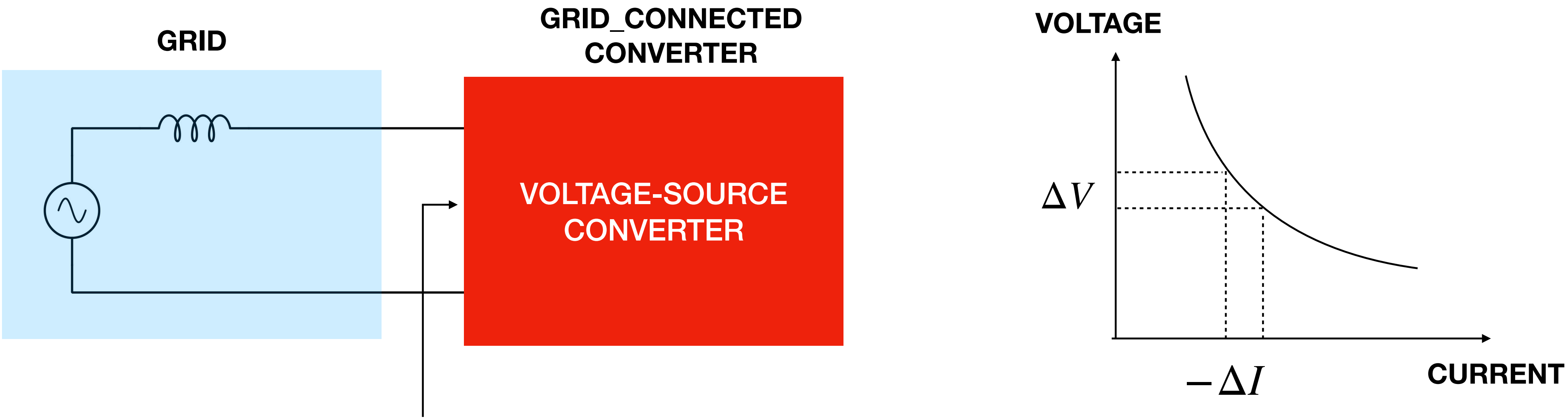


*R*eview of Bottom-Up Approach

(relatively more mature)

A Conventional Perspective

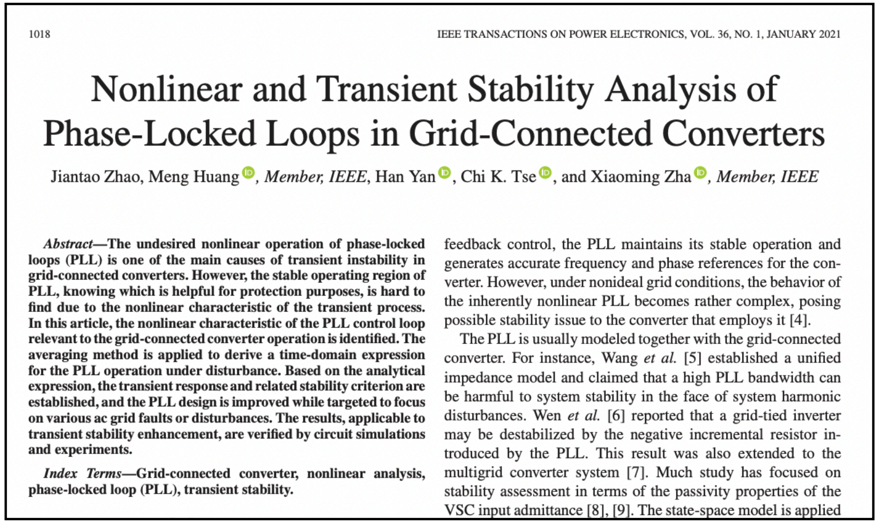
- Traditional small-signal models and linearized analysis
- Impedance based stability criteria (e.g., Middlebrook's criterion, Nyquist, …)



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

More Sources of Nonlinearity

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


1018 IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 36, NO. 1, JANUARY 2021

Nonlinear and Transient Stability Analysis of Phase-Locked Loops in Grid-Connected Converters

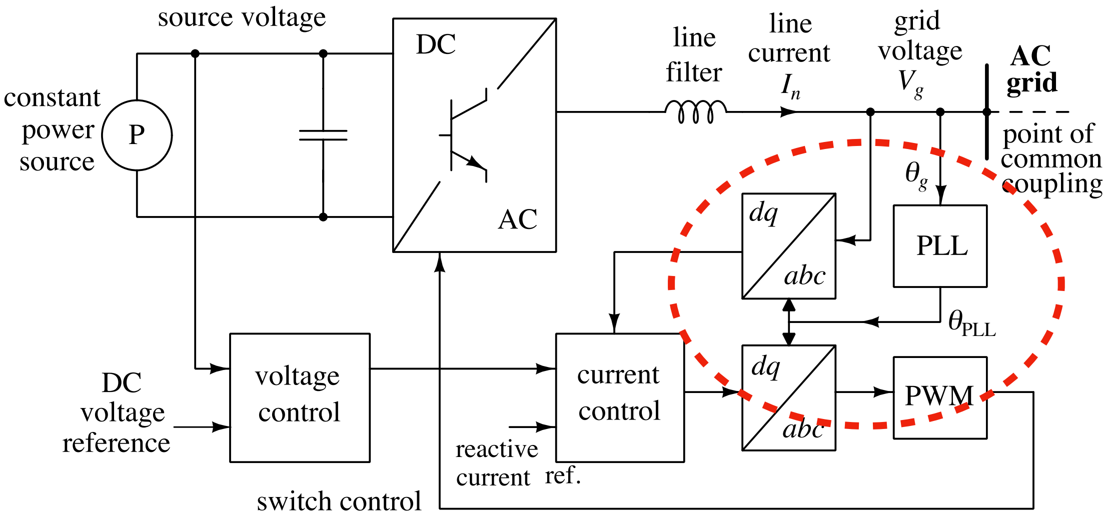
Jiantao Zhao, Meng Huang, *Member, IEEE*, Han Yan, Chi K. Tse, and Xiaoming Zha, *Member, IEEE*

***Abstract*—The undesired nonlinear operation of phase-locked loops (PLL) is one of the main causes of transient instability in grid-connected converters. However, the stable operating region of PLL, knowing which is helpful for protection purposes, is hard to find due to the nonlinear characteristic of the transient process. In this article, the nonlinear characteristic of the PLL control loop relevant to the grid-connected converter operation is identified. The averaging method is applied to derive a time-domain expression for the PLL operation under disturbance. Based on the analytical expression, the transient response and related stability criterion are established, and the PLL design is improved while targeted to focus on various ac grid faults or disturbances. The results, applicable to transient stability enhancement, are verified by circuit simulations and experiments.**

***Index Terms*—Grid-connected converter, nonlinear analysis, phase-locked loop (PLL), transient stability.**

feedback control, the PLL maintains its stable operation and generates accurate frequency and phase references for the converter. However, under nonideal grid conditions, the behavior of the inherently nonlinear PLL becomes rather complex, posing possible stability issue to the converter that employs it [4].

The PLL is usually modeled together with the grid-connected converter. For instance, Wang *et al.* [5] established a unified impedance model and claimed that a high PLL bandwidth can be harmful to system stability in the face of system harmonic disturbances. Wen *et al.* [6] reported that a grid-tied inverter may be destabilized by the negative incremental resistor introduced by the PLL. This result was also extended to the multigrid converter system [7]. Much study has focused on stability assessment in terms of the passivity properties of the VSC input admittance [8], [9]. The state-space model is applied



Nonlinear damping of PLL

Nonlinear phase detector:

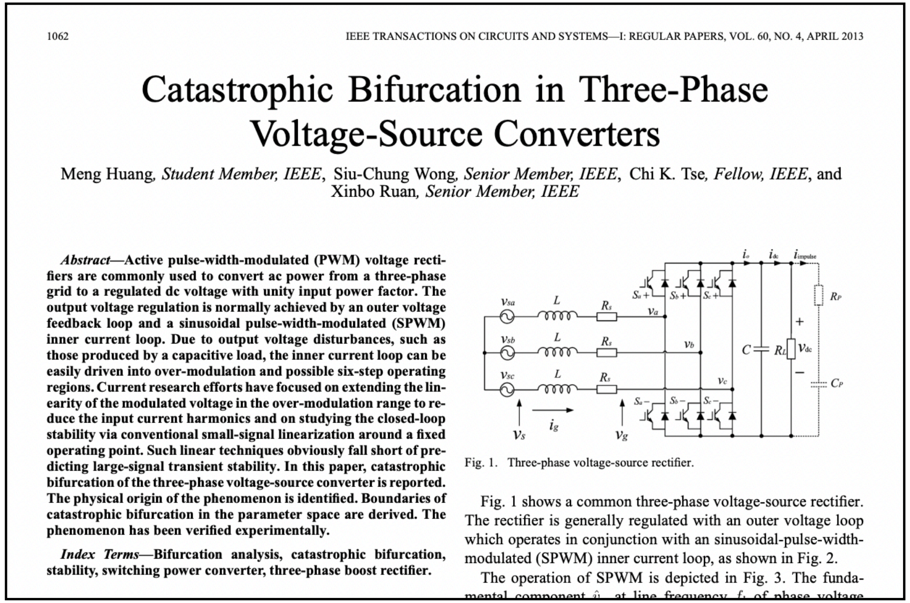
- **Rapid drop in damping at small short-circuit ratio (weak grid)**
- **Short-circuit ratio = Vg / In Zs**

grid voltage — **line current** — **source impedance of grid**

- **Unstable operation as damping weakens**

More Sources of Nonlinearity

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



Catastrophic Bifurcation in Three-Phase Voltage-Source Converters

Meng Huang, *Student Member, IEEE*, Siu-Chung Wong, *Senior Member, IEEE*, Chi K. Tse, *Fellow, IEEE*, and Xinbo Ruan, *Senior Member, IEEE*

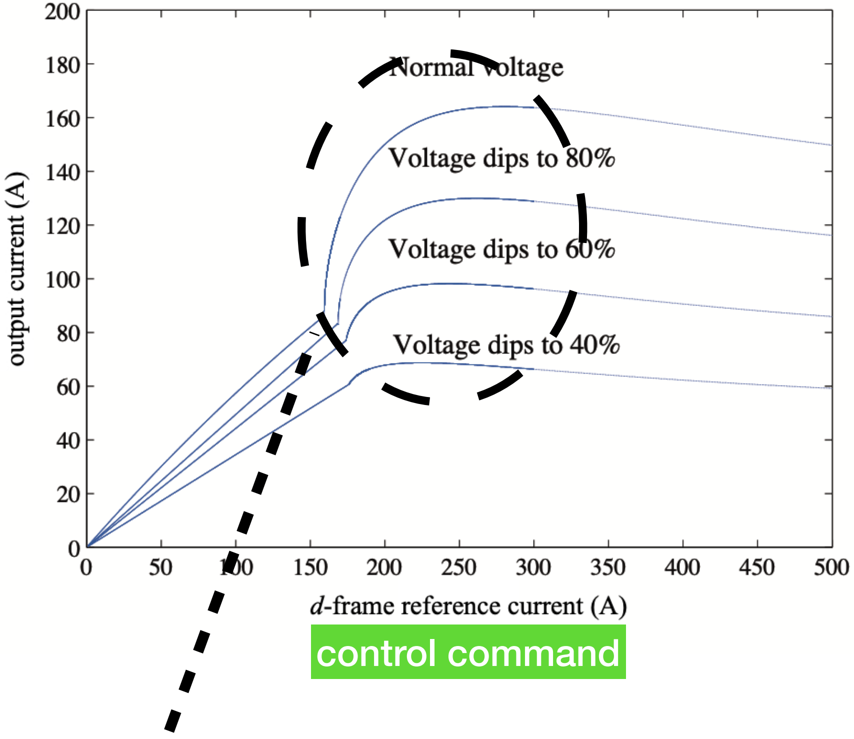
***Abstract*—Active pulse-width-modulated (PWM) voltage rectifiers are commonly used to convert ac power from a three-phase grid to a regulated dc voltage with unity input power factor. The output voltage regulation is normally achieved by an outer voltage feedback loop and a sinusoidal pulse-width-modulated (SPWM) inner current loop. Due to output voltage disturbances, such as those produced by a capacitive load, the inner current loop can be easily driven into over-modulation and possible six-step operating regions. Current research efforts have focused on extending the linearity of the modulated voltage in the over-modulation range to reduce the input current harmonics and on studying the closed-loop stability via conventional small-signal linearization around a fixed operating point. Such linear techniques obviously fall short of predicting large-signal transient stability. In this paper, catastrophic bifurcation of the three-phase voltage-source converter is reported. The physical origin of the phenomenon is identified. Boundaries of catastrophic bifurcation in the parameter space are derived. The phenomenon has been verified experimentally.**

***Index Terms*—Bifurcation analysis, catastrophic bifurcation, stability, switching power converter, three-phase boost rectifier.**

Fig. 1. Three-phase voltage-source rectifier.

Fig. 1 shows a common three-phase voltage-source rectifier. The rectifier is generally regulated with an outer voltage loop which operates in conjunction with an sinusoidal-pulse-width-modulated (SPWM) inner current loop, as shown in Fig. 2.

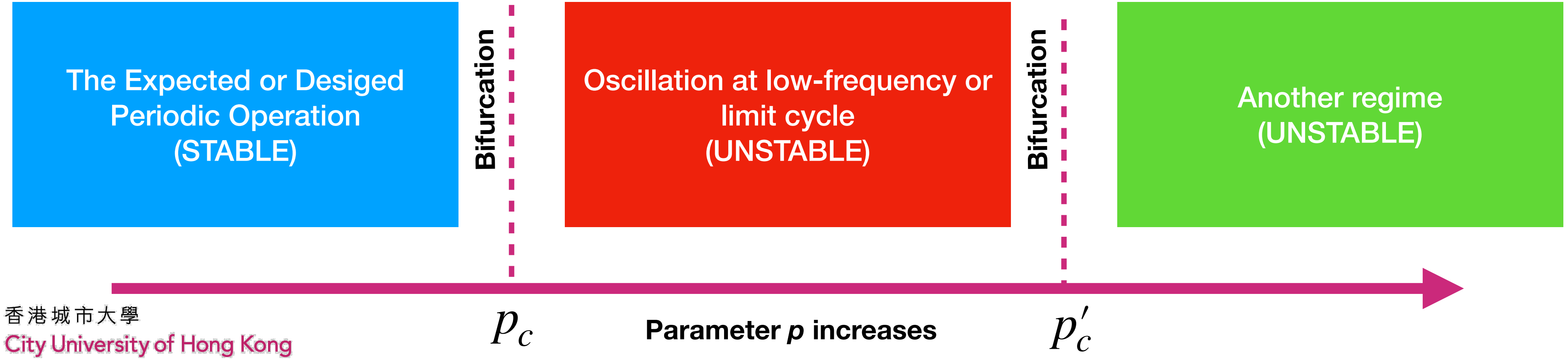
The operation of SPWM is depicted in Fig. 3. The funda-



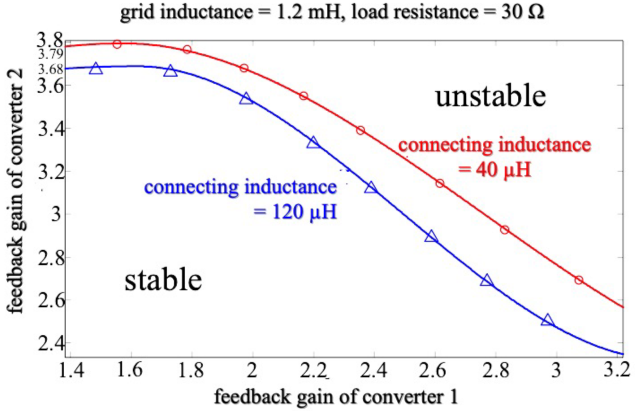
OUTPUT CURRENT expands catastrophically

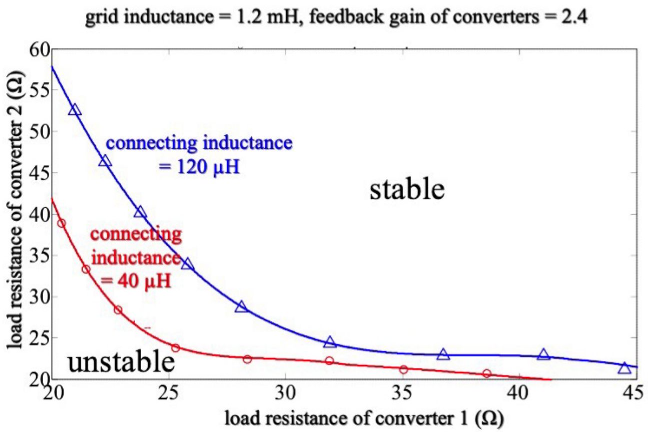
It's all about "Bifurcation"!

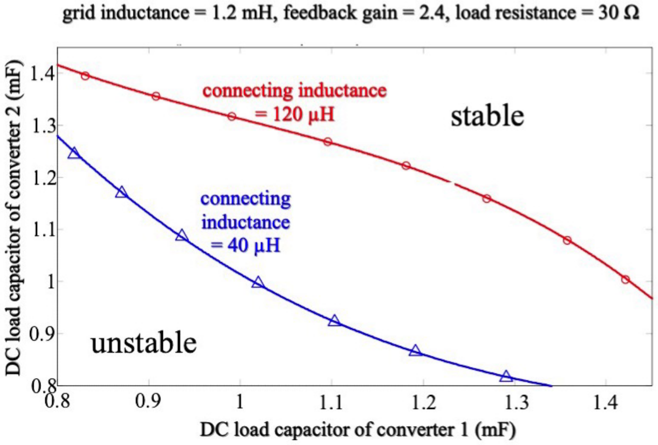
- Bifurcation — *Change in qualitative behavior as one or more parameters are varied.*
- It is basically a study of STABILITY, if we define one kind of behavior as the stable operation (one of the regimes).
- Bifurcation analysis is therefore nothing but stabilty analysis extended to MORE THAN one operating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



Design-Oriented Bifurcation Analysis







Bifurcation Analysis

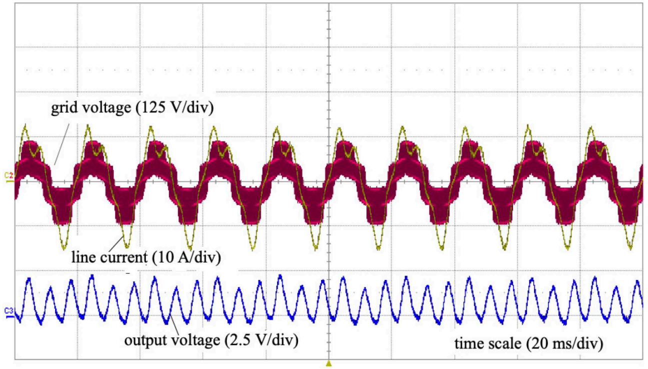
— Stability analysis of local linearized models, but MOVING operating point.
It is thus NOT a linear method strictly speaking, though at each operating point, it is!

Regions of different operating regimes in parameter space

Location of stable / unstable operation boundaries

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

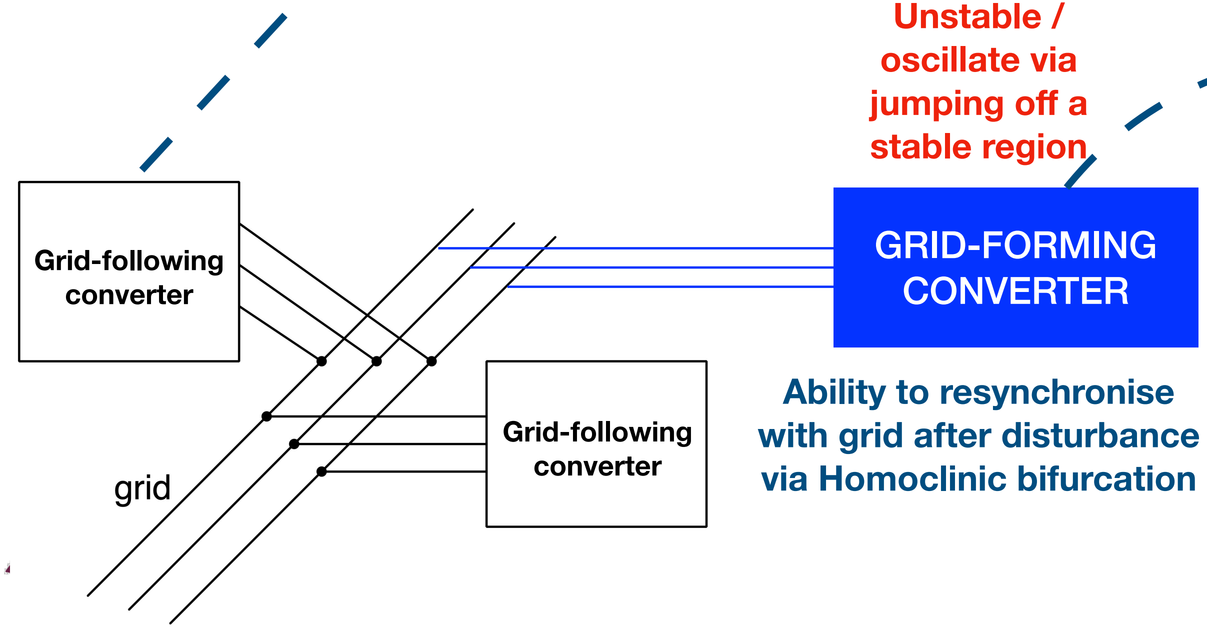
Examples of Bifurcation or Loss of Stability



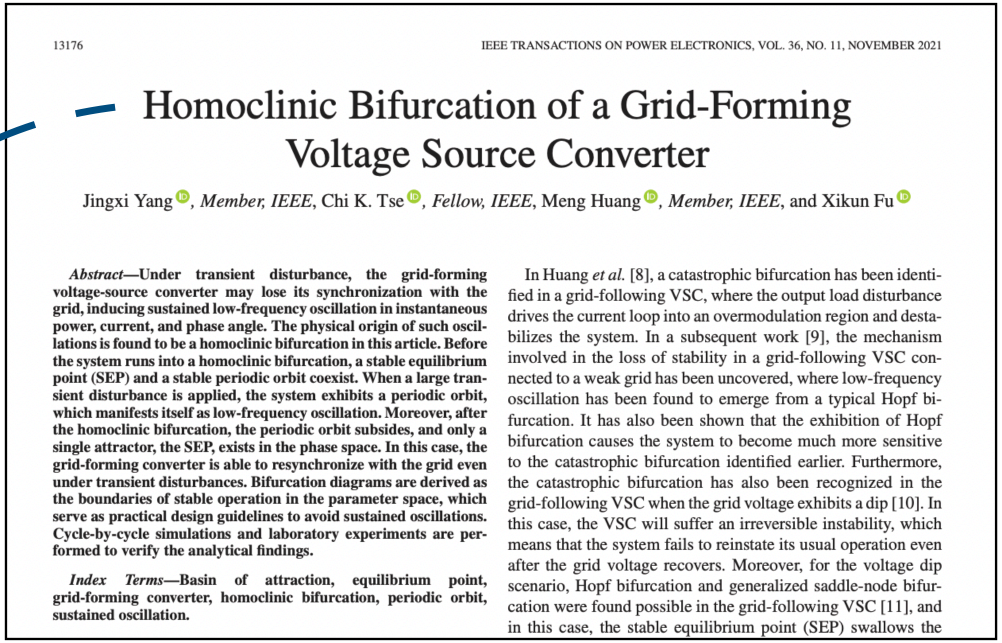
OSCILLATIONS

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 (feedback gain too high).

Unstable / oscillate via jumping off a stable region



Ability to resynchronise with grid after disturbance via Homoclinic bifurcation


13176 IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 36, NO. 11, NOVEMBER 2021

Homoclinic Bifurcation of a Grid-Forming Voltage Source Converter

Jingxi Yang, *Member, IEEE*, Chi K. Tse, *Fellow, IEEE*, Meng Huang, *Member, IEEE*, and Xikun Fu

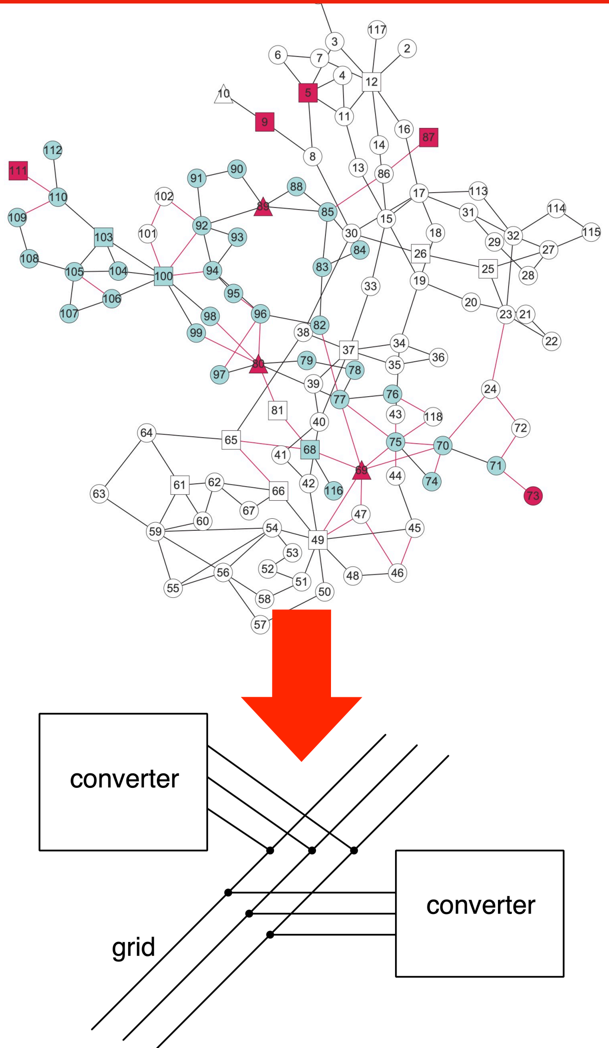
***Abstract*—Under transient disturbance, the grid-forming voltage-source converter may lose its synchronization with the grid, inducing sustained low-frequency oscillation in instantaneous power, current, and phase angle. The physical origin of such oscillations is found to be a homoclinic bifurcation in this article. Before the system runs into a homoclinic bifurcation, a stable equilibrium point (SEP) and a stable periodic orbit coexist. When a large transient disturbance is applied, the system exhibits a periodic orbit, which manifests itself as low-frequency oscillation. Moreover, after the homoclinic bifurcation, the periodic orbit subsides, and only a single attractor, the SEP, exists in the phase space. In this case, the grid-forming converter is able to resynchronize with the grid even under transient disturbances. Bifurcation diagrams are derived as the boundaries of stable operation in the parameter space, which serve as practical design guidelines to avoid sustained oscillations. Cycle-by-cycle simulations and laboratory experiments are performed to verify the analytical findings.**

***Index Terms*—Basin of attraction, equilibrium point, grid-forming converter, homoclinic bifurcation, periodic orbit, sustained oscillation.**

In Huang *et al.* [8], a catastrophic bifurcation has been identified in a grid-following VSC, where the output load disturbance drives the current loop into an overmodulation region and destabilizes the system. In a subsequent work [9], the mechanism involved in the loss of stability in a grid-following VSC connected to a weak grid has been uncovered, where low-frequency oscillation has been found to emerge from a typical Hopf bifurcation. It has also been shown that the exhibition of Hopf bifurcation causes the system to become much more sensitive to the catastrophic bifurcation identified earlier. Furthermore, the catastrophic bifurcation has also been recognized in the grid-following VSC when the grid voltage exhibits a dip [10]. In this case, the VSC will suffer an irreversible instability, which means that the system fails to reinstate its usual operation even after the grid voltage recovers. Moreover, for the voltage dip scenario, Hopf bifurcation and generalized saddle-node bifurcation were found possible in the grid-following VSC [11], and in this case, the stable equilibrium point (SEP) swallows the

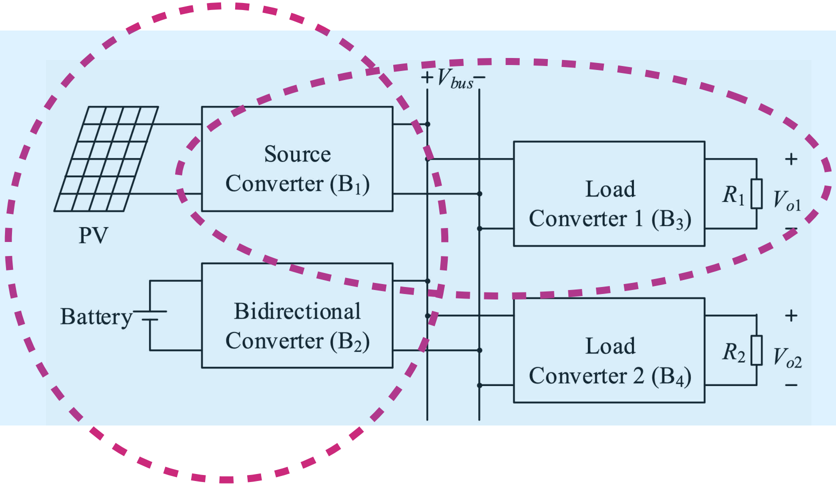
*Pre*view of Top-Down Approach

(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*, **but with very limited capability!**



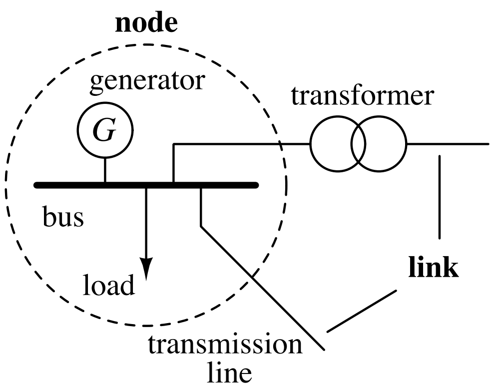
- We ***will soon get stuck*** *by the escalating complexity when the number of interacting devices becomes large or the area of interaction widens.*

⇒

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

Network Model

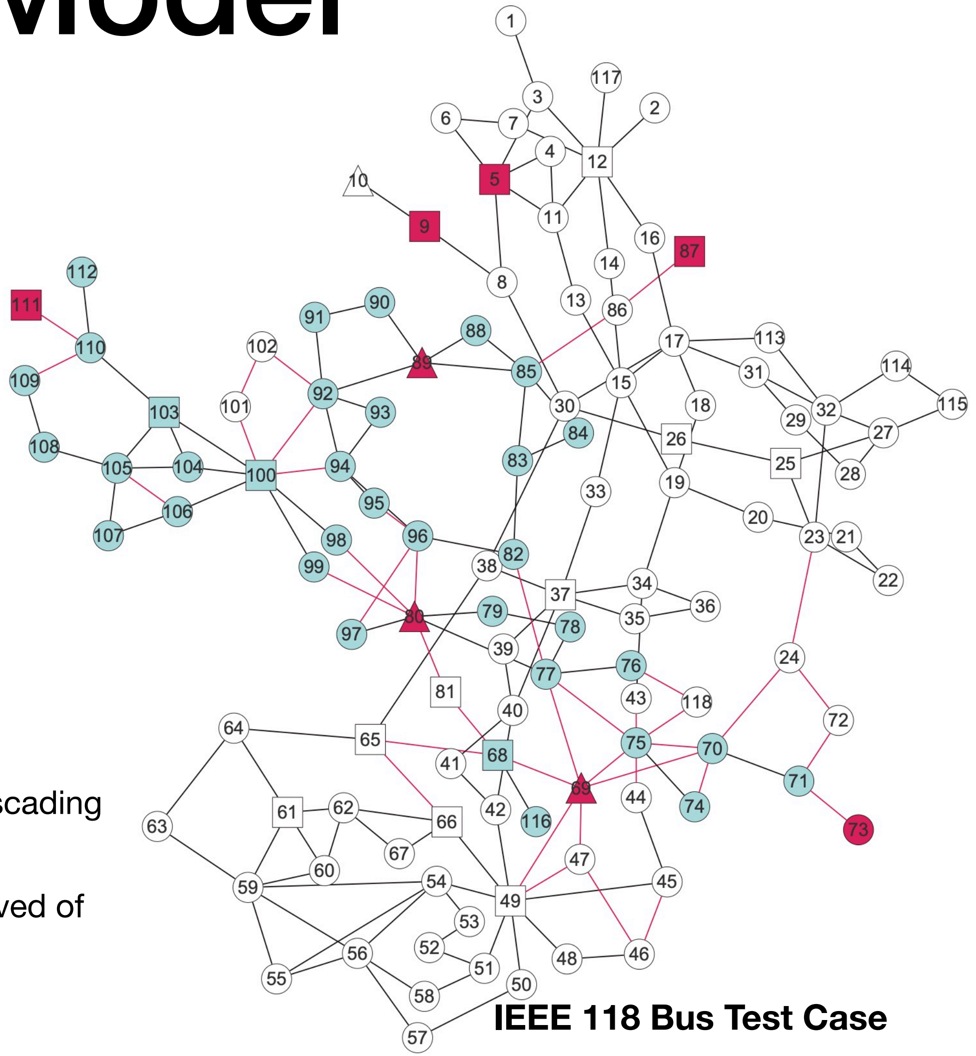
NETWORK:
NODES
LINKS



- □ synchronous generator-based power source nodes;
- △ 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.

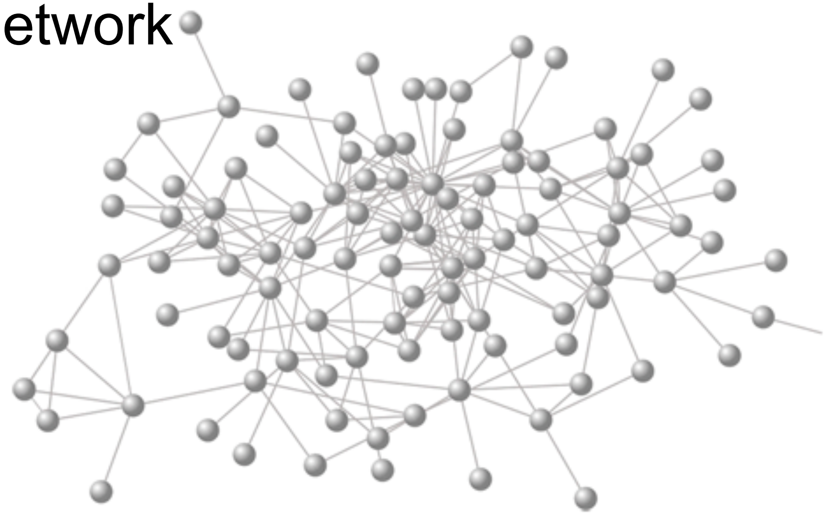


IEEE 118 Bus Test Case

Making Network Model Realistic

Theoretic network

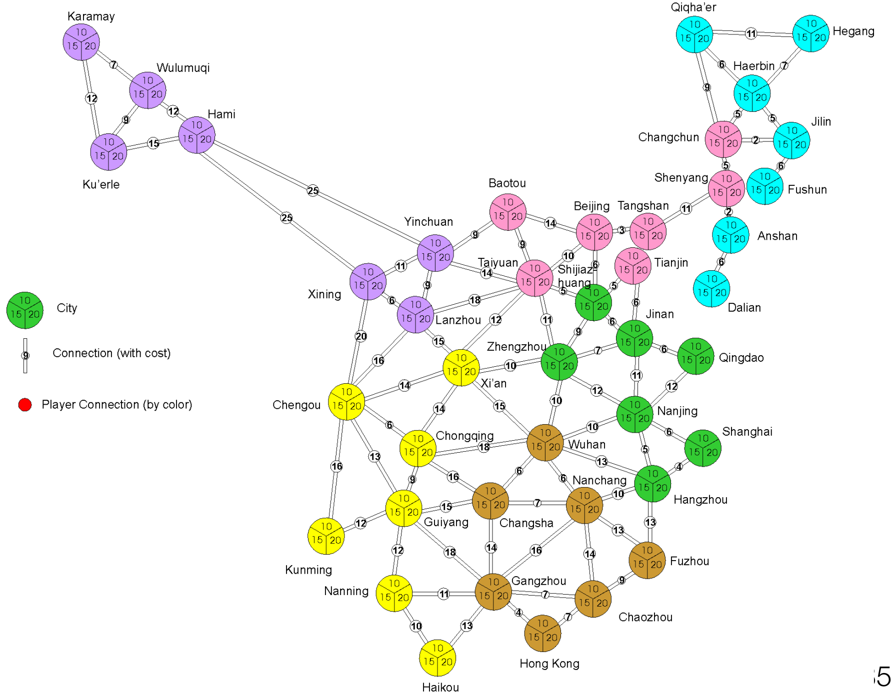
- nodes
- links



- Rich theoretical results
  - characterisations: degree, distance, betweenness, clustering, …
  - impact of structures
  - efficiency of information transfer
  - routing, etc.

Power grid follows physical laws

- **generators, transformers, loads**
- **transmission lines**



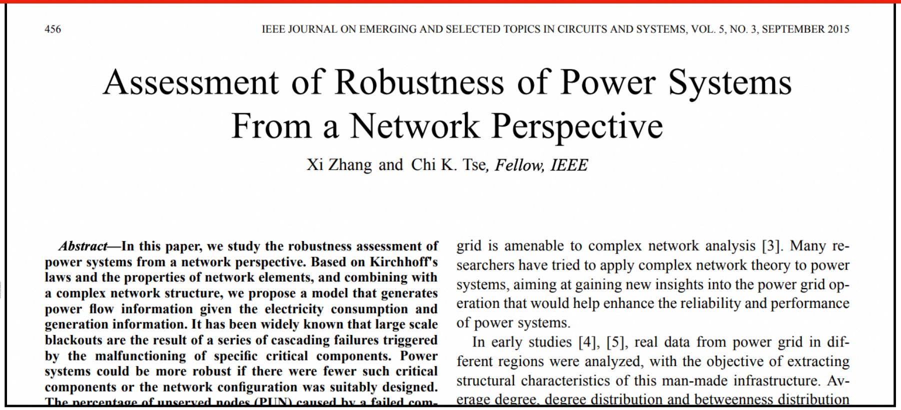
Crucial Steps to Mimic Failure Propagation

Physical process must be considered.

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

- **Zhang-Tse model** (2015) use the DC power flow calculation to accurately track the overloading nodes (components)
- We also applied stochastic modelling to solve the timing issue (2017)

Featured in IEEEXplore Innovation Spotlight, Nov 2015


456 IEEE JOURNAL ON EMERGING AND SELECTED TOPICS IN CIRCUITS AND SYSTEMS, VOL. 5, NO. 3, SEPTEMBER 2015

Assessment of Robustness of Power Systems From a Network Perspective

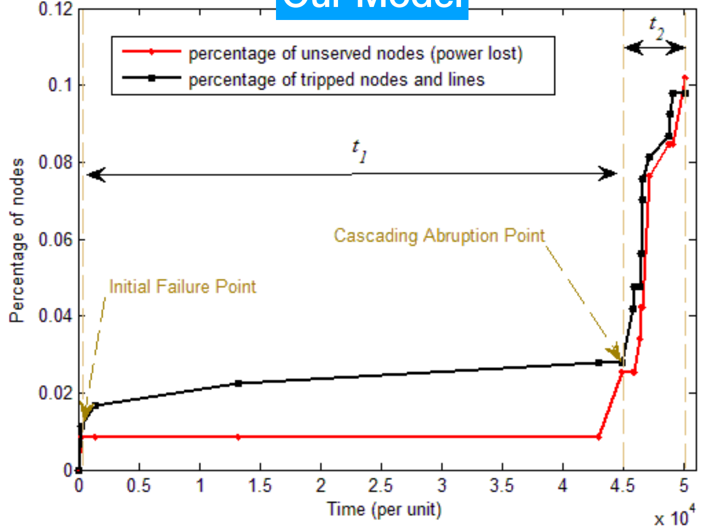
Xi Zhang and Chi K. Tse, *Fellow, IEEE*

***Abstract*—In this paper, we study the robustness assessment of power systems from a network perspective. Based on Kirchhoff's laws and the properties of network elements, and combining with a complex network structure, we propose a model that generates power flow information given the electricity consumption and generation information. It has been widely known that large scale blackouts are the result of a series of cascading failures triggered by the malfunctioning of specific critical components. Power systems could be more robust if there were fewer such critical components or the network configuration was suitably designed. The percentage of unserved nodes (PUN) caused by a failed com-**

grid is amenable to complex network analysis [3]. Many researchers have tried to apply complex network theory to power systems, aiming at gaining new insights into the power grid operation that would help enhance the reliability and performance of power systems.

In early studies [4], [5], real data from power grid in different regions were analyzed, with the objective of extracting structural characteristics of this man-made infrastructure. Average degree, degree distribution and betweenness distribution

Our Model



Historical Data

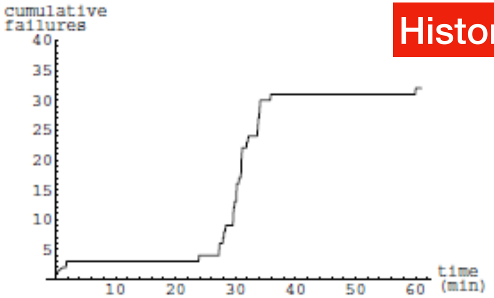


Figure 1. Cumulative line trips in WSCC July 1996 blackout. Time scale is minutes after 14:00 MDT.

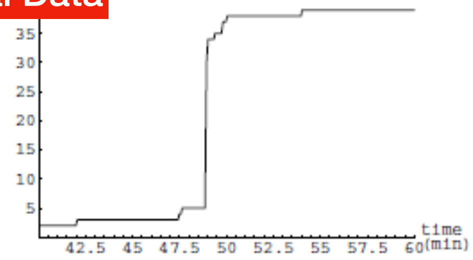
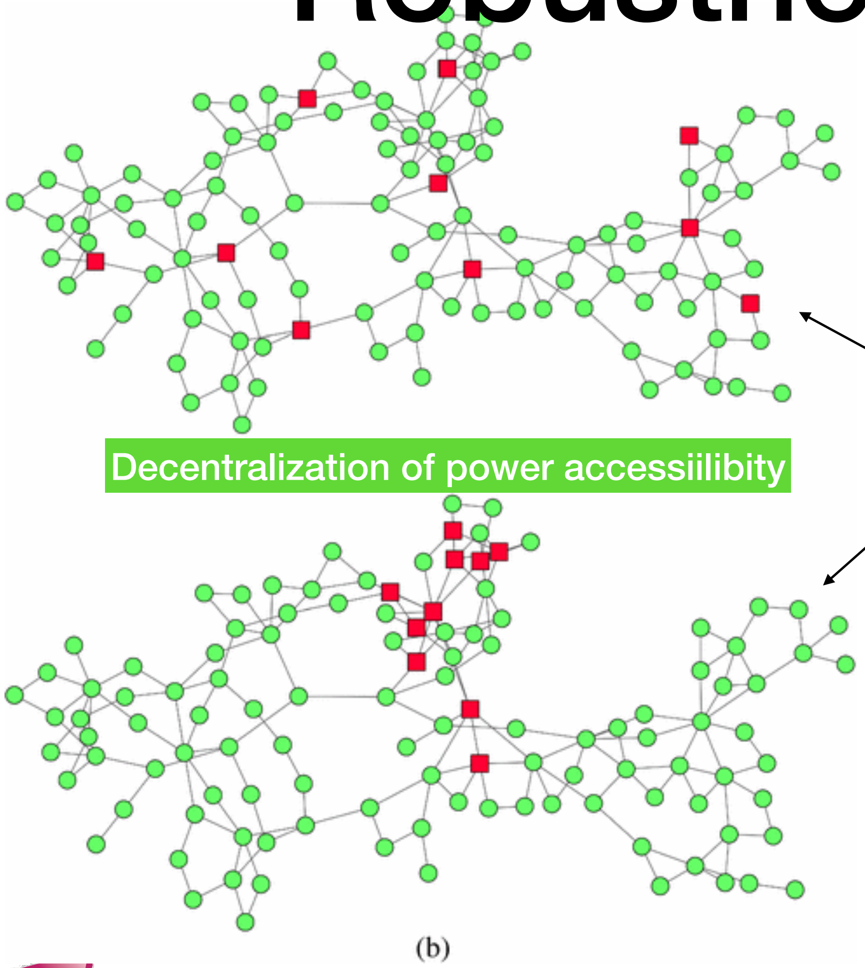


Figure 3. Cumulative line trips in WSCC August 1996 blackout. Time scale is minutes after 15:00 PDT.

Robustness & Resilience



- We have a network model for assessing cascading failure. Applications have been attempted in
  - Robustness assessment (2015, 2017)
  - Prediction of outage coverage (2017)
  - Comparison of network structures (2018, 2019)
  - Restoration strategies (2020, 2021)

- 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.

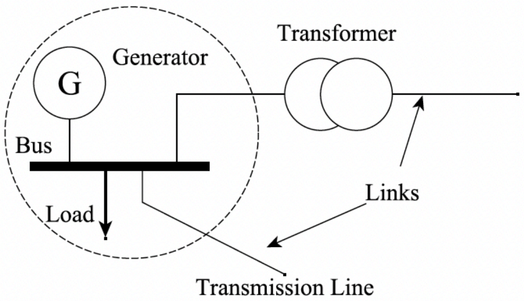
Developing control strategies that balance the grid-following function and grid-forming support.

Effects of Power Electronics Penetration on Grid Control

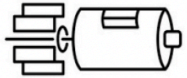
- Conventional grid relies on frequency variation to indicate deviation from normal operation
- Inertia resists frequency variation — **PE has no inertia!**

GENERATOR SIDE

SYNCHRONOUS MACHINE BASED GENERATOR NODE



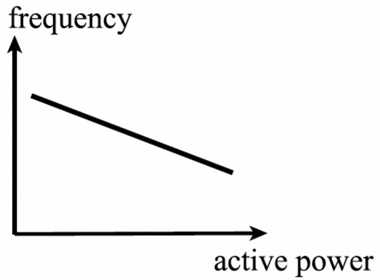
HYDRO



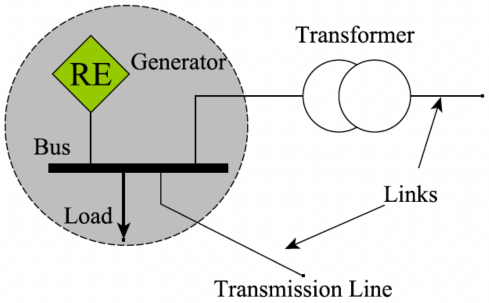
SYNC MACHINE (INERTIA)

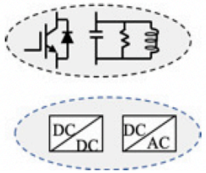
THERMAL

DROOP CHARACTERISTIC



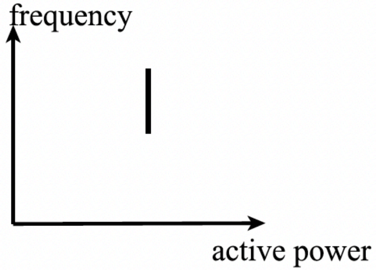
POWER ELECTRONICS BASED GENERATOR NODE





POWER ELECTRONICS

NO DROOP CHARACTERISTIC



LOAD SIDE

EFFECTS OF POWER ELECTRONICS

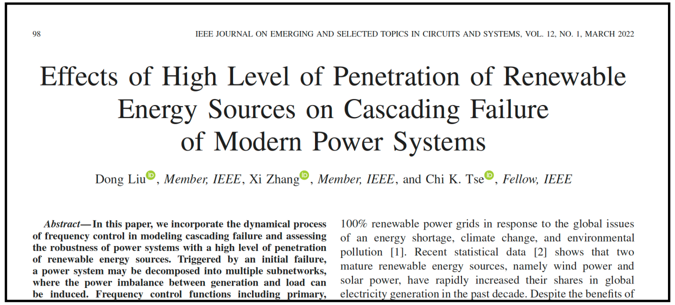
Grid-following inverters inject current to grid with a PLL and do not help control the frequency!

More PE will weaken the control of frequency.

Need for **grid-forming** converters

Robustness Assessment

Recent Study 2021

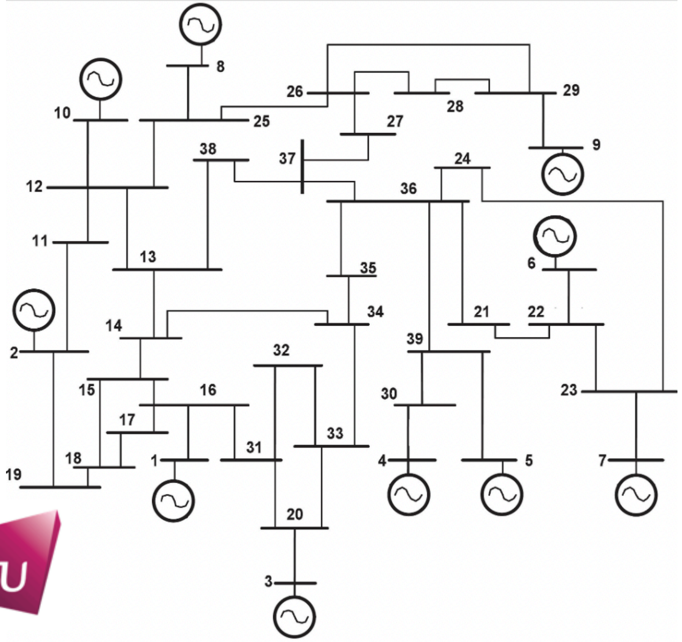

98 IEEE JOURNAL ON EMERGING AND SELECTED TOPICS IN CIRCUITS AND SYSTEMS, VOL. 12, NO. 1, MARCH 2022

Effects of High Level of Penetration of Renewable Energy Sources on Cascading Failure of Modern Power Systems

Dong Liu, *Member, IEEE*, Xi Zhang, *Member, IEEE*, and Chi K. Tse, *Fellow, IEEE*

Abstract—**In this paper, we incorporate the dynamical process of frequency control in modeling cascading failure and assessing the robustness of power systems with a high level of penetration of renewable energy sources. Triggered by an initial failure, a power system may be decomposed into multiple subnetworks, where the power imbalance between generation and load can be induced. Frequency control functions including primary,**

100% renewable power grids in response to the global issues of an energy shortage, climate change, and environmental pollution [1]. Recent statistical data [2] shows that two mature renewable energy sources, namely wind power and solar power, have rapidly increased their shares in global electricity generation in the past decade. Despite the benefits of

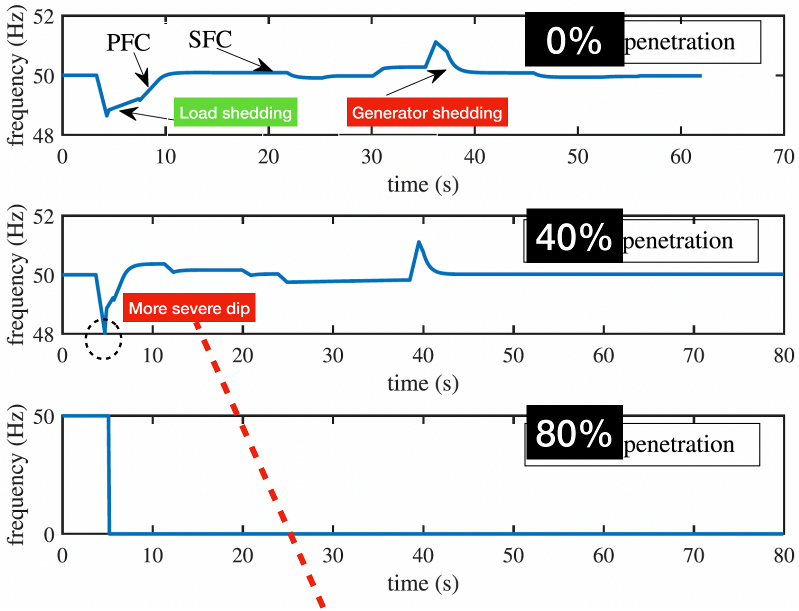


Realistic simulation of cascading failure with frequency control. PE nodes suffer more generation loss.

0 PE: control effective

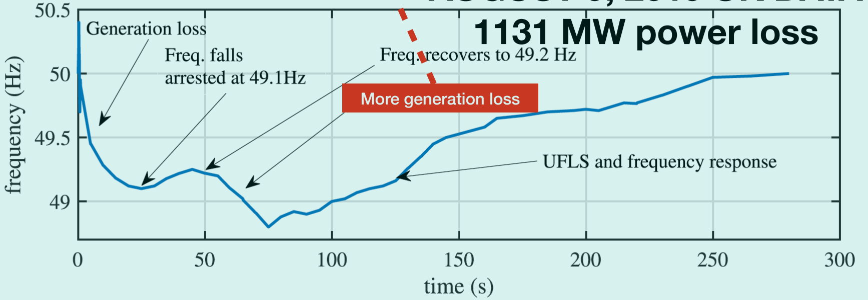
40%: still effective

80%: control failed



AUGUST 9, 2019
England, Wales and some Scotland were out of power for about 45 min.

AUGUST 9, 2019 UK DATA
1131 MW power loss



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

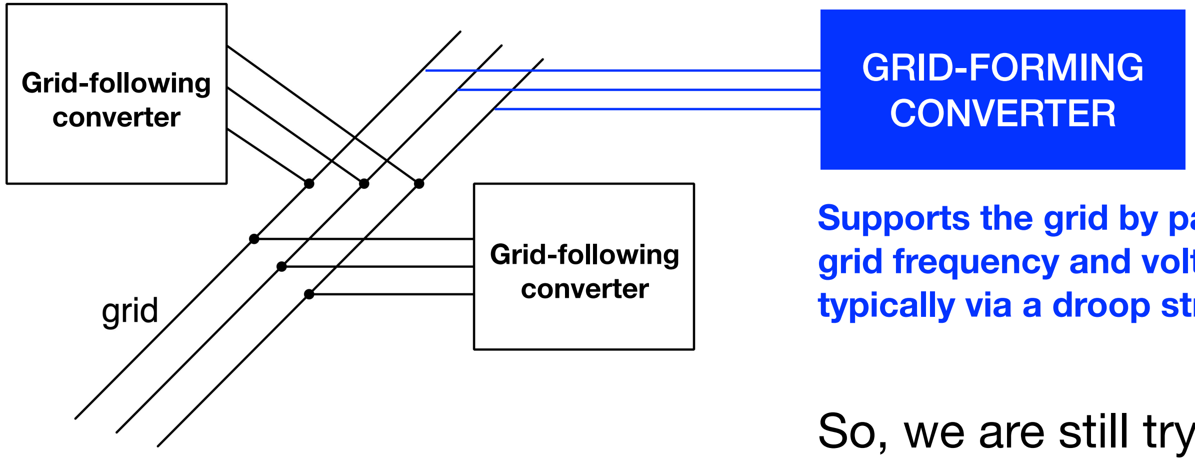
Challenge 3:
Defining Appropriate Measures for Robustness Assessment

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!*



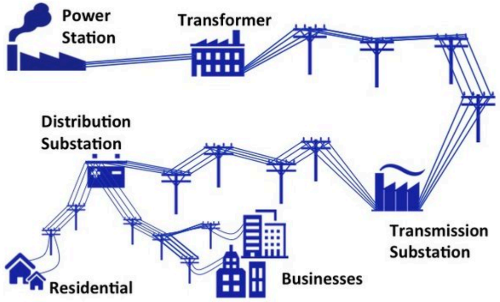
Supports the grid by participating in grid frequency and voltage control, typically via a droop strategy.

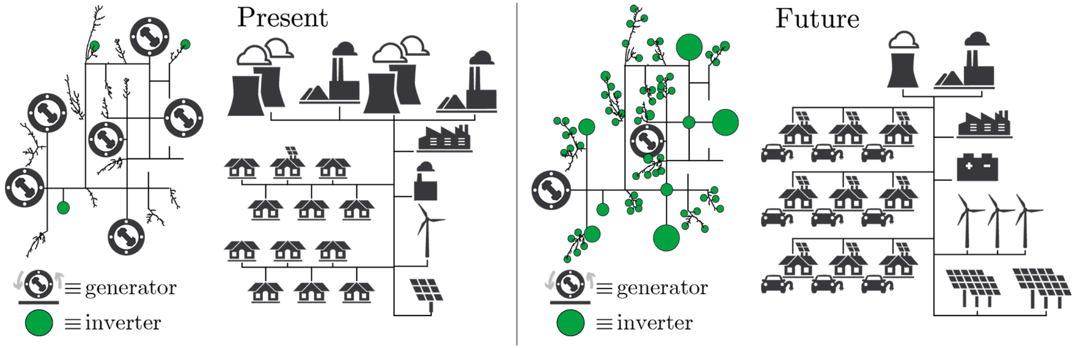
The grid gets less stiff as the percentage of synchronous machines drops and PE increases!

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

Can the grid control be completely changed?

The Dilemma of Transition





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 and more renewable being used,
the grid weakens as sync machines get a lesser share!

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

If PE & renewables eventually dominates,
the grid's old properties are maintained artificially. Do we continue along the same path (???)

The PE-dominated grid is no longer the same grid, then why still mimic the same old properties?
Eventually, we will have to make a real change!

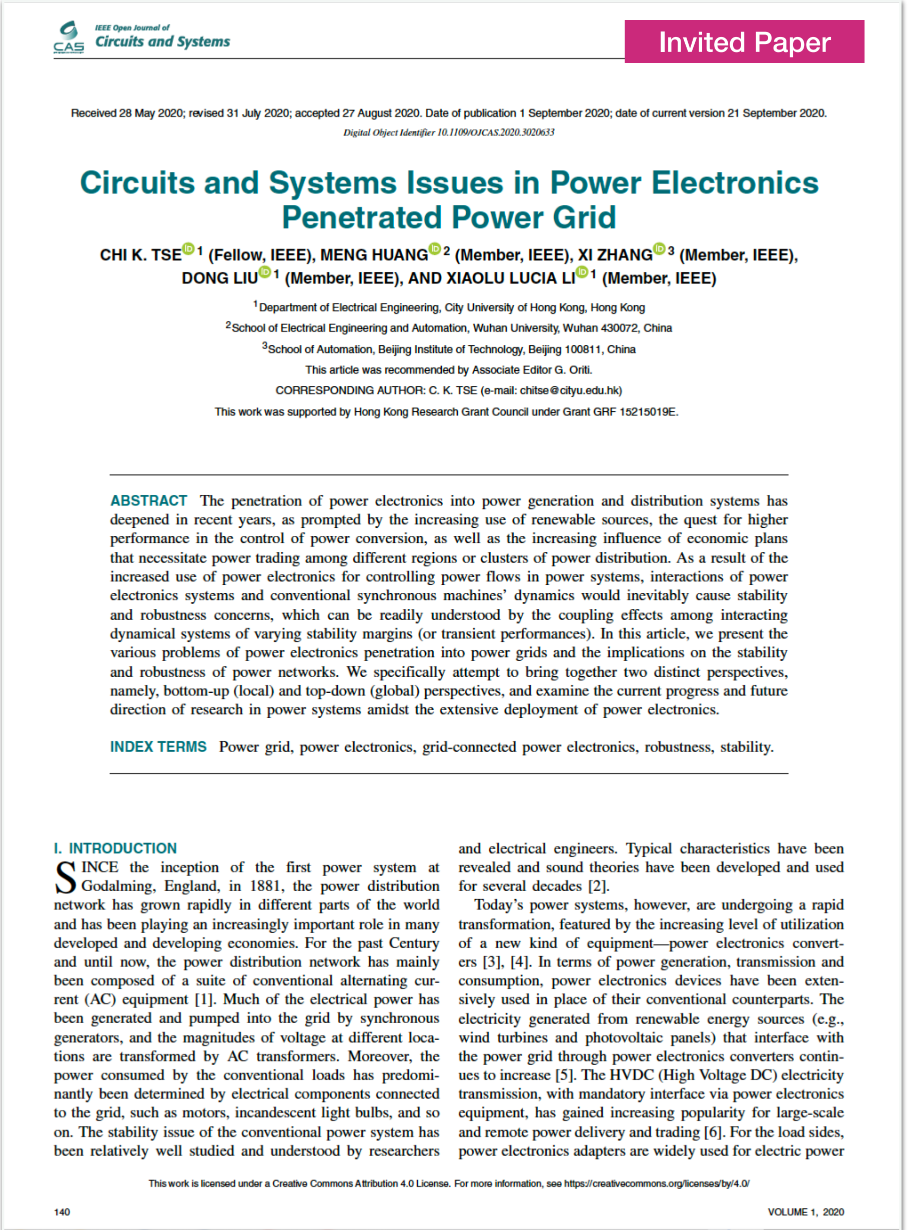
KEY REFERENCES

Bottom-Up Approach

https://www.ee.cityu.edu.hk/~chitse/mypubl-archive.htm#nonlinearPE

Top-Down Approach

https://www.ee.cityu.edu.hk/~chitse/mypubl-archive.htm#ps



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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

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.

- Can we build more chargers?
- Can we deploy more renewables?
- Can we design more high-performance PE equipment?

Bottom-Up Approach

(relatively more mature)

Acknowledgement

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Prof. Siew Chong Tan, The University of Hong Kong
Prof. Xinbo Ruan, NUAA Nanjing

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Prof. Herbert Iu, Professor, University of Western Australia
Dr Ding Li, The Hong Kong Polytechnic University
Dr Daniel Zhen Li, Associate Professor, Beijing Institute of Technology
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