Next-Generation Smart Grids: Completely Autonomous Power Systems (CAPS)

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The University of Sheffield

- Sheffield Medical School (1828), University Charter granted (1905)
- 5 Nobel Prize winners
- QS World University Rankings: 71st
- One of the Red Brick universities
- 25,000 students from 117 countries, over 6,000 staff
- ACSE: The only department in control in the UK, the largest in EU and one of the best in the world.




Power systems

- ". . . the greatest engineering achievement of the 20th century." (National Academy of Engineering '2000)

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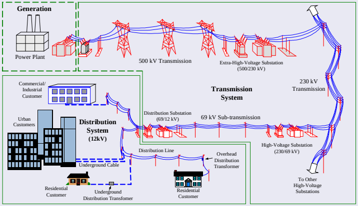
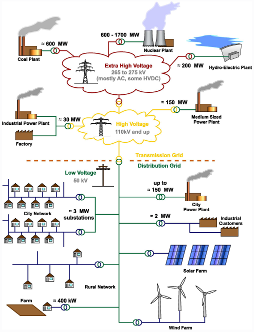
Evolution of power systems

Centralised Generation



Karady G and Holbert K 2004

Distributed Generation



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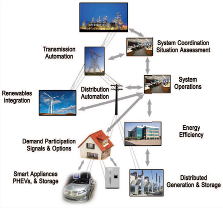
Smart Grid



DOE: Smart Grid System Report

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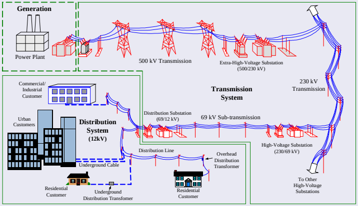

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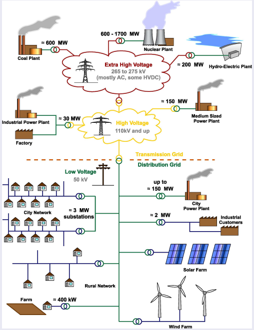

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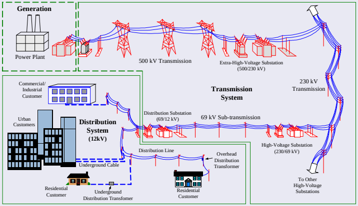

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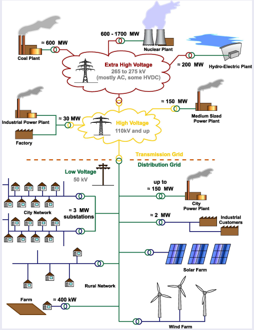

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Smart Grid

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What's next?

Next-Generation Smart Grids:

Completely Autonomous Power Systems (CAPS).

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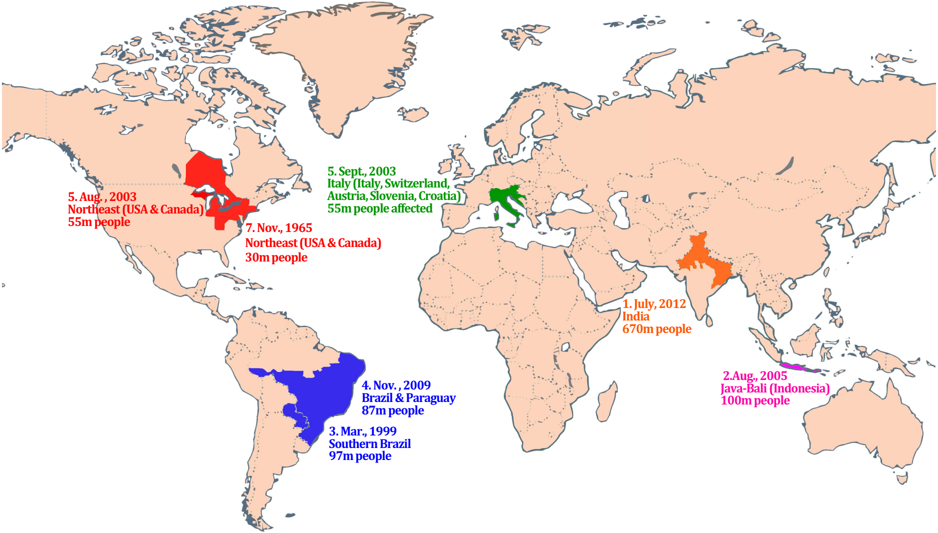
Outline of the talk

- Why? — Challenges faced by power systems
- What is the root cause? — Fundamentals
- How? — Technical route
- What is the solution? — Architecture
- Summary

Challenges being faced by power systems

- Ageing infrastructure (mostly over 100 years old)
  - Faults
  - Blackouts

Largest blackouts in the history



Generated from the data at http://en.wikipedia.org/wiki/List_of_power_outages

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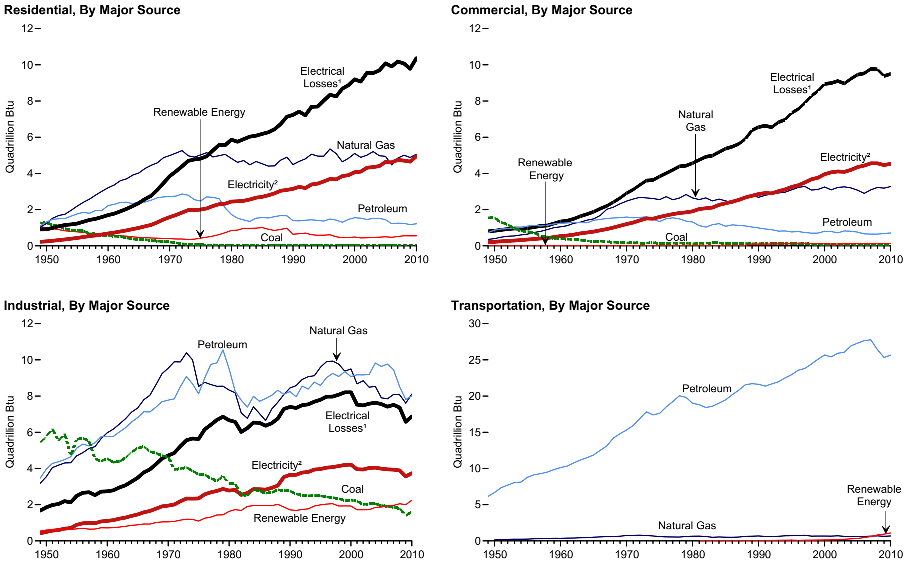
- Fast growth of electricity consumption
  - Civilisation: $>$ 30 cities with 10+ million people by 2020 (Wiki)
  - Digital economy: Data centres to consume 20% electricity in the USA by 2030 (EPRI)

US Energy Consumption Estimates by End-Use Sector, 1949-2010



http://www.eia.gov/totalenergy/data/annual/archive/038410.pdf.

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How to address the challenges?

- Upgrading the system, e.g. by introducing
  - Phase Measurement Units (PMU)
  - Wide-Area Monitoring Systems (WAMS)

PMUs and WAMS in China

X.R. Xie, Y.Z. Xin, J.Y. Xiao, J.T. Wu, and Y.D. Han. WAMS applications in Chinese power systems. IEEE Power & Energy Magazine. Vol. 4, No. 1, pp. 54-63, Jan.-Feb. 2006.

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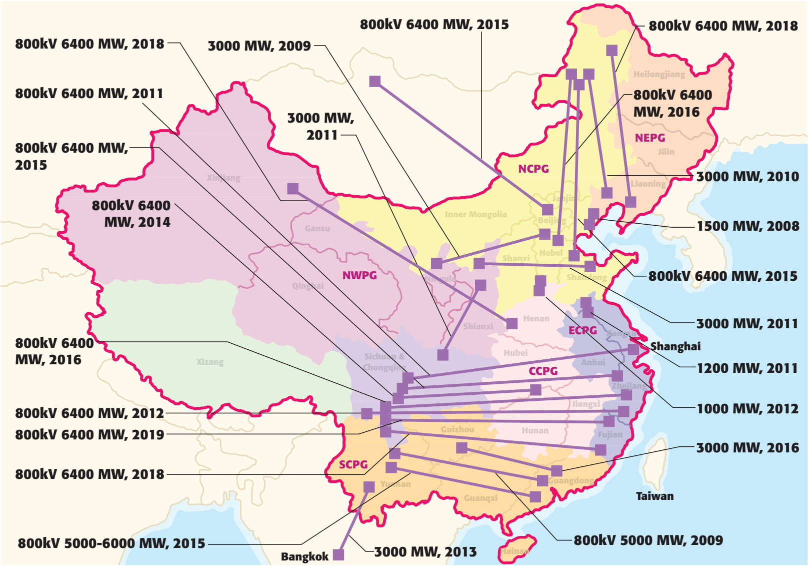
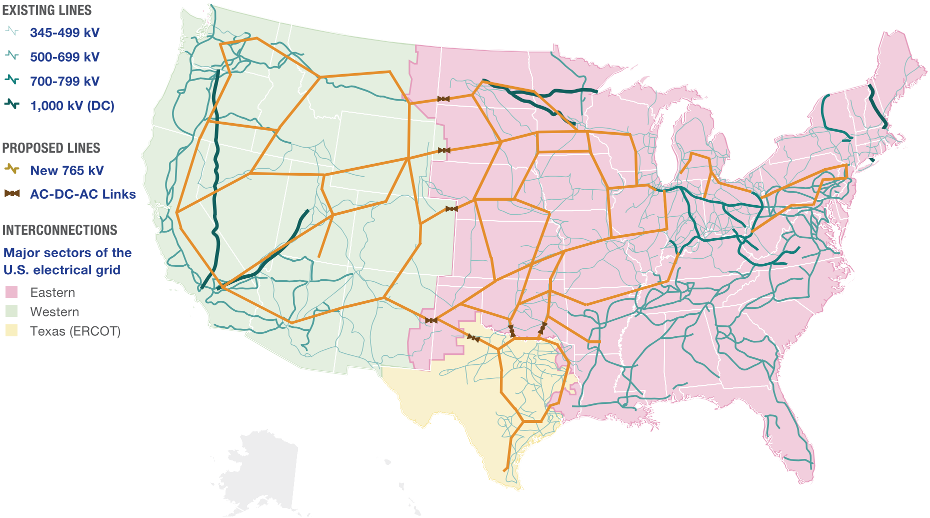
The mainland Chinese power system



X-P. Zhang, C. Rehtanz and Y. Song., ''A grid for tomorrow,'' Power Engineer , vol.20, no.5, pp.22-27, Oct.-Nov. 2006.

The US power system



Source: http://views.cira.colostate.edu/fed/Egrid/.

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But are we doing enough?

Let's go one step back and recall the challenges:

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What do these challenges really mean/what is fundamental behind these challenges?/What will these make future power systems look like?

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Power electronics-based.

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Fundamental challenge

Future power systems will be

power electronics-based,

with a huge number of heterogeneous players.

- Less of a power problem but more of a systems problem
  - How to guarantee system stability?
  - How to organically expand power systems without jeopardising stability?
- No longer able to heavily rely on communication networks
  - It is fine for monitoring, information systems and high-level functions.
  - But for low-level control, this will cause a great concern of reliability.
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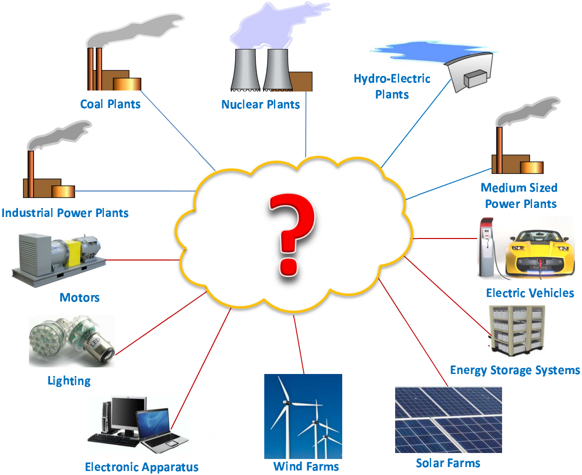
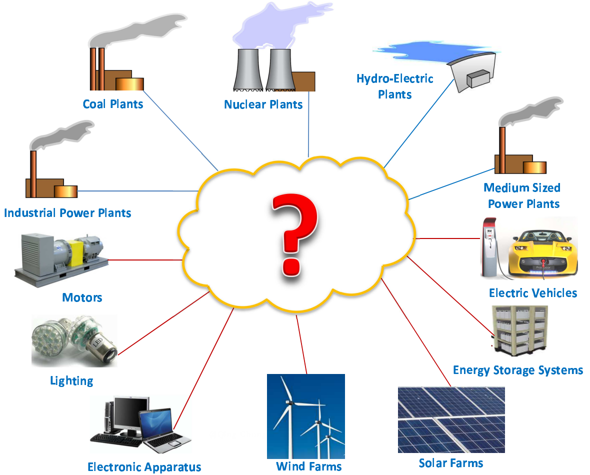


- Is there ONE simple mechanism to enable organic growth and autonomous operation of power systems?
- Is it possible for new add-ons to play an equal role as conventional generators in regulating the system stability?
- Is it possible for the majority of loads to play the same role too?
- If yes, can these happen regardless of size and capacity?



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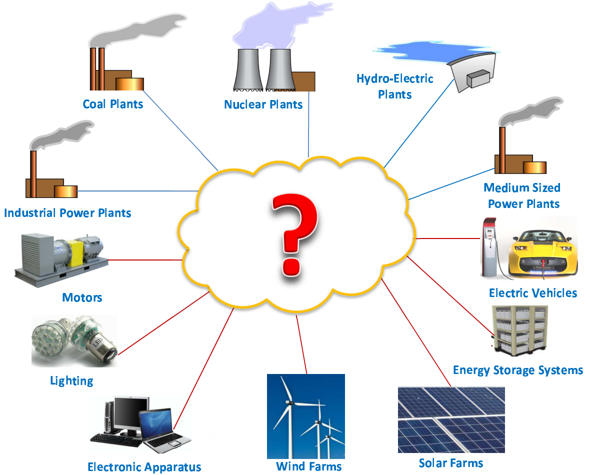

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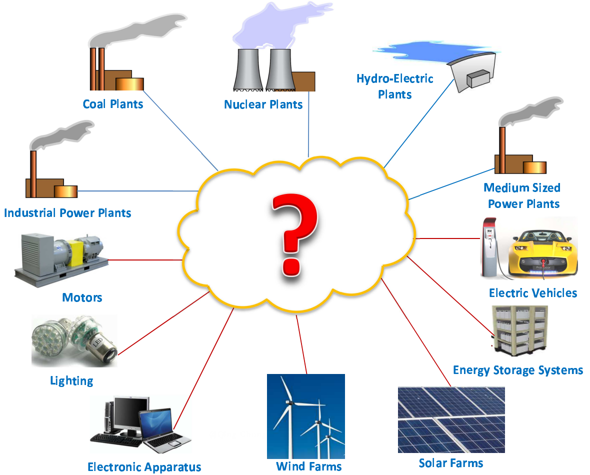

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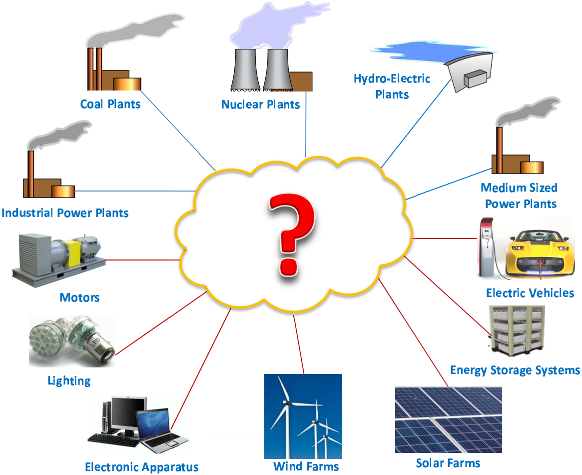

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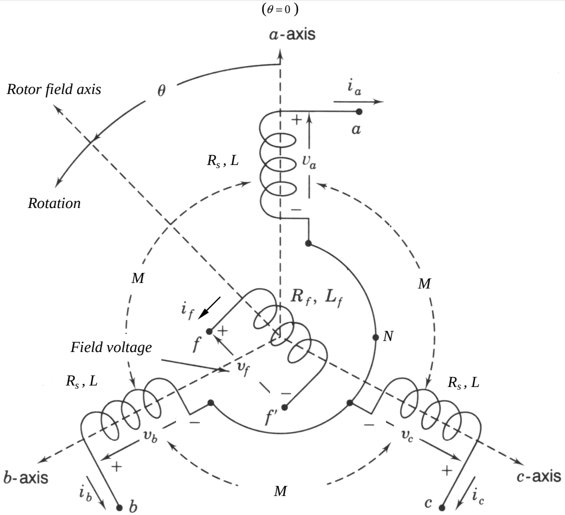
Conventional electricity generation



Conventionally, the generation of electricity is dominated by synchronous generators.

Why synchronous generators (SG)?

The real power P flowing out of an SG is

$$P = \frac{VE}{X_s} \sin(\theta - \theta_g)$$

where E and V are the RMS values of the generated voltage and the terminal voltage. Moreover, an SG obeys the swing equation

$$J\ddot{\theta} = T_m - T_e - D_p\dot{\theta}$$

and a power system can be regarded as a system of coupled oscillators. Because of the sin term, an SG can synchronise with the grid or an SG.

The underlying principle that holds a power system is

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New add-ons of generation

- Renewable energy
  - Wind
  - Solar
  - Tide
  - Wave etc
- Electric vehicles
- Energy storage systems

It is a real mess.

Is there anything in common?

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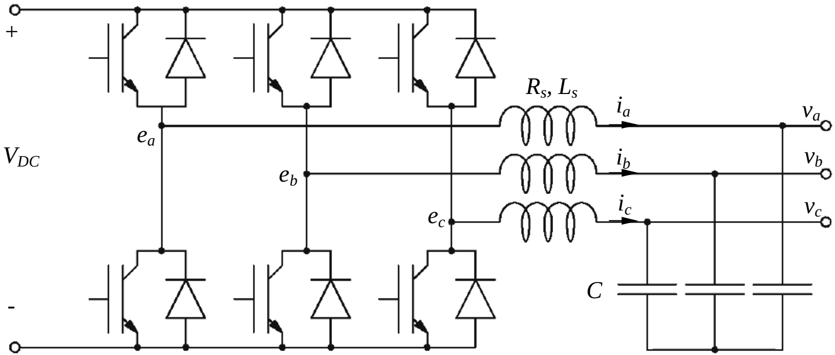
Inverters: — Common devices for smart grid integration



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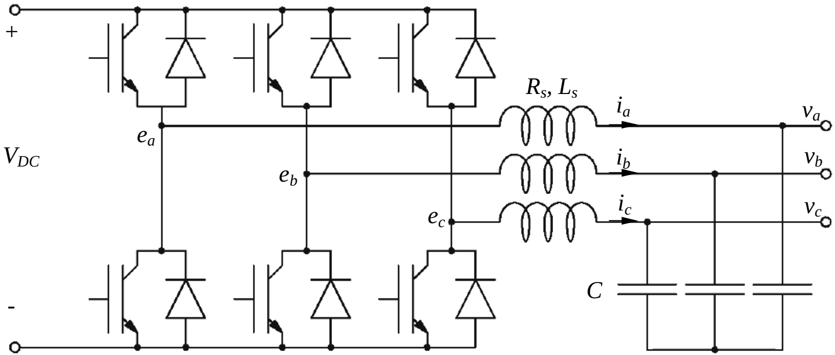

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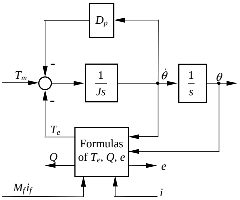
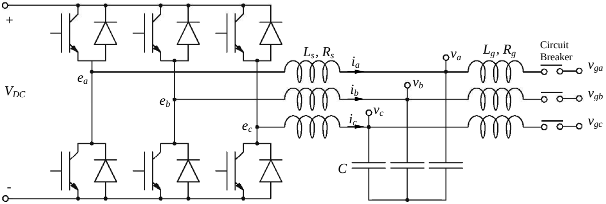
Our solution: Synchronverters

- Synchronverters are inverters that mimic synchronous generators (SG).
- Dynamically behave like SG and hence possess the inherent synchronisation mechanism.
- Can operate autonomously without communication.

The basic idea

- Taking the mathematical model of a synchronous generator as the core of the controller for an inverter.
- Converting the generated voltage e to PWM signals to drive the switches so that the average values of e_a, e_b and e_c over a switching period is equal to e.
- Feeding back the phase current i to the mathematical model as the stator current.





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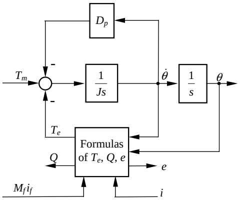

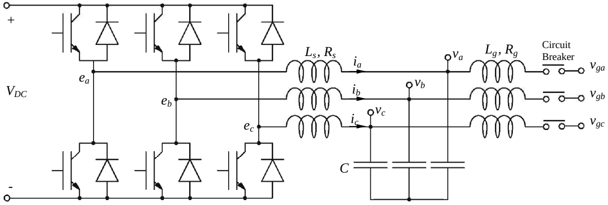

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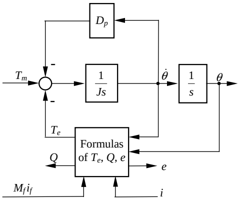
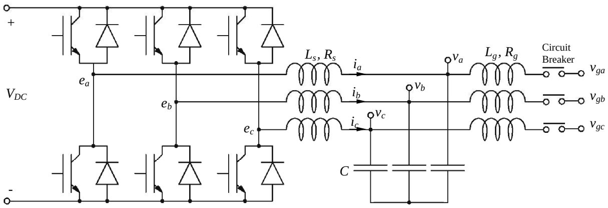
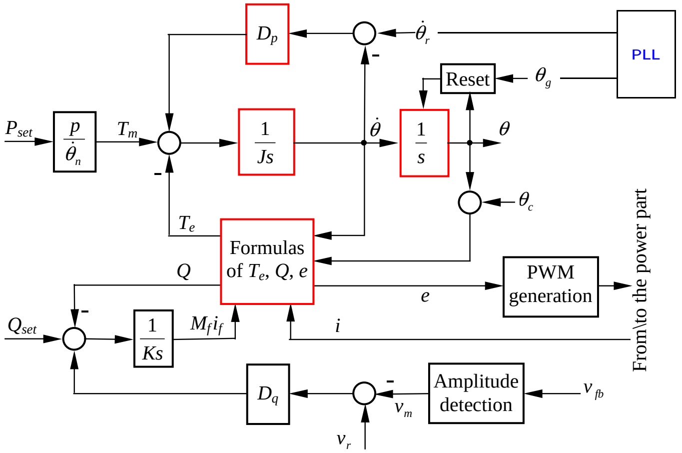




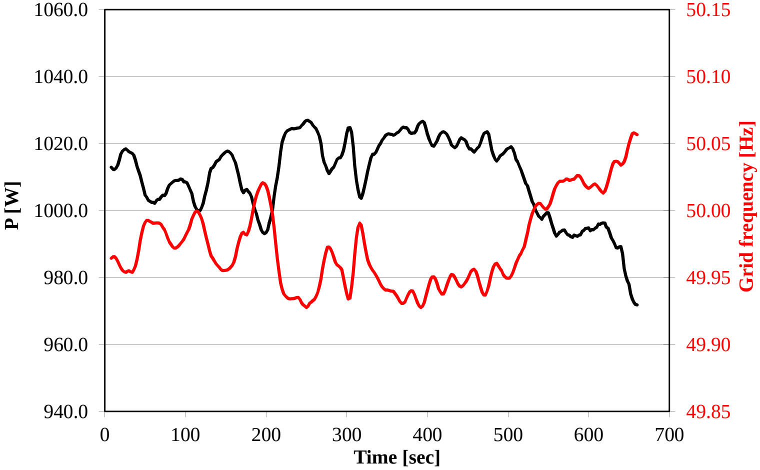
The complete controller



- Four parameters
- No conventional PI control
- No dq transformation etc
- Frequency regulation via frequency droop control
- Voltage regulation via voltage droop control
- Real power and reactive power control

Experimental results

Frequency regulation



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Load types

Many different types of loads exist in a power system:

- Home appliances
- Lighting devices
- Elevators
- Computers/servers
- Air-conditioners
- Machines
- ...

Is there anything in common?

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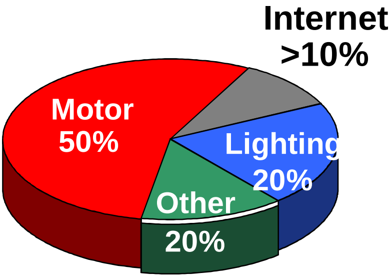
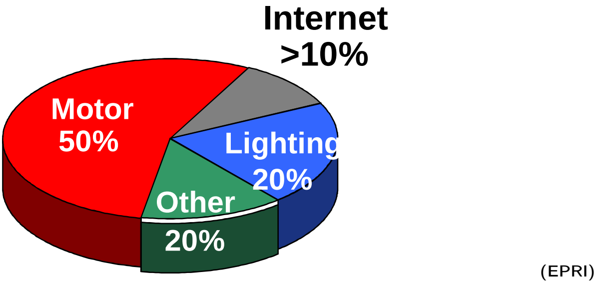


(EPRI)

The majority of loads (will) have a front-end rectifier because

- Motors are often equipped with AC drives to improve efficiency and performance
- Light bulbs are being replaced with energy-efficient devices, e.g. LED
- Internet devices consume DC electricity

If these loads (rectifiers) are made to behave like synchronous motors then the majority of loads in a power system will have the synchronisation mechanism we are looking for.



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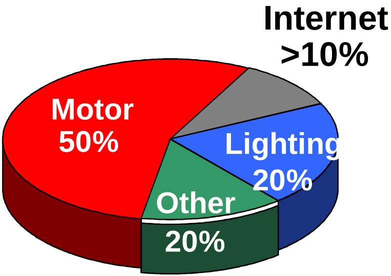

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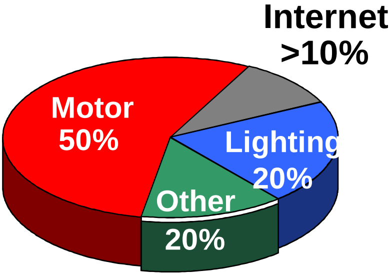

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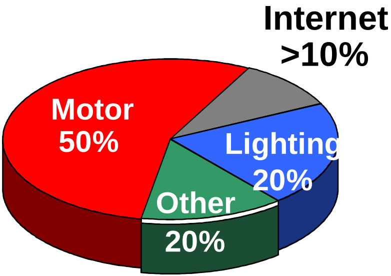

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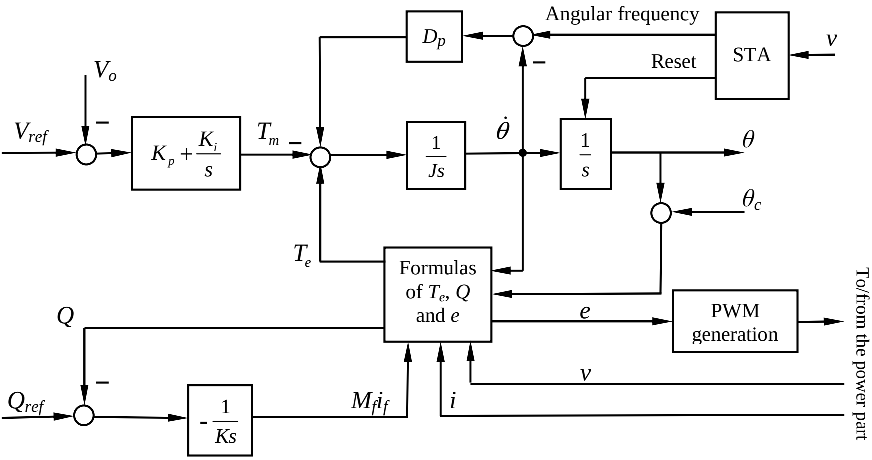
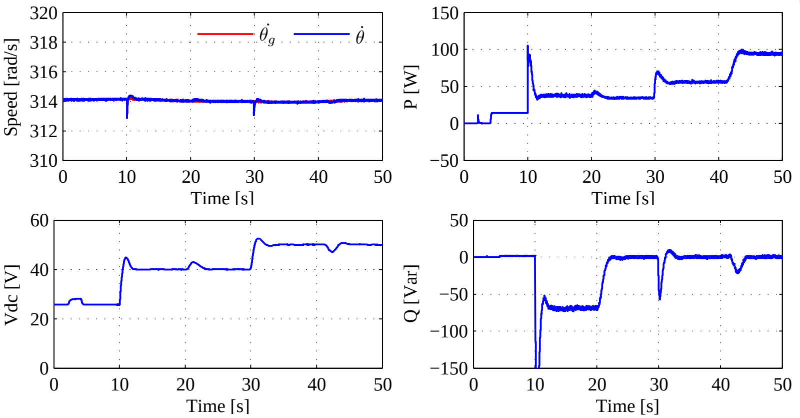
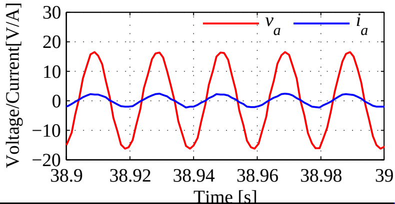
Running rectifiers as synchronous motors



Experimental results





1) Circuit breaker turned on at t=2s;
2) Load R=50Ω connected at t=4s;
3) PWM signals enabled at t=10s with V_{ref}=40 V and the Q-loop disabled;
4) The Q-loop enabled at t=20s;
5) V_{ref} changed to 50 V at t=30s;
6) The load changed to R=30Ω at t=41s.

So, we have made

- inverters to have the synchronisation mechanism of synchronous generators
- the majority of loads to have the same synchronisation mechanism

Is there any problem left?

— There is a dedicated synchronisation unit.

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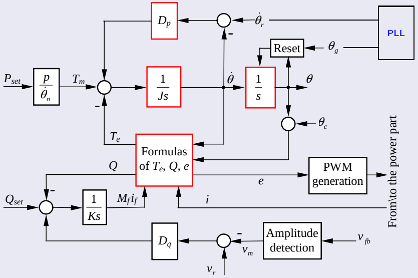
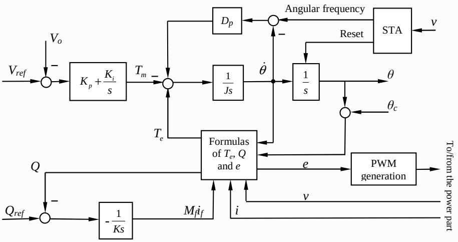
Inverters



Rectifiers



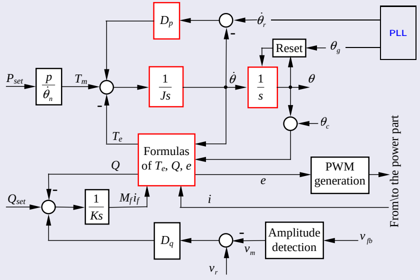
Problems with dedicated synchronisation units (PLL etc)

- Fight with each other
- Cause instability
- Reduce performance

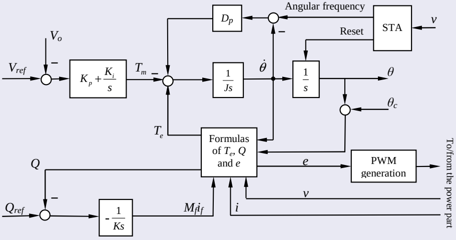
?

Is it possible to get rid of the dedicated synchronisation unit, although it is believed to be a must-have component?

Inverters



Rectifiers



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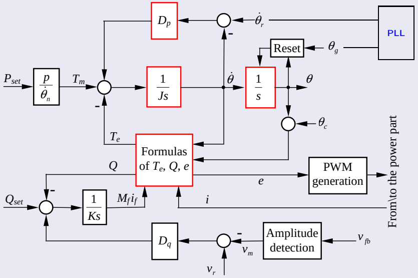

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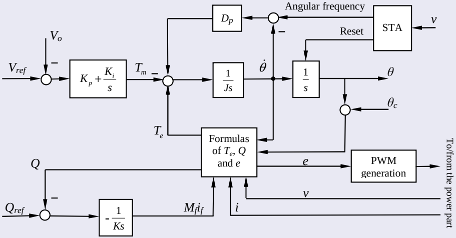

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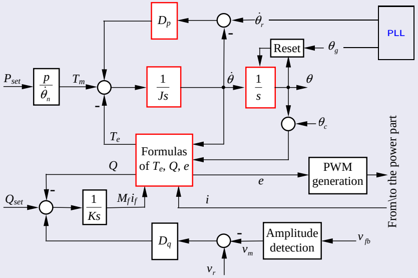

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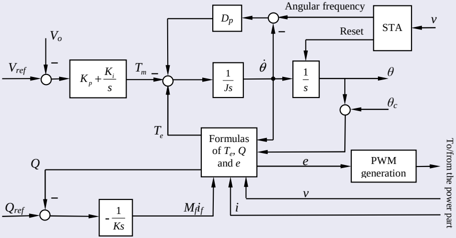

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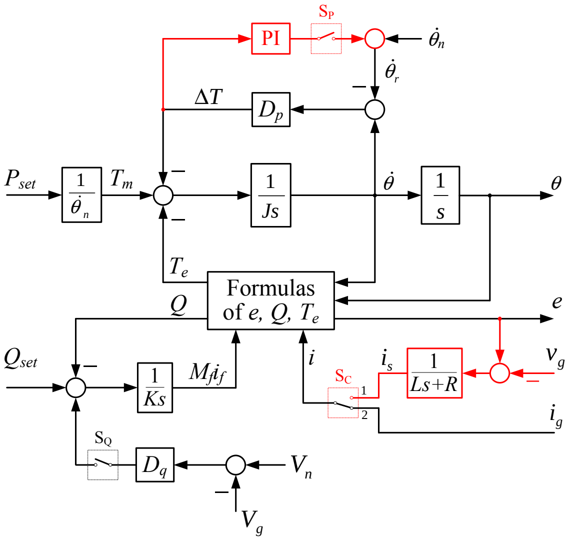
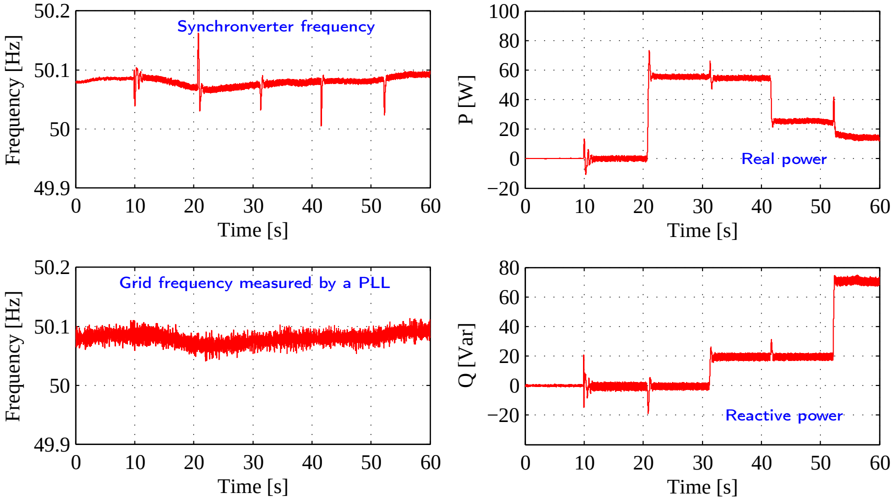
Self-synchronised synchronverters

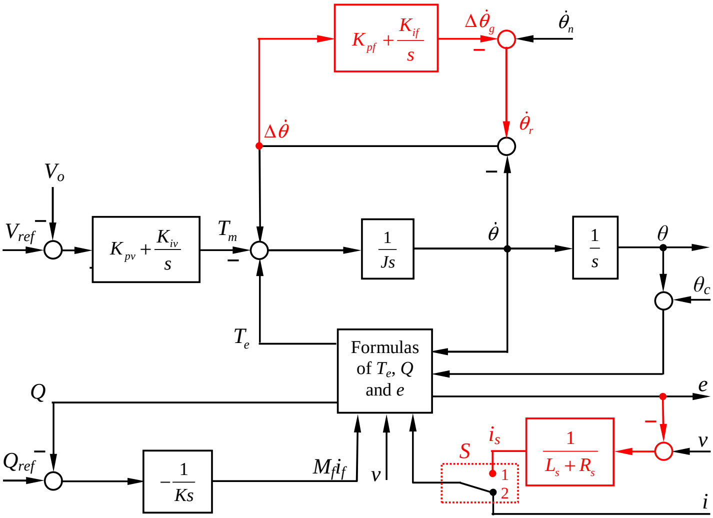


- A mechanism is introduced to generate the reference frequency
- A mechanism is introduced to synchronise with the grid before connection

Experimental results



Self-synchronised PWM rectifiers



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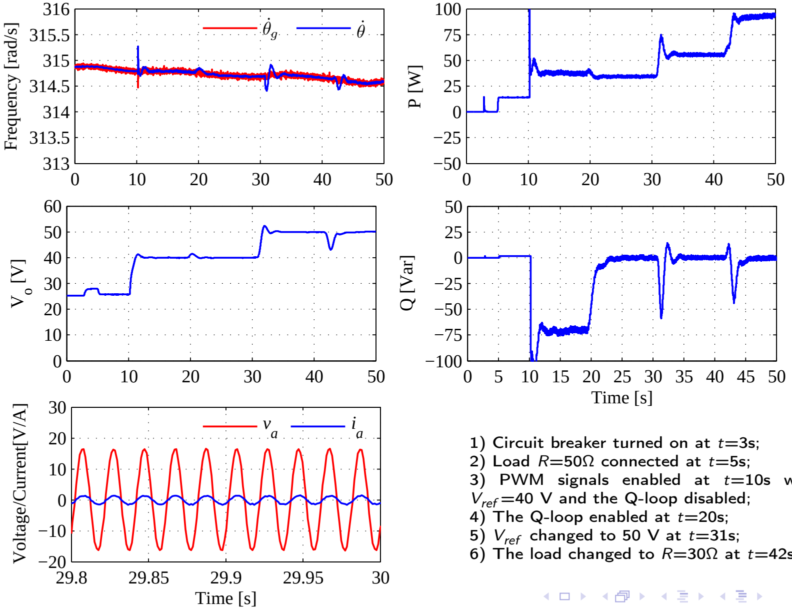

1) Circuit breaker turned on at t=3s;
2) Load R=50Ω connected at t=5s;
3) PWM signals enabled at t=10s with V_{ref}=40 V and the Q-loop disabled;
4) The Q-loop enabled at t=20s;
5) V_{ref} changed to 50 V at t=31s;
6) The load changed to R=30Ω at t=42s.

So, we have indeed made it.

- All new add-ons of generation can behave like synchronous generators.
- The majority of loads can behave like synchronous motors.
- They all possess the inherent synchronisation mechanism, without a dedicated synchronisation unit, so they are naturally held together.

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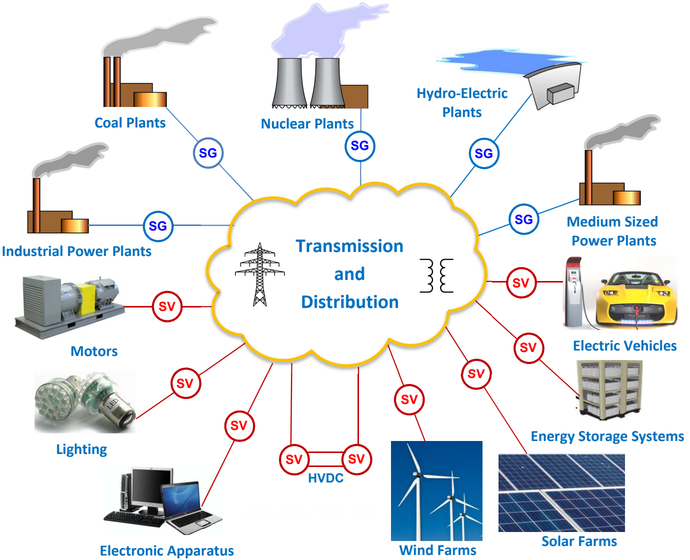
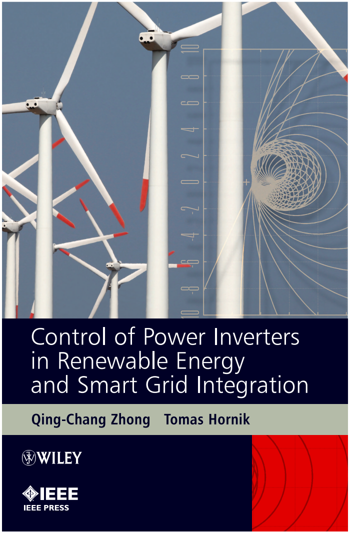
Architecture for next-generation smart grid

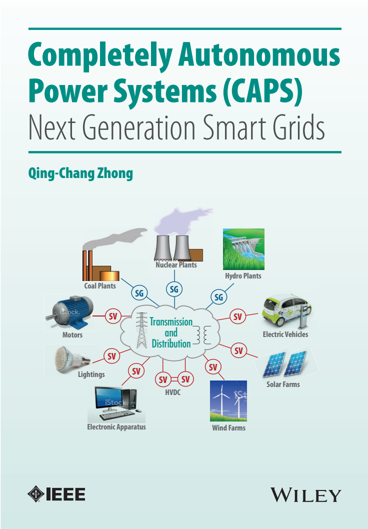


Summary

- Due to the integration of a huge number of renewable energy etc into the smart grid, it is no longer possible to coordinate its operation by human interaction.
- An architecture (CAPS) for the next-generation smart grids has been established
  - to standardise the interface of integration,
  - to achieve completely autonomous operation, with minimum demand on communication for control.
- A technical route based on the synchronisation mechanism of SG has been demonstrated, through
  - operating inverters as synchronous generators,
  - operating rectifiers as synchronous motors.
- The dedicated synchronisation units that were believed to be a must-have for converters have been removed.

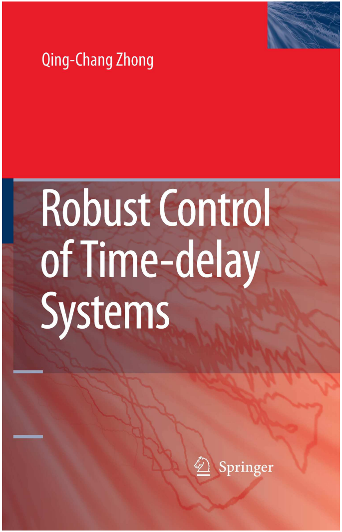
Further reading

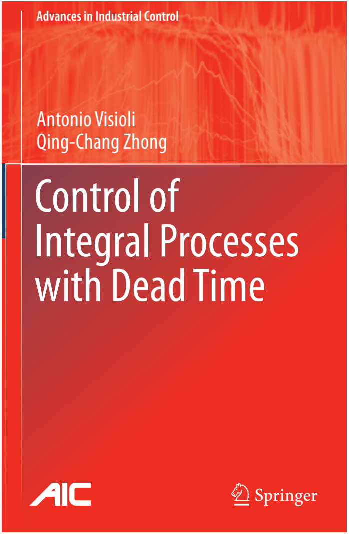




(to appear in 2015)

Something more mathematical?





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  - Zhenyu Ma, China, for implementing the idea of applying synchronverters to rectifiers
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  - Royal Academy of Engineering
  - Technology Strategy Board

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国家电网公司 STATE GRID CORPORATION OF CHINA

Rolls-Royce

nationalgrid

SIEMENS

OPAL-RT TECHNOLOGIES

ALSTOM

turbopowersystems Electrical Machines & Power Electronics

NATIONAL INSTRUMENTS

YOKOGAWA

POWERSYSTEMSWAREHOUSE

TEXAS INSTRUMENTS

add2

nheolis 3D wind turbines

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- Two topics:
  - Topic A: High-efficiency Wireless Charging System for Electric Vehicles and Other Applications, Univ of Michigan, Dearborn, USA (Topic Chair: Kevin Bai & Wencong Su, USA)
  - **Topic B: Battery Energy Storage with an Inverter that Mimics Synchronous Generators, Univ of Sheffield, UK (Topic Chair: Qing-Chang Zhong)**
- Key dates:
  - Proposals due: Sept. 15, 2014
  - Notification of acceptance: Nov. 1, 2014
  - Final on-site competition: July 2015
- Financial support for travel, and also for components (Topic B)
- One team per university of undergraduates with maximum two advisory postgraduates

http://www.energychallenge.org/

Thank you.

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Architecture for next-generation smart grid