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

Qing-Chang Zhong

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The University of Sheffield
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China

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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)

“. . . the largest and most complex machine engineered by humankind.”

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Evolution of power systems

Centralised Generation

Distributed Generation

Smart Grid

Karady G and Holbert K 2004


Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI) IEEE PELS DL on Next-Generation Smart Grids (CAPS)
Evolution of power systems

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Smart Grid

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DOE: Smart Grid System Report

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What’s next?

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

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)
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

- 5. Aug., 2003
  Northeast (USA & Canada)
  55m people

- 7. Nov., 1965
  Northeast (USA & Canada)
  30m people

- 5. Sept., 2003
  Italy (Italy, Switzerland, Austria, Slovenia, Croatia)
  55m people affected

- 4. Nov., 2009
  Brazil & Paraguay
  87m people

  Southern Brazil
  97m people

  India
  670m people

- 2. Aug., 2005
  Java-Bali (Indonesia)
  100m people

Generated from the data at http://en.wikipedia.org/wiki/List_of_power_outages
Challenges being faced by power systems

- Ageing infrastructure (mostly over 100 years old)
  - Faults
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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)
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- Demand of high energy efficiency
- Large-scale utilisation of renewable energy, EVs and energy storage systems etc.
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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

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The mainland Chinese power system

800kV 6400 MW, 2018
800kV 6400 MW, 2011
800kV 6400 MW, 2015
800kV 6400 MW, 2014
3000 MW, 2009
3000 MW, 2011
3000 MW, 2015
800kV 6400 MW, 2018
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3000 MW, 2009
3000 MW, 2010
1500 MW, 2008
800kV 6400 MW, 2015
3000 MW, 2013
1200 MW, 2011
1000 MW, 2012
3000 MW, 2016
800kV 5000-6000 MW, 2015
3000 MW, 2013
800kV 5000 MW, 2009

The US power system

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

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)

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These actions are all important and effective. But are we doing enough? Let’s go one step back and recall the challenges:

- Ageing infrastructure
- Fast growth of electricity consumption
- Demand of high energy efficiency
- Large-scale utilisation of renewable energy, EVs and ESS etc.

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

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.

- No longer manageable with human interaction
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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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If yes, can these happen regardless of size and capacity?
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 the synchronisation mechanism of SG.

This will be adopted to construct the next-generation smart grids, CAPS.
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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?
New add-ons of generation

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Is there anything in common?
Are we able to make inverters have the vital synchronisation mechanism?
Inverters: —

Common devices for smart grid integration

Are we able to make inverters have the vital synchronisation mechanism?

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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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\[
\begin{align*}
T_m &\quad 1/J_s \\
1/\theta &\quad 1/s \\
\theta &\quad \theta
\end{align*}
\]

Formulas of $T_e, Q, e$

\[
\begin{align*}
M_{ij} &\quad e \\
M_{ij} &\quad i
\end{align*}
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\[ \begin{align*}
T_m & \quad \frac{1}{J_s} \quad \frac{1}{s} \\
Q & \quad M_{Jf} \\
e & \quad e_a \quad e_b \quad e_c
\end{align*} \]

\[ V_{DC} \quad L, R \quad C \]

Circuit Breaker

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)
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

From to the power part

\[ P_{set} \]
\[ \frac{p}{\theta_n} \]
\[ T_m \]
\[ D_p \]
\[ \dot{\theta}_r \]
\[ \theta_g \]
\[ \theta_c \]
\[ \dot{\theta} \]
\[ \frac{1}{J_s} \]
\[ Q \]
\[ Q_{set} \]
\[ \frac{1}{K_s} \]
\[ M_{fi_f} \]
\[ i \]
\[ e \]
\[ D_q \]
\[ \dot{v}_m \]
\[ v_m \]
\[ v_f \]

Formulas of \( T_e, Q, e \)

From to the power part

\[ \text{PWM generation} \]

\( Q.-C. \, Zhong \) (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)
Experimental results

Frequency regulation

Grid frequency [Hz]

Time [sec]

P [W]
So, all the generators can have the vital synchronisation mechanism and take part in the grid regulation.

How about the loads?
So, all the generators can have the vital synchronisation mechanism and take part in the grid regulation.

How about the loads?
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?
Load types

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- Air-conditioners
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- ...

Is there anything in common?
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.
The majority of loads (will) have a front-end rectifier because:

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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.
Running rectifiers as synchronous motors

\[ V_o = V_{ref} \left( K_p + \frac{K_i}{s} \right) T_m \quad \text{Formulas of} \quad T_e, \quad Q \quad \text{and} \quad e \]

Angular frequency

Reset

\[ D_p \]

STA

\[ v \]

To/from the power part

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Experimental results

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

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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

Problems with dedicated synchronisation units (PLL etc)
- Fight with each other
- Cause instability
- Reduce performance

Rectifiers

Is it possible to get rid of the dedicated synchronisation unit, although it is believed to be a must-have component?
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A mechanism is introduced to generate the reference frequency

A mechanism is introduced to synchronise with the grid before connection
Experimental results

Synchronverter frequency

Grid frequency measured by a PLL

Real power

Reactive power
A mechanism is introduced to generate the reference frequency

A mechanism is introduced to synchronise with the grid before connection
Experimental results

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

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)
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.

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)
Further reading

Completely Autonomous Power Systems (CAPS)
Next Generation Smart Grids
Qing-Chang Zhong
(to appear in 2015)
Something more mathematical?

Qing-Chang Zhong

Robust Control of Time-delay Systems

Antonio Visioli
Qing-Chang Zhong

Control of Integral Processes with Dead Time

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)
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Dushan Boroyevich, Virginia Tech, USA, Immediate Past President of IEEE PELS, for the collaborative work on the equivalence of PLL and droop control.

Research Assistants and Associates

Tomas Hornik, Turbo Power Systems, UK, for the help with the exp. about synchronverters

Long Nguyen, add2 Ltd, UK, for implementing the idea of self-synchronised synchronverters

Zhenyu Ma, China, for implementing the idea of applying synchronverters to rectifiers

Wen-Long Ming, Zhaohui Cen and Yu Zeng, Univ. of Sheffield, for getting the real-time simulation and the video done

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Technology Strategy Board
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- Rolls-Royce
- National Grid
- Siemens
- OPAL-RT Technologies
- Alstom
- Turbopowersystems
- National Instruments
- Yokogawa
- Powersystems Warehouse
- Texas Instruments
- Add2
- Nheolis
- 3D wind turbines
Well-established international colleague students competition since 2001
Four prizes: $10,000, $5000, $3000 and $1000
IFEC’2015 General Chair: Dehong Xu, China
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.

zhongqc@ieee.org
Architecture for next-generation smart grid

Coal Plants → SG → Nuclear Plants → SG → Hydro-Electric Plants

Industrial Power Plants → SG

Motors → SV

Lighting → SV

Electronic Apparatus → SV

Wind Farms → SV

Solar Farms → SV

Energy Storage Systems → SV

Electric Vehicles

HVDC Transmission and Distribution

Q.-C. Zhong (zhongqc@ieee.org, Univ. of Sheffield/CEPRI)

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