Integrated Control and Power Electronics for Energy and Power Systems

Qing-Chang Zhong

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The evolution, philosophy, and current standing of our research

Sample enabling technologies developed
- Smart grid integration
- Power quality control
- Parallel operation of inverters
- Synchronisation strategies
- Removal of electrolytic capacitors

Our vision and future research plan
Evolution of our research

Pushing boundaries and breaking limits
- From hardware to software
- From applied to theoretical
- From control to power
- Cover many application areas

Research philosophy / How I think
- Focused and thorough research: Deep thinking
- Holistic approach: Down to details but keep the big picture in mind
- Looking for solutions and problems as well
- Looking for hidden links

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org) Control and Power Electronics for Energy and Power Systems
Current standing

Seamless integration of control and power electronics.

Associate Editor for

- IEEE Trans. on Automatic Control
- IEEE Trans. on Control Systems Technology
- IEEE Trans. on Power Electronics
- IEEE Trans. on Industrial Electronics
- IEEE Journal of Emerging and Selected Topics in Power Electronics
- IEEE Access
- European Journal of Control
Activities in control theory

- **Robust control of time-delay systems (frequency-domain approaches):** Solved a series of fundamental problems in this area:
  - Projections
  - $J$-spectral factorisation
  - Delay-type Nehari problem
  - Standard $H^\infty$ problem of single-delay systems
  - Unified Smith predictor
  - Realisation of distributed delays in controllers

- **Infinite-dimensional systems:** applied the generic theory of infinite-dimensional systems to time-delay systems and solved problems about feedback stabilizability, approximate controllability, passivity etc.

- **Uncertainty and disturbance estimator (UDE)-based robust control:** can be applied to linear or nonlinear, time-varying or time-invariant systems with or without delays; attracted several groups worldwide.
Activities in control applications

- Control of integral processes with dead-time
  - Disturbance observer-based control strategy
  - Dead-beat response
  - Stability region on the control parameter space
  - Achievable specifications etc.

- Practical experience with a production line
  - 16 reactors, controlled by 3 industrial computers
  - Effective object code > 100 KB (Intel 8086 assembler)

- Continuous Stirred Tank Reactors (CSTR)
- Unmanned Aerial Vehicles (UAVs) and quadrotors
- Positioning systems with hysteresis
Activities in energy and power

- Sample platform technologies
  - **Smart grid integration**: Synchronverters, self-synchronised synchronverters, STATCOM without a PLL etc.
  - **Parallel operation of inverters**: Robust droop control, universal droop control, harmonic droop control
  - **Removal of phase-locked loops**
  - **Removal of electrolytic capacitors**
  - **Power quality in microgrids**: C-inverters, bypassing harmonic current components, H-infinity repetitive control
  - **Provision of a neutral line**: Common-mode currents, removal of isolating transformers
  - **Synchronisation**: sinusoid-locked loops
  - **Active capacitors**

- **Applications**
  - Wind power
  - Hybrid electric vehicles
  - High-speed trains
  - Single-phase to three-phase conversion
Completely Autonomous Power Systems (CAPS)
Next Generation Smart Grids
Qing-Chang Zhong

IEEE Power Electronics Society Distinguished Lecturer, 2014-2015
FREEDM Systems Center Scientific Advisor, NCSU, 2014
Rolls-Royce UTP Board Member in Power Electronics, 2013-

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
Industrial Advisory Board

- Chaired by Kevin Daffey, Global Head of Rolls-Royce Electrical Power and Control Systems
- Members:
Facilities

- Largest OPAL RT Real Time Digital Simulator in EU and North America for control, power electronics and power systems
- A microgrid consisting of one 80kVA gen-set, three 200 kVA inverters (max 400 kVA), which is highly reconfigurable for fundamental applied research in control and energy management strategies.
- A 60kW Chroma grid simulator
The evolution, philosophy, and current standing of our research

Sample enabling technologies developed

- **Smart grid integration**
  - Power systems challenges
  - Synchronverters: Inverters that mimic SG
  - Self-synchronised synchronverters: No more PLLs
  - Self-synchronised PWM rectifiers

- Power quality control
- Parallel operation of inverters
- Synchronisation strategies
- Removal of electrolytic capacitors

- Our vision and future research plan
Power systems

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

“. . . the largest and most complex machine engineered by humankind.”
(P. Kundur '94)
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Evolution of power systems

Centralised Generation

Distributed Generation

Smart Grid

Karady G and Holbert K 2004

Evolution of power systems

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Control and Power Electronics for Energy and Power Systems
Evolution of power systems

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Smart Grid

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What’s next?

Next-Generation Smart Grids:
Power Electronics Based Autonomous Power Systems
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Power Electronics Based Autonomous Power Systems
Challenges being faced by power systems

- Ageing infrastructure (mostly over 100 years old)
  - Faults
  - Blackouts
Top 10 blackouts in the history

India
670m people

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

3. Mar, 1999
Southern Brazil
97m people

4. Nov, 2009
Brazil & Paraguay
87m people

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

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

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

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

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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

Residential, By Major Source

- Natural Gas
- Electrical Losses¹
- Renewable Energy
- Electricity²
- Petroleum
- Coal

Commercial, By Major Source

- Natural Gas
- Electrical Losses¹
- Renewable Energy
- Electricity²
- Petroleum

Industrial, By Major Source

- Natural Gas
- Electrical Losses¹
- Petroleum
- Electricity²
- Coal
- Renewable Energy

Transportation, By Major Source

- Petroleum
- Natural Gas
- Renewable Energy


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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


Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org) Control and Power Electronics for Energy and Power Systems
How to address the challenges?

- upgrading the system, e.g. by introducing
  - phase measurement units (PMU)
  - wide-area monitoring systems (WAMS)
- strengthening the system, e.g. by introducing HVDC and HVAC links
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The UK national grid

Adapted from Department of Energy & Climate Change, UK, Our electricity transmission network: A vision for 2020.

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Control and Power Electronics for Energy and Power Systems
The mainland Chinese power system


Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org) Control and Power Electronics for Energy and Power Systems
The US power system

EXISTING LINES
- 345-499 kV
- 500-699 kV
- 700-799 kV
- 1,000 kV (DC)

PROPOSED LINES
- New 765 kV
- AC-DC-AC Links

INTERCONNECTIONS
Major sectors of the U.S. electrical grid
- Eastern
- Western
- Texas (ERCOT)

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

\[\downarrow\]

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Power electronics-based.
Fundamental challenge

Future power systems will be power electronics-based, with a huge number of heterogeneous players.

- It is 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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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 another SG.

The underlying principle that holds a power system is the synchronisation mechanism of SG.

We are going to adopt this to facilitate smart grid integration.
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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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Is there anything in common?
Inverters: —

**Common devices for smart grid integration**

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

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Control and Power Electronics for Energy and Power Systems
Inverters: —

Common devices for smart grid integration

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

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org) Control and Power Electronics for Energy and Power Systems
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

Many different types of loads exist in a power system:

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

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
- **Internet devices** consume DC electricity
- **Light bulbs** are being replaced with energy-efficient devices, e.g. **LED**

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

Formulas of $T_e$, $Q$ and $e$

PWM generation

Angular frequency

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 \( V_{\text{ref}}=40 \, V \) 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 \( t=41s \).
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

Formulas of $T_e$, $Q$, $e$

Reset

Amplitude detection

PWM generation

From to the power part

Problems with dedicated synchronisation units (PLL etc.)

- Fighting with each other
- Causing instability
- Degraded 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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### Inverters

![Diagram of Inverter System]

- Formula of $T_e$, $Q$, and $e$
- PWM generation
- From/to the power part

### Rectifiers

![Diagram of Rectifier System]

- Formula of $T_e$, $Q$, and $e$
- Angular frequency
- PWM generation
- From/to the power part

### Problems with dedicated synchronisation units (PLL etc.)

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Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
A mechanism is introduced to generate the reference frequency

A mechanism is introduced to synchronise with the grid before connection

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Experimental results

Synchronverter frequency

Grid frequency measured by a PLL

Real power

Reactive power

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

Formulas of $T_e$, $Q$ and $e$
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 V at $t=31s$;
6) The load changed to $R=30\Omega$ at $t=42s$. 

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
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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How to Achieve Completely Autonomous Power in the Next Generation of Smart Grids

Written by Qing-Chang Zhong

The paradigm of future power systems described here offers a method of standardizing the interface of all electrical supplies, including conventional power plants and new add-ons, such as wind/solar farms, electrical vehicles and energy storage systems, and a majority of loads with the transmission and distribution networks, by exploiting the synchronisation principle of synchronous machines. This model opens the prospect of achieving completely autonomous operation of power systems.

Due to civilisation and economic development, demand for electricity is constantly growing, leading directly to supply issues.

Smart Grid Technology

What's next after self-healing? How about a self-directed smart grid

Sep 17, 2013

Talk Back  Free Alerts  More On This Topic

Quick Take: Back in 2010, I told you about an Electric Power Research Institute (EPRI) paper that predicted the demise of centralized control for the smart grid. EPRI described it as the move from "command and control" to "inform and motivate." That same year I pointed out SCE Electric’s vision for distributed intelligence that would coordinate with centralized control.

Then in June of 2013, I suggested that transactive energy might be the "language" we should use for that coordination. Transactive energy, among other things, sends "value signals" so that devices can "negotiate" how much power they will use and how much they will pay for it.

Now the IEEE is reporting on an alternative approach for a self-directed, semi-autonomous grid. Qing-Chang Zhong, a professor in the Department of Automatic Control and Systems Engineering at the University of Sheffield in the U.K., proposes a scheme that could accommodate millions of active players. Click the link above to review the post, or skim the short summary below. - By Jesse Berst
At conferences: 12 plenary talks

- IEEE PEDG, USA, July 2013
- Annual Conference of Chinese Universities in Power Systems and Automation, China, Nov. 2013
- 3rd Int. Conf. on Advances in Control and Optimization of Dynamical Systems, IIT Kanpur, India, Mar. 2014.
- IEEE GreenTech, USA, April 2014
- Annual Conference of Chinese Universities in Power Electronics, Wuhan, China, April 2014
- Delta Power Electronics Forum, Suzhou, China, May 2014.
- The 26th Chinese Control and Decision Conference (CCDC), Changsha, China, May 2014.
- OPAL RT Annual Conference, Montreal, Canada June 2014.
- 20th International Conference on Automation and Computing (ICAC2014), Cranfield, UK, Sept., 2014
- The 1st Indian Systems and Controls Conference, Chennai, India, Jan. 2015.
Outline

- The evolution, philosophy, and current standing of our research
- Sample enabling technologies developed
  - Smart grid integration
  - Power quality control
    - Principles to improve power quality
    - C-inverters
    - Bypassing harmonic currents
  - Parallel operation of inverters
  - Synchronisation strategies
  - Removal of electrolytic capacitors
- Our vision and future research plan
Harmonics is becoming an important problem because future power systems are becoming converters-dominated. Harmonics can cause overheating, increased losses, decreased power capacity, neutral line overloading, distorted voltage and current waveforms.

Converters are sources of voltage harmonics:

- PWM and switching effects: can be handled with LC filters, PWM strategies etc.
- Voltage reference $v_r$
- Voltage drop on the output impedance

\[ S = P + jQ \]

\[ i \]

\[ Z_o \angle \theta \]

\[ E \angle \delta \]

\[ (v_r) \]

\[ V_o \angle 0^\circ \]

\[ (v_o) \]

\[ v_o = v_r - Z_o(s) \cdot i, \]
Principles to improve power quality

\[ S = P + jQ \]

\[ E \angle \delta \]

\[ Z_o \angle \theta \]

\[ V_o \angle 0^\circ \]

\[ v_o = v_r - Z_o(s) \cdot i, \]

- to make the reference voltage \( v_r \) provide the right amount of harmonic voltages to compensate the harmonic voltage dropped on the output impedance (harmonic droop control).
- to bypass the harmonic components of load current so that the current \( i \) is clean; and
- to keep \( v_r \) clean and maintain a small output impedance \( Z_o \) over the frequency range of the major harmonic current components (C-inverters);
- In addition to these, other control strategies, e.g. \( H^\infty \) repetitive control, can be adopted.
The output impedance of an inverter is normally inductive (L-inverters) but can be made capacitive (C-inverters) via the controller below.

\[ \frac{1}{sC_o} \]

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
Experimental results

(a) C-inverter with $C_o = 4500 \mu F$

(b) C-inverter with $C_o = 3100 \mu F$

(c) R-inverter with $K_i = 0.4$

(d) L-inverter
Bypassing harmonic currents

The voltage controller introduced above is equivalent to putting a parallel branch with $C$.

$$Z_o(s) = \frac{sL + K_i}{1 + K_R(s)}.$$
Then $K_R$ can be chosen as a series resonant circuit at given harmonic frequencies to short-circuit harmonic current components.

\[ K_R(s) = \sum_{h=3,5,\ldots} \frac{2\xi h \omega s}{s^2 + 2\xi h \omega s + (h\omega)^2} \times K_h. \]
Experimental results with a nonlinear Load

(a) without bypassing

(b) with bypassing
The evolution, philosophy, and current standing of our research

Sample enabling technologies developed

- Smart grid integration
- Power quality control
- **Parallel operation of inverters**
  - Limitations of conventional droop controller
  - Robust droop controller
  - Universal droop controller
  - Harmonic droop controller
  - Droop control is intrinsically an EPLL

- Synchronisation strategies
- Removal of electrolytic capacitors

Our vision and future research plan
Parallel operation of inverters

\[ S_1 = P_1 + jQ_1 \quad S_2 = P_2 + jQ_2 \]

Inverters would be inevitably operated in parallel because of
- inverters naturally operated in parallel in a large-scale system
- the limited capacity of power semiconductor devices
- the requirement of redundancy and reliability

They are required to provide
- Accurate sharing of real power and reactive power at the same time
- Excellent voltage regulation capability
- Good power quality

Common control strategies
- with the help of a communication: master-slave or supervisory control
- without the help of a communication network: droop control.
An inverter can be modelled as a reference voltage source with an output impedance $Z_o$.

The real power and reactive power dispatched to the terminal via the output impedance $Z_o$ are

\[
P = (\frac{E V_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o}) \cos \theta + \frac{E V_o}{Z_o} \sin \delta \sin \theta,
\]

\[
Q = (\frac{E V_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o}) \sin \theta - \frac{E V_o}{Z_o} \sin \delta \cos \theta,
\]

where $\delta$ is the power angle.
Conventional Droop Control: L-inverters

For inductive output impedance, $\theta = 90^\circ$, then

\[ P = \frac{E V_o}{Z_o} \sin \delta, \quad Q = \frac{E V_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o} \]

\[ \Downarrow \text{when } \delta \text{ is small} \]

\[ P \approx \frac{E V_o}{Z_o} \delta, \quad Q \approx \frac{E - V_o}{Z_o} V_o \quad \Rightarrow \quad P \sim \delta, \quad Q \sim V_o \]

conventional control strategy \( \Downarrow \)

\[ E_i = E^* - n_i Q_i, \]
\[ \omega_i = \omega^* - m_i P_i, \]
Conventional Droop Control: R-inverters

For resistive output impedance, $\theta = 0^\circ$, then

$$P = \frac{E V_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o}, \quad Q = -\frac{E V_o}{Z_o} \sin \delta$$

⇓ when $\delta$ is small

$$P \approx E - V_o V_o, \quad Q \approx -\frac{E V_o}{Z_o} \delta \quad \Rightarrow \quad P \sim V_o, \quad Q \sim -\delta$$

conventional control strategy ⇓

$$E_i = E^* - n_i P_i, \quad \omega_i = \omega^* + m_i Q_i$$
Conventional Droop Control: C-inverters

For capacitive output impedance, $\theta = -90^\circ$, then

$$P = -\frac{E V_o}{Z_o} \sin \delta \quad \text{and} \quad Q = -\frac{E V_o}{Z_o} \cos \delta + \frac{V_o^2}{Z_o}.$$  

\[\Downarrow\] \hspace{1cm} \text{when } \delta \text{ is small}

$$P \approx -\frac{E V_o}{Z_o} \delta \quad \text{and} \quad Q \approx -\frac{E - V_o}{Z_o} V_o, \quad \implies \quad P \sim -\delta, \quad Q \sim -V_o$$

\[\text{conventional control strategy} \Downarrow\]

\begin{align*}
E_i &= E^* + n_i Q_i, \\
\omega_i &= \omega^* + m_i P_i,
\end{align*}
The theory seems perfect but it does not work well in practice. What went wrong?
Revisit of the droop controller (for R-inverters)

\[ E_i = E^* - n_i P_i, \]
\[ \omega_i = \omega^* + m_i Q_i. \]

Fundamental limitations:

- The same \( E_i \)
- The same per-unit output impedance
- Inherent trade-off between power sharing and voltage regulation

\[ \Rightarrow \text{Not robust at all!} \]
Revisit of the droop controller (for R-inverters)

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Revisit of the droop controller (for R-inverters)

\[ E_i = E^* - n_i P_i, \]
\[ \omega_i = \omega^* + m_i Q_i. \]

**Fundamental limitations:**

- The same \( E_i \)
- The same per-unit output impedance
- Inherent trade-off between power sharing and voltage regulation

\[ \not \Rightarrow \text{Not robust at all!} \]
Robust droop controller (patented)

Accurate sharing of both real power and reactive power
Excellent voltage regulation
Low THD
Fast response

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
Experimental results

- Real Power [W]
- Reactive Power [Var]
- Voltage [V]
- Output Voltage [V]
- Current [A]
- THD of $v_o$ [%]

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
Droop controllers take different forms for inverters with different output impedance. What happens if the inverters in parallel operation have different types of output impedance?

Is it possible to find a universal droop controller that works for inverters having different types of output impedance?
Droop controllers take different forms for inverters with different output impedance. What happens if the inverters in parallel operation have different types of output impedance?

Is it possible to find a universal droop controller that works for inverters having different types of output impedance?
Revisit of the power delivery

\[ S = P + jQ \]

\[ P = \left( \frac{EV_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o} \right) \cos \theta + \frac{EV_o}{Z_o} \sin \delta \sin \theta \]

\[ Q = \left( \frac{EV_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o} \right) \sin \theta - \frac{EV_o}{Z_o} \sin \delta \cos \theta \]

which can be re-written as

\[
\begin{bmatrix}
P \\
Q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\frac{EV_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o} \\
-\frac{EV_o}{Z_o} \sin \delta
\end{bmatrix}.
\]
Define
\[
\begin{bmatrix}
\tilde{P} \\
\tilde{Q}
\end{bmatrix} = \begin{bmatrix}
\frac{E V_o}{Z_o} \cos \delta - \frac{V_o^2}{Z_o} \\
-\frac{E V_o}{Z_o} \sin \delta
\end{bmatrix}.
\]

Then,
\[
\tilde{P} \sim E \quad \text{and} \quad \tilde{Q} \sim -\delta
\]
when \(|\delta|\) is small. As a result,
\[
\begin{bmatrix}
P \\
Q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
\tilde{P} \\
\tilde{Q}
\end{bmatrix}.
\]

This means that the vector \(P + jQ\) is obtained by rotating the vector \(\tilde{P} + j\tilde{Q}\) by \(\theta\). The eigenvalues of
\[
\begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix}
\]
are
\(\cos \theta \pm j \sin \theta\), of which the real part \(\cos \theta\) is positive for any output impedance with \(\theta \in (-\frac{\pi}{2}, \frac{\pi}{2})\). Hence,
\[
P \sim \tilde{P} \quad \text{and} \quad Q \sim \tilde{Q}
\]
\(\implies P \sim E \quad \text{and} \quad Q \sim -\delta\).
Since $P \sim E$ and $Q \sim -\delta$. the conventional droop controller takes the form of

$$E_i = E^* - n_i P_i$$

$$\omega_i = \omega^* + m_i Q_i.$$ 

In practice, there are often small resistance in series with the output impedance even if the output impedance is designed to be inductive or capacitive. Hence, $\theta \in (-\frac{\pi}{2}, \frac{\pi}{2})$ and this droop control strategy is universal and does not dependent on the type of the output impedance.

Coincidently, this is the same as the droop control strategy for R-inverters.
We have proven that the droop controller for R-inverters is universal for inverters having impedance with $\theta \in \left( -\frac{\pi}{2}, \frac{\pi}{2} \right)$.

\[
\begin{align*}
E_i & \quad \frac{1}{s} \\
\omega_i t + \delta_i & \quad 1 \\
\omega^* & \quad m_i \\
E^* & \quad n_i \\
\end{align*}
\]
L-, C- and R-inverters, one each, share a load in the ratio of 1:2:3.

(a) Real power

(b) Reactive power
R-, L-, C-inverters in parallel
Experimental results

- $P$: [5 W/div]
- $Q$: [1.5 Var/div]
- $v_0$: [15V/div]
- $i$: [1 A/div]
- $t$: [3 s/div]
Injecting harmonic voltage components

(a) One circuit including all harmonics

\[ S_h = P_h + Q_h \]

\[ Z_o(jh\omega^*) \]

(b) The circuit at the \( h \)-th harmonic frequency

\[ v_{oh} = 0 \text{ if } v_{rh} \text{ is the same as the voltage dropped on the output impedance } Z_o \text{ by the harmonic current component } i_h. \]
Power delivery

\[ S = P + jQ \]

(a) To a voltage source

(b) To a current source
Harmonic droop controller

Fourier Analysis to calculate $P_h, Q_h$ at the $h$-th harmonics

It does not depend on the impedance type at the harmonic frequency concerned.
In order to reduce multiple harmonics in the output voltage, several harmonic droop controllers corresponding to the harmonic orders can be included in the controller to generate the required $\Sigma_h v_{rh}$.

The difficulty in defining the reactive power for the conventional droop controller has been avoided because the reactive power in this strategy is defined at the corresponding frequency. Here, the fundamental droop controller is designed for R-inverters, which can also be used for C-inverters and R-inverters.
Without With 3rd and 5th harmonics droop controller

(a) Currents

(b) Output voltage

(c) Harmonic voltage components
Droop control v.s. PLL

<table>
<thead>
<tr>
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<th>Phase-locked loops (PLL)</th>
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We have found that they are intrinsically the same!

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
Control and Power Electronics for Energy and Power Systems
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We have found that they are intrinsically the same!
A droop controller is intrinsically an EPLL

\[ e = \sqrt{2} \left( \frac{K_e}{s} H(s) \right) \]

\[ e_q = \frac{1}{s} K_f H(s) \]

Droop control

\[ EPLL \]

\[ e = \sqrt{2} \left( \frac{1}{s} E \mu_1 \right) \left( \frac{1}{s} \right) \]

\[ e_q = \frac{1}{s} \left( \mu_2 \left( \mu_3 + \frac{1}{s} \right) \right) \]

EPLL

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
What does this mean?

No more phase-locked loops in grid-tied converters!
What does this mean?

No more phase-locked loops in grid-tied converters!
The evolution, philosophy, and current standing of our research

Sample enabling technologies developed

- Smart grid integration
- Power quality control
- Parallel operation of inverters
- Synchronisation strategies
  - Sinusoid-locked loops (SLL)
- Removal of electrolytic capacitors

Our vision and future research plan
Phase-locked loops (PLL)

(a) Operating concept
SOGI-based PLL

Quadrature-signal generator based on a second-order-generalised integrator (SOGI-QSG)

A single phase PLL equipped with the SOGI-QSG
Sinusoidal Tracking Algorithm (STA)

Also called the enhanced PLL (EPLL)

\[ v \times \varphi \times s \sin \theta \]

\[ E - \theta \]

\[ \mu_1 \]

\[ \frac{1}{s} \]

\[ \sin \]

\[ \cos \]

\[ \mu_2 \]

\[ \frac{1}{s} \]

\[ \dot{\theta} \]

\[ \theta_n \]

\[ \mu_3 \]
What is the problem?

- Response speed is low: often takes more than one cycle
- Robustness against frequency variations
- Harmonics in the recovered signal

Solution:
A small synchronous machine can quickly synchronise with the terminal voltage.
The real power $P$ and reactive power $Q$ flowing out of the machine are

$$P = \frac{v_m E}{2X_s} \sin(\theta - \theta_v), \quad Q = \frac{v_m}{2X_s} [E \cos(\theta - \theta_v) - v_m].$$

where $E$ and $v_m$ are peak amplitude values instead of RMS values.

The machine is considered to be synchronised and floating on the grid when

$$E = v_m, \quad \theta = \theta_v.$$
Mathematical model of a SG

\[ e = M_f i_f \dot{\theta} \tilde{\sin} \theta - M_f \frac{d}{dt} \tilde{\cos} \theta, \]

\[ T_e = pM_f i_f \langle i, \tilde{\sin} \theta \rangle, \]

\[ Q = -\dot{\theta} M_f i_f \langle i, \tilde{\cos} \theta \rangle, \]

\[ J \ddot{\theta} = T_m - T_e - D_p \dot{\theta}, \]
Revisit of the synchronverter

\[ \frac{P}{\dot{\theta}_n} \]

\[ T_m \]

\[ \frac{1}{Js} \]

\[ \frac{1}{s} \]

\[ \theta \]

\[ \theta_g \]

\[ \theta_c \]

\[ P_{set} \]

\[ Q_{set} \]

\[ \frac{1}{Ks} \]

\[ M_f i_f \]

\[ D_q \]

\[ \dot{\theta}_r \]

\[ v_{fb} \]

\[ v_{m} \]

\[ v_r \]

\[ \text{PWM generation} \]

\[ \text{Amplitude detection} \]

\[ i \]

\[ e \]

\[ T_e \]

\[ \text{Eqn. (7)} \]

\[ \text{Eqn. (8)} \]

\[ \text{Eqn. (9)} \]

\[ \text{From to the power part} \]
The idea of the proposed SLL is to operate a virtual (single-phase) synchronous generator with $P = 0$ and $Q = 0$ so that the generated voltage $e$ is the same as the fundamental component of the terminal voltage $v$. 
In single-phase systems, average values are used for

\[ T_e = \frac{1}{T} \int_{t-T}^{t} M_f i_f i \sin \theta \, dt, \]

\[ Q = -\frac{1}{T} \int_{t-T}^{t} \dot{\theta} M_f i_f i \cos \theta \, dt, \]

where \( T = \frac{2\pi}{\dot{\theta}} \) is the period of voltage \( \nu \).

The recovered voltage \( e \) is

\[ e = \dot{\theta} M_f i_f i \sin \theta = E \sin \theta, \]

and the amplitude is

\[ E = \dot{\theta} M_f i_f. \]

The stator current \( i \) is generated internally as the voltage difference between \( e \) and \( \nu \) divided by the virtual synchronous reactance \( X_s(s) = sL + R \), i.e.,

\[ i = \frac{e - \nu}{sL + R}. \]
Tracking the frequency and phase

- The frequency $\dot{\theta}$ should be the same as $\dot{\theta}_v$ in the steady state, which means the reference frequency $\dot{\theta}_r$ should be the same as $\dot{\theta}$. This is achieved by the integrator $\frac{K_i}{s}$.

- After setting the desired real power to 0, the electromagnetic torque $T_e$ is driven to zero when $\dot{\theta}_r = \dot{\theta}_v$.

  - At the steady state, $T_e$ is driven to zero and
    
    $$ P = \dot{\theta} T_e = 0 $$

  - As a result, $\dot{\theta}$ is the same as the (angular) frequency $\dot{\theta}_v$ of voltage $v$ and $\theta$ is the same as the phase $\theta_v$ of voltage $v$, i.e.,
    
    $$ \begin{cases} 
    \dot{\theta} = \dot{\theta}_v, \\
    \theta = \theta_v.
    \end{cases} $$

  The SLL locks to the frequency and phase of $v$. 

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Tracking the voltage amplitude

- The voltage droop control in synchronverters is not needed for the SLL because the generated voltage is expected to be the same as the voltage \( v \). The desired reactive power is set to 0 and the loop to drive the reactive power \( Q \) to zero is kept. At the steady state, \( Q = 0 \) in addition to \( P = 0 \). Hence,

\[
E = v_m.
\]

- The SLL is synchronised with the voltage \( v \) because voltage amplitude, frequency, and phase are well tracked at the steady state.

- It is worth noting that one advantage of the SLL is that the frequency, phase, voltage amplitude and the recovered signal are all directly available internally without any extra calculation.
The time constant of the frequency loop is
\[ \tau_f = \frac{J}{D_p}. \]

A large \( \tau_f \) is equivalent to having a large \( J \), which makes the SLL less sensitive to the variations in the grid frequency and improves the stability. However, the response is slow. A small \( \tau_f \) is equivalent to having a small \( J \), which leads to fast frequency tracking. As a general rule of thumb, \( \tau_f \) can be chosen much smaller than the period of the voltage \( v \) so that the frequency can be tracked very quickly.

The time constant of the amplitude loop is proportional to
\[ \tau_q = \frac{K}{\dot{\theta}_n}. \]

Generally, \( \tau_q \gg \tau_f \), the frequency loop should be tuned much faster than the amplitude loop. However, if a very large \( \tau_q \) is chosen, it would take long time for the voltage amplitude \( E \) to track \( v_m \).
The inductance $L$ and resistance $R$ of the virtual synchronous reactance $X_s$ can be chosen small to enable a large transient current $i$, which helps speed up the synchronisation process.

The ratio $\frac{R}{L}$ is the cut-off frequency of the filter $\frac{1}{sL+R}$, which determines the capability of filtering out the harmonics from the voltage $v$.

The loop to generate the reference frequency $\dot{\theta}_r$ is an outer loop for the frequency loop so it should be tuned much slower than the frequency loop. Its time constant is

$$\tau_{fn} = \frac{1}{D_p K_i}$$

and can be tuned as $\tau_{fn} = (10 \sim 100) \tau_f$. 
## Experimental results

Parameters of the SLL for experiments

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_n$</td>
<td>50 Hz</td>
<td>$J$</td>
<td>$2.0264 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\tau_f$</td>
<td>0.0005 s</td>
<td>$K$</td>
<td>4809.6</td>
</tr>
<tr>
<td>$\tau_{fn}$</td>
<td>0.049 s</td>
<td>$K_i$</td>
<td>100</td>
</tr>
<tr>
<td>$\tau_q$</td>
<td>18.37 s</td>
<td>$L$</td>
<td>0.3 mH</td>
</tr>
<tr>
<td>$D_p$</td>
<td>0.2026</td>
<td>$R$</td>
<td>0.01 $\Omega$</td>
</tr>
</tbody>
</table>
Tracking a grid voltage

(b) Frequency tracking

(c) Detection of the voltage amplitude

(d) Voltage tracking

(e) THD of $e$

(e) Phase tracking

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Tracking a voltage with a varying freq.

With the proposed SLL

With the SOGI-based PLL

With the STA

(a) Frequency tracking

(b) Amplitude tracking
Tracking a square wave

(a) Input signal

(b) Frequency tracking

(c) Amplitude tracking

(d) Recovered voltage

(e) THD of e

(f) Phase tracking

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The evolution, philosophy, and current standing of our research

Sample enabling technologies developed

- Smart grid integration
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- Removal of electrolytic capacitors

Our vision and future research plan
Ripples in DC microgrids

- DC microgrids are becoming more and more popular
- Electrolytic capacitors are used to reduce voltage ripples

But

- Fuel cells, batteries etc. do not like ripple currents
- Electrolytic capacitors are
  - bulky
  - heavy and
  - with limited lifetime

Is it possible to obtain low voltage ripples with small capacitors?

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Ripple eliminators

(a) without

(b) with

Qing-Chang Zhong (IIT, Chicago, zhongqc@ieee.org)
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  - Synchronisation strategies
  - Removal of electrolytic capacitors
- Our vision and future research plan
Our Vision

To achieve seamless integration of control, power electronics and power systems.
Future research plan

Future research plan for power and energy systems includes:

1. **General Control Theory**
2. **Fundamental Understanding of Power and Energy Systems**
3. **Advanced Control Strategies for Power and Energy Systems**

These strategies cover:

- Wind Power
- Solar Power
- Marine Power
- Hybrid EV
- High-speed trains
- Heavy-duty Vehicles
- More-electric Aircraft
- All-electric ships
- Smart Grids

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Summary — Enabling technologies

- Smart grid integration
  - Synchronverters: Inverters that mimic SG
  - Self-synchronised synchronverters: No more PLLs
  - Self-synchronised PWM rectifiers

- Power quality control
  - C-inverters
  - Bypassing harmonic currents

- Parallel operation of inverters
  - Limitations of conventional droop controller
  - Robust droop controller
  - Universal droop controller
  - Harmonic droop controller
  - Droop control is intrinsically an EPLL

- Synchronisation strategies
  - Sinusoid-locked loops (SLL)

- Removal of electrolytic capacitors
Acknowledgements


- Funding agencies: EPSRC, Royal Academy of Engineering, TSB

- Industrial partners:

  - State Grid Corporation of China
  - Rolls-Royce
  - National Instruments
  - Texas Instruments
  - OPAL-RT Technologies
  - ALSTOM
  - TurboPowerSystems
  - Siemens
  - Yokogawa
  - PowerSystemsWarehouse
  - Chroma
  - National Grid
  - Add2
  - Nheolis
Further reading

Completely Autonomous Power Systems (CAPS)
Next Generation Smart Grids
Qing-Chang Zhong

Control of Power Inverters in Renewable Energy and Smart Grid Integration
Qing-Chang Zhong, Tomas Hornik

(to appear in 2015)
Thank you.

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