Power Electronics-enabled Autonomous Power Systems: Synchronized and Democratized (SYNDEM) Smart Grids

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Power systems are being democratized ... 

- Conventional large power plants, such as coal-fired and nuclear power plants, are going away.
- Right after Fukushima, Germany shut down 8 of its oldest reactors and envisages to close the remaining 9 by 2022.
- China closed or canceled 103 coal-fired power plants earlier this year. Dozens more coal-fired plants closed in the U.S. and India*.
- In January 2018, UK announced to shut down all coal plants by 2025.
- More and more relatively small distributed generators, such as renewables, EVs and storage systems, are being added on to the grid.

*Keith Schneider, Massive Infrastructure Projects Are Failing at Unprecedented Rates, National Geographic, Nov. 20, 2017.
Unfortunately, more blackouts ...

South Australia Blackout, Sept 28, 2016

affecting 850,000 customers

In both cases, wind farms played a role.
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How to keep our lights on
Outline of the talk

- The Fundamental Challenge in Power Systems
- The Concept of Synchronized and Democratized (SYNDEM) Smart Grid
  - Rule of Law
  - Legal Equality
- Enabling Technologies — Virtual Synchronous Machines
- SYNDEM Grid Architecture
- Summary
The fundamental challenge

Future power systems will be power electronics-based, instead of electric machines-based, with a huge number of non-synchronous incompatible players.

- This is less of a power problem but more of a systems problem: it is not about connecting one or two converters but about connecting millions without causing problems.
- We can no longer rely on communication networks
  - Reliability - April 1, 2019: Aerodata failure caused 3000 flights delays/cancellations
  - Cybersecurity - June 27, 2019: U.S. Senate passed a bill to protect our grid from cyberattacks
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How are we going to operate power systems with millions of converters?
We need to better understand the root cause -

The democratization of power systems.
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Democracy

Democracy is a political concept that empowers all eligible individuals to play an equal role in decision making.

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Two recent examples

2016 UK Brexit Referendum

Leave
17,410,742 Votes
(51.9%)

Remain
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2016 UK Brexit Referendum

- **Leave**: 17,410,742 Votes (51.9%)
- **Remain**: 16,141,241 Votes (48.1%)

2016 US Presidential Election

- **Hillary Clinton**: 62,523,126 votes (48%)
- **Donald Trump**: 61,201,031 votes (47%)
- **Others**: (5%)
This is not acceptable for power systems.

A power system has to maintain the stability of system frequency and voltage.
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A power system has to maintain the stability of system frequency and voltage.
The concept of SYNDEM

It is not enough just to democratize power systems; we also need all power system players to synchronize their actions for the same goal.

Synchronization and Democratization (SYNDEM)
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Synchronization and Democratization (SYNDEM)
Two important features:

- **Rule of law:** All players follow the same rule.
- **Legal equality:** All players are equal.
For a SYNDEM smart grid

- Rule of law:
  - Is there ONE simple mechanism for all power systems players to follow?
  - If yes, can this mechanism synchronize all the players?

- Legal equality:
  - There are many different players in a power system.
  - Is it possible for new add-ons of generators to play an equal role in regulating system stability?
  - Is it possible for most loads to play the same role too?
  - If yes, can we equalize all players regardless of size and capacity?
What rule has underpinned the operation and growth of power systems for over 100 years?
The generation of electricity is dominated by synchronous machines.
Why synchronous machines (SMs)?

- Synchronous machines have an intrinsic property, i.e., the synchronization mechanism.
- Synchronous machines can synchronize with each other or the grid, autonomously.

It is this intrinsic synchronization mechanism that has underpinned the operation and growth of power systems for over 100 years.
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The synchronization mechanism of SM.
Now, let’s look at the legal equality.
New add-ons of generation

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

Is there anything in common?
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Is there anything in common?
Power electronic inverters: Common devices for smart grid integration

Can we equip inverters with the synchronization mechanism of SM?
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Can we equip inverters with the synchronization mechanism of SM?
Yes!
Virtual Synchronous Machines (VSM)

That is to operate power converters to have the internal dynamics and external properties of SMs.

- **1st Generation:** Synchronverters
  - Basic, conceptual implementation
  - For converters with inductive impedance
  - Number of key control parameters: 4

- **2nd Generation:** Universal droop controller
  - Universal for inverters with different types of impedances
  - Robust against parameter shifts, component mismatches etc.
  - Number of key control parameters: 3

- **3rd Generation:** Cybersync machines
  - Guaranteed passivity (stability)
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1G VSM: Synchronverters

- Take the mathematical model of a synchronous generator as the core of the controller for a converter.
- Convert 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 $e$.
- Feed back the phase current $i$ to the mathematical model as the stator current.
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The complete controller of a synchronverter

From the power part

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

PWM generation

From the power part

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
So, all generators can be harmonized with the intrinsic synchronization mechanism and equally take part in grid regulation.

How about the loads?
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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
- ...

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Is there anything in common?
Most 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 LED lights.

If these loads (rectifiers) are made to behave like synchronous motors, then most loads will have the synchronization mechanism we need.
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If these loads (*rectifiers*) are made to behave like synchronous motors then most loads will have the *synchronization* mechanism we need.
Running rectifiers as synchronous motors

\[ V_o \]

\[ V_{ref} \]

\[ K_p + \frac{K_i}{s} \]

\[ T_m \]

\[ \frac{1}{J_s} \]

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

\[ \dot{\theta} \]

\[ \theta \]

\[ \theta_c \]

\[ D_p \]

\[ STA \]

\[ e \]

\[ Q \]

\[ Q_{ref} \]

\[ -\frac{1}{K_s} \]

\[ M_{fi} \]

\[ i \]

\[ v \]

Formulas of \( T_e, Q \) and \( e \)

Angular frequency

Reset
So, we have achieved legal equality!

- Whether conventional or new add-on generators
- Whether generators or loads
- Whether large or small

They can all behave like (virtual) SM and follow the same rule of law: the synchronization mechanism.
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The SYNDEM architecture for next-generation smart grids
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- Fossil Fuel Plants
- Nuclear Plants
- Hydro-Electric Plants
- Industrial Power Plants
- Wind Farms
- Solar Farms
- Motors
- Lighting
- Electronic Apparatus
- Electric Vehicles
- Energy Storage

Transmission and Distribution

Q.-C. Zhong (Illinois Tech, zhongqc@ieee.org) NSF Workshop on Power Electronics-Enabled Operation of Power Systems 34/45
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- It harmonizes the grid integration of renewable energy sources, contributing to sustainability.
SYNDEME grids are scalable

- Home grids
- Neighborhood grids
- Community grids
- District grids
- Regional grids
SYNDEM home grid

Wind Power

Solar Power

VSM

VSM

VSM

VSM

VSM

VSM

VSM

VSM

Lighting

Electronic Apparatus

Refrigerator

Washing Machine
SYNDEM neighborhood grid
SYNDEM community grid

Energy Bridge

Energy Bridge

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SYNDEM district grid

Energy Bridge

Energy Bridge
SYNDEM regional grid
Some latest developments

- Self-synchronization without a phase-locked loop (PLL)
- Mathematically proven why we can get rid of PLLs
- Characterized the stability region of synchronverters
- Developed a strategy to limit currents at all time, even under grid faults
- ...

Q.-C. Zhong (Illinois Tech, zhongqc@ieee.org) NSF Workshop on Power Electronics-Enabled Operation of Power Systems 42/45
Future power systems will be power electronics based, instead of electrical machines based, with a huge number of non-synchronous players.

In order to guarantee stability, power systems players should be synchronized as well, leading to synchronized and democratized (SYNDEM) smart grids.

The synchronization mechanism of SM can continue to be adopted to synchronize non-synchronous players, via operating power electronic converters as VSM.

Three generations of VSM technologies:
- 1G: Synchronverters (basic, conceptual)
- 2G: Robust droop controllers (universal)
- 3G: Cybersync machines (passive)
Conclusions

The future is brighter than today -
Power systems can be harmonized!

Thank you very much.

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