Interoperability of Grid-Forming Controls for Inverter-Based Resources

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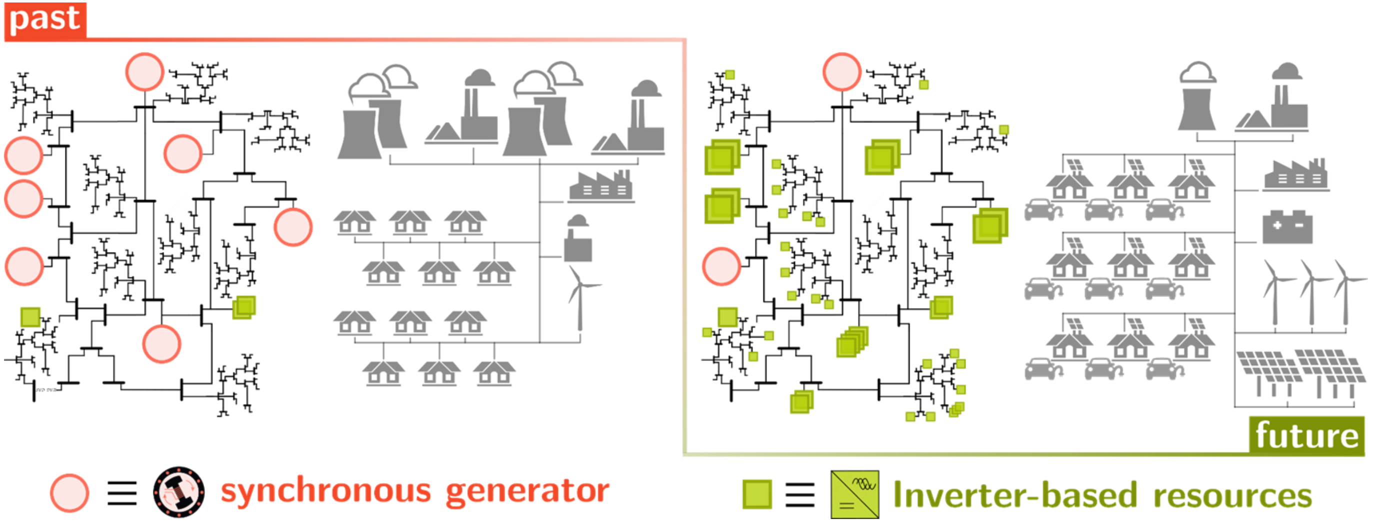
University of Minnesota

ALFRED P. SLOAN FOUNDATION



few generators

operation: taming physics

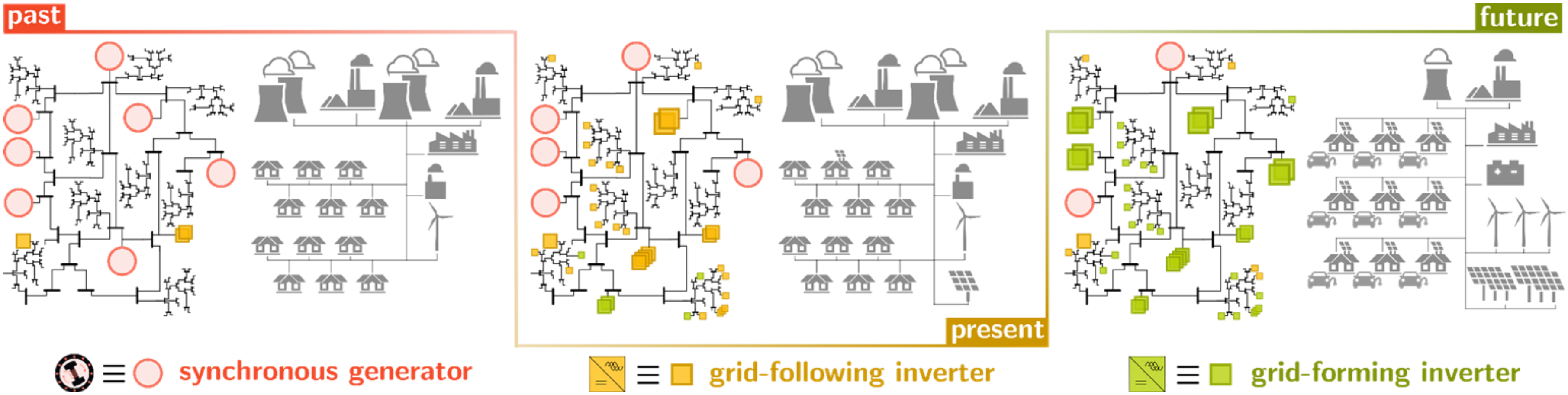
electric frequency: tied to (mechanical) speed of rotation

uncountable inverters

operation: imposing physics

electric frequency: tied to (digital) control methods

Grid-forming Technology



NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

GFM control for IBRs maintains an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid.

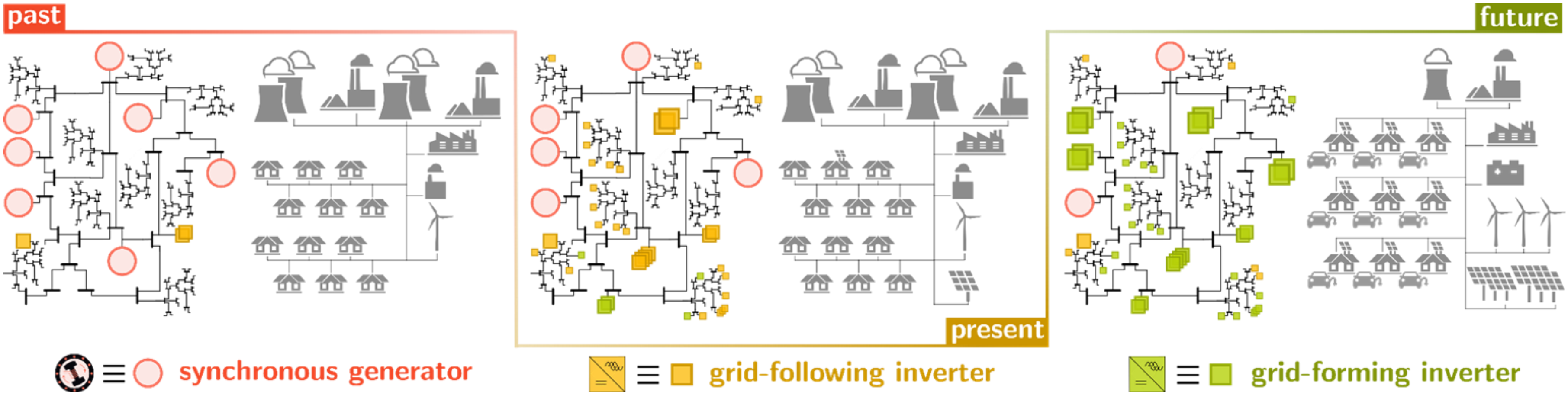
OSMOSE
OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

A grid forming unit shall, within its rated power and current, be capable of self-synchronise, stand alone and provide synchronisation services, which includes synchronising power, system strength, fault current and inertial response.

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

A grid-forming (GFM) inverter maintains a constant internal voltage phasor in a short time frame, with magnitude and frequency set locally by the inverter, thereby allowing immediate response to a change in the external grid. On a longer timescale, the internal voltage phasor may vary to achieve desired performance.

Grid-forming Technology



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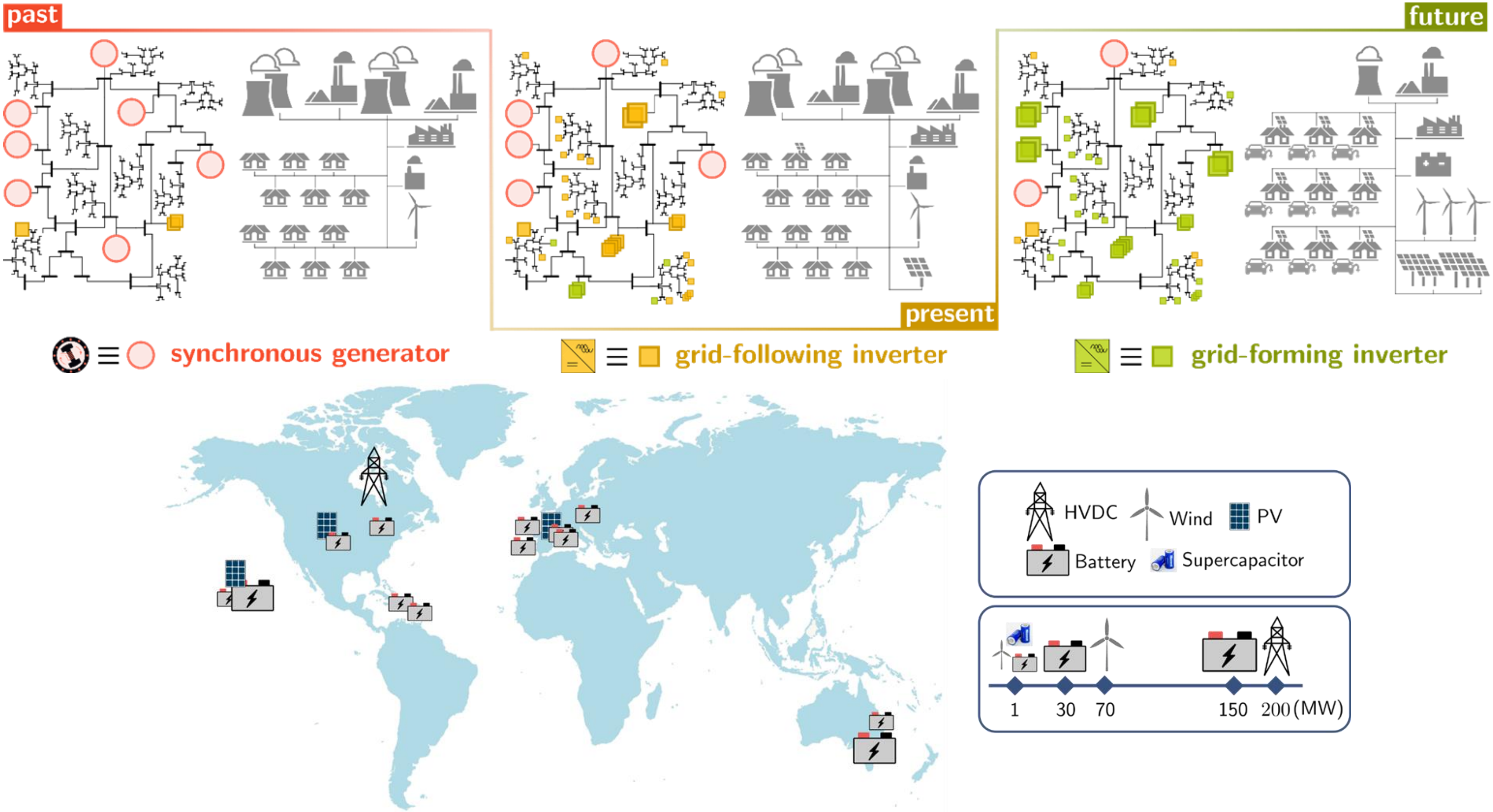
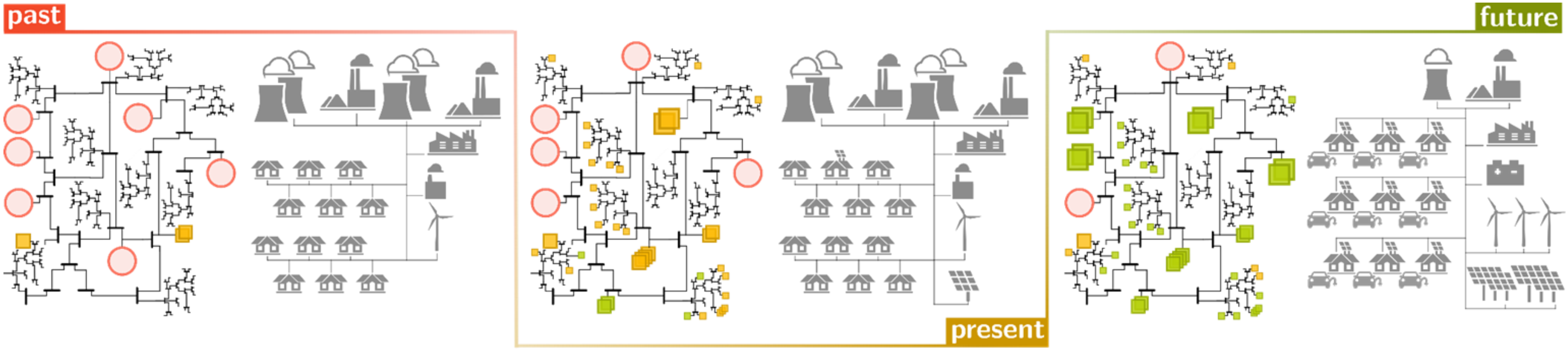
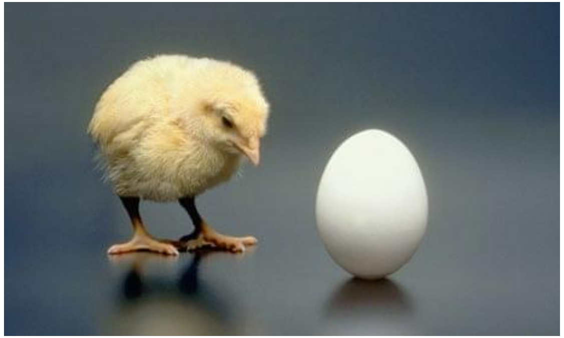


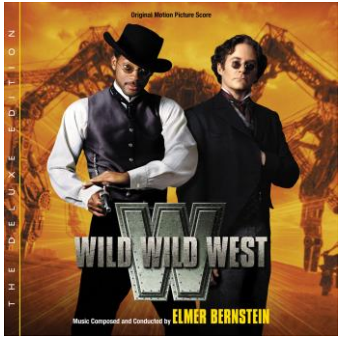
Grid-forming Technology



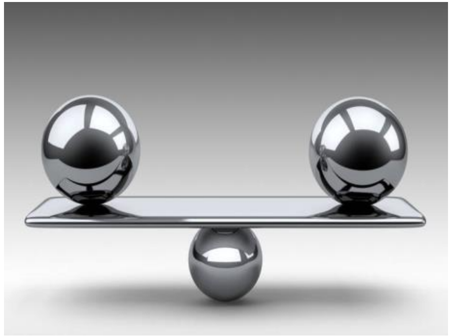
≡ synchronous generator ≡ grid-following inverter ≡ grid-forming inverter



do we anticipate problems
or go with the norm



limited guidelines
on performance



system is apparently
robust yet fragile

Interoperability

interoperability. The ability of two or more systems or components to exchange information and to use the information that has been exchanged. *See also:* **compatibility.** [610.12]

IEEE Standard Computer Dictionary

A Compilation of IEEE Standard Computer Glossaries

610

Sponsor

Standards Coordinating Committee of the IEEE Computer Society

Abstract: *IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*, identifies terms currently in use in the computer field. Standard definitions for those terms are established.
Keywords: Glossary; terminology; definitions; dictionary.

Library of Congress Catalog Number 90-086306

ISBN 1-55937-079-3

The Institute of Electrical and Electronics Engineers
345 East 47th Street, New York, NY 10017, USA

Pop quiz

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> 20,000 members

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NFC and Bluetooth are both relatively short-range communication technologies on mobile phones. NFC operates at slower speeds, has a shorter range, consumes far less power, and doesn't require pairing.
> 120 members

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S.W.I.F.T. executes financial transactions & payments between banks. Its principal function is to serve as the main messaging network through which international payments are initiated.

> 11,000 institutions

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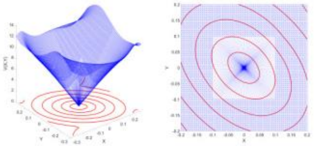
> 11,000 institutions

Qi is the interface standard for wireless power transfer using inductive charging. Allows compatible devices, such as smartphones, to charge their batteries over distances up to four cm.
> 600 members

Outline

- A suite of grid-forming inverter technology attributes that are related to interoperability.



tractability

scalability

- A journey through time covering a few key interoperable architectures, principles, and algorithms.

tipping points have driven (will drive) change

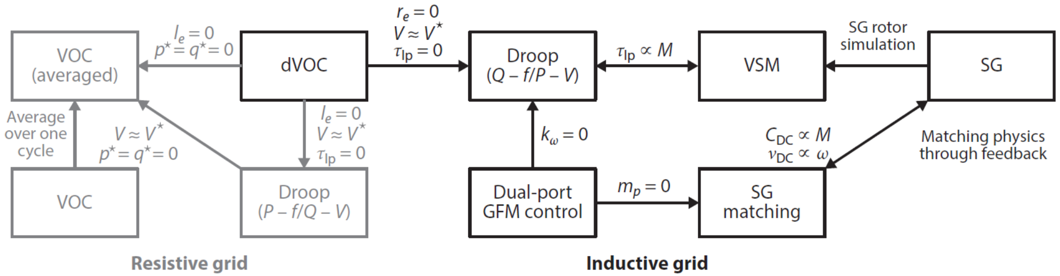
science follows(ed) engineering

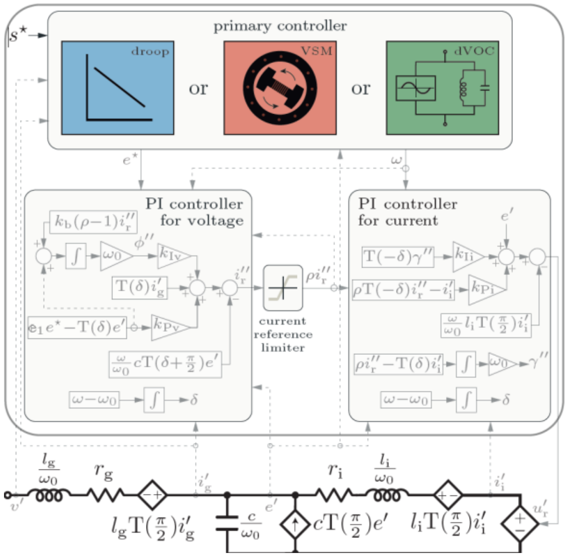
solutions appear (are) determinative

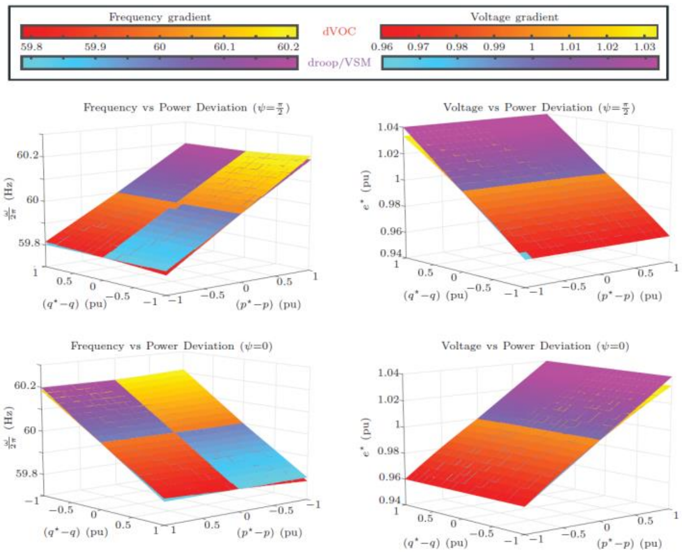
- The path forward in guaranteeing interoperability with grid-forming inverter technology.

1. Equivalence of primary control & implications

A variety of primary-control types have been proven to possess similar performance attributes in sinusoidal steady state.

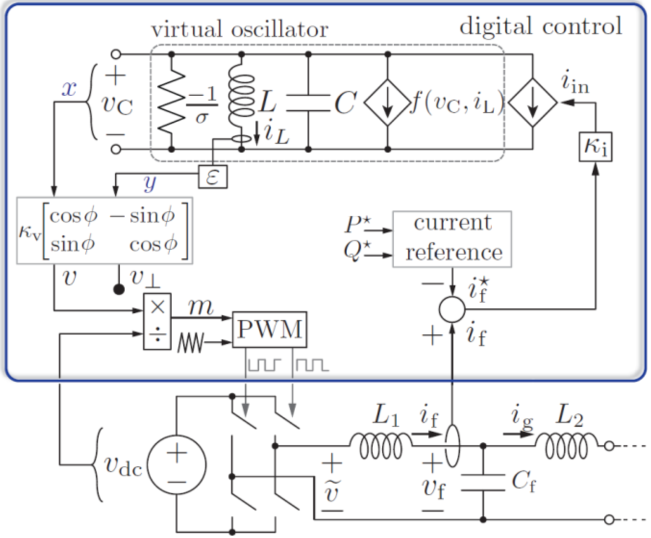


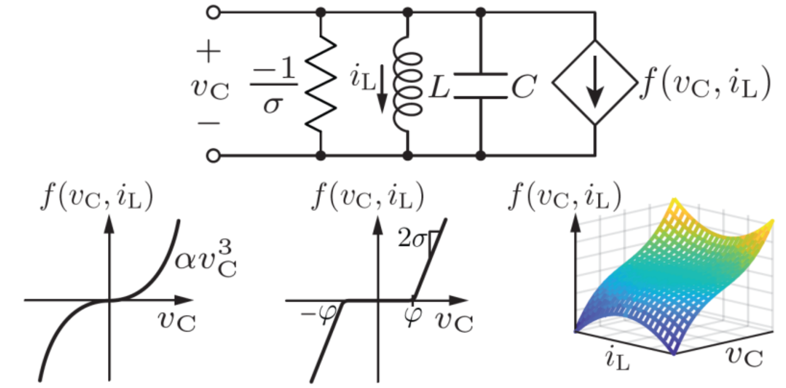




- Interconnected networks of GFM IBRs with different primary-control types synchronize frequency.
- Power sharing (real power in inductive networks, reactive power in resistive networks) can be ensured by matching (equivalent) droop slopes.
- Tracking references is equivalent to frequency restoration to nominal.

1. Equivalence of primary control: a deeper dive into VOC

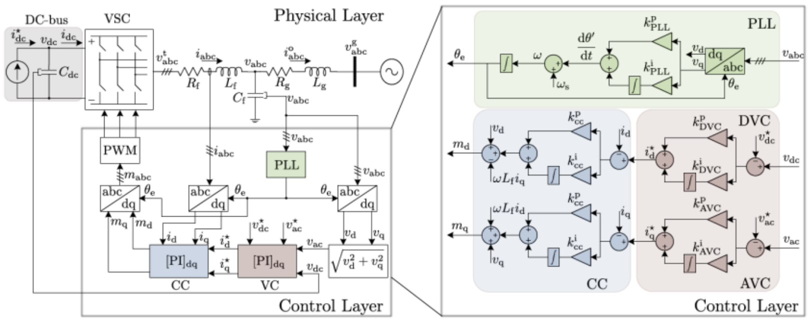




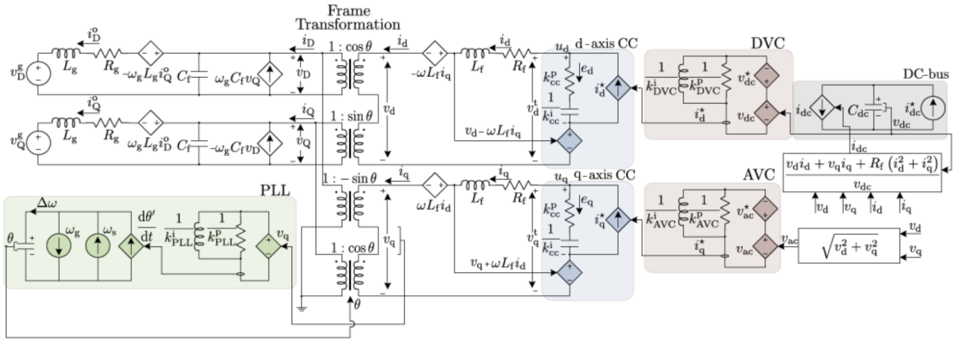
(a) Van der Pol (b) Dead-zone (c) Andronov-Hopf

- Guarantee on local asymptotic stability of sinusoidal orbits for a wide class of nonlinear oscillators.
- Analytically characterize steady-state amplitude, frequency, rise time, and harmonic content in waveforms.

2. Countering complexity with the familiarity of circuits

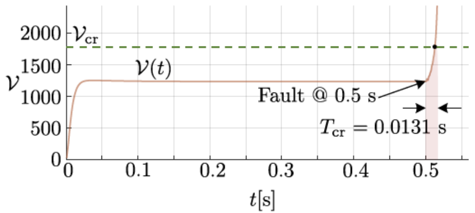


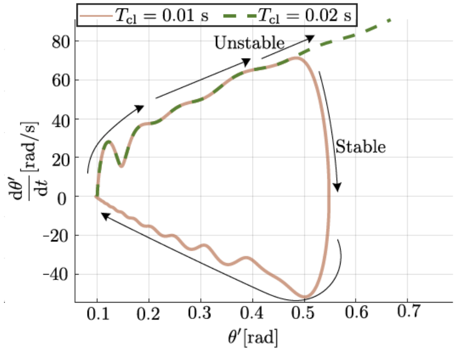
Grid-following IBR.



Equivalent-circuit representation.

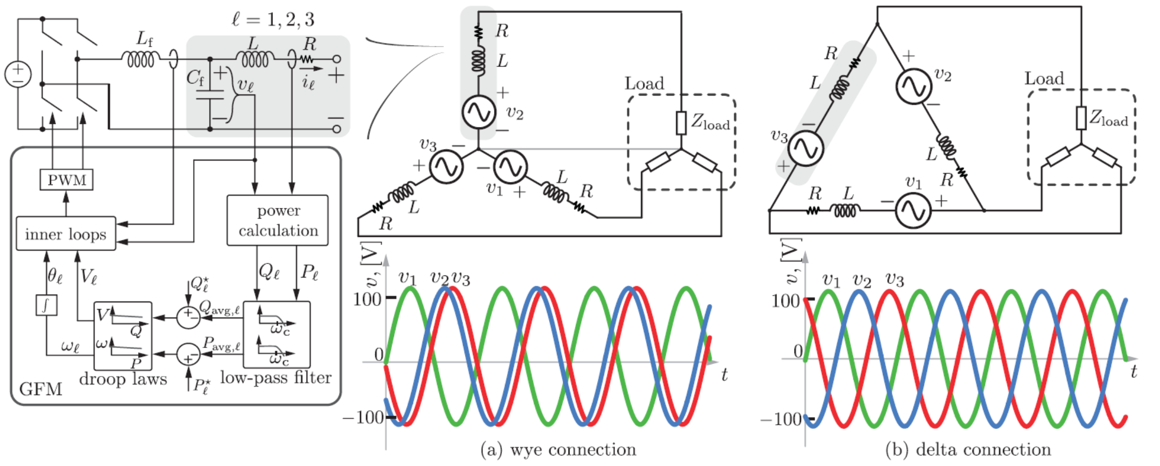
- Leverage familiar elements (resistors, inductors, capacitors, transformers, dependent elements) to cast control and physical layer-dynamics as equivalent circuits.
- Orders-of-magnitude decrease in simulation time with comparable accuracy for large networks with COTS circuit simulator tools.
- Large-signal stability analysis improves estimates of performance indices over reduced-order models (5% vs. 35%).



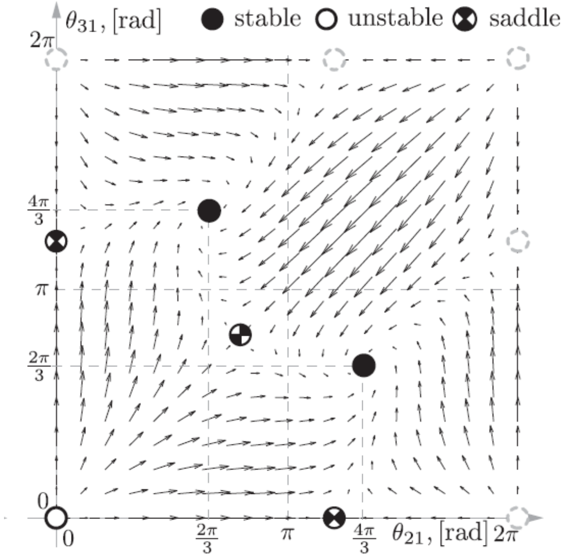


Analytical characterization of clearing time reveals results comparable to repeated simulations.

3. Resilient grids from the bottom up



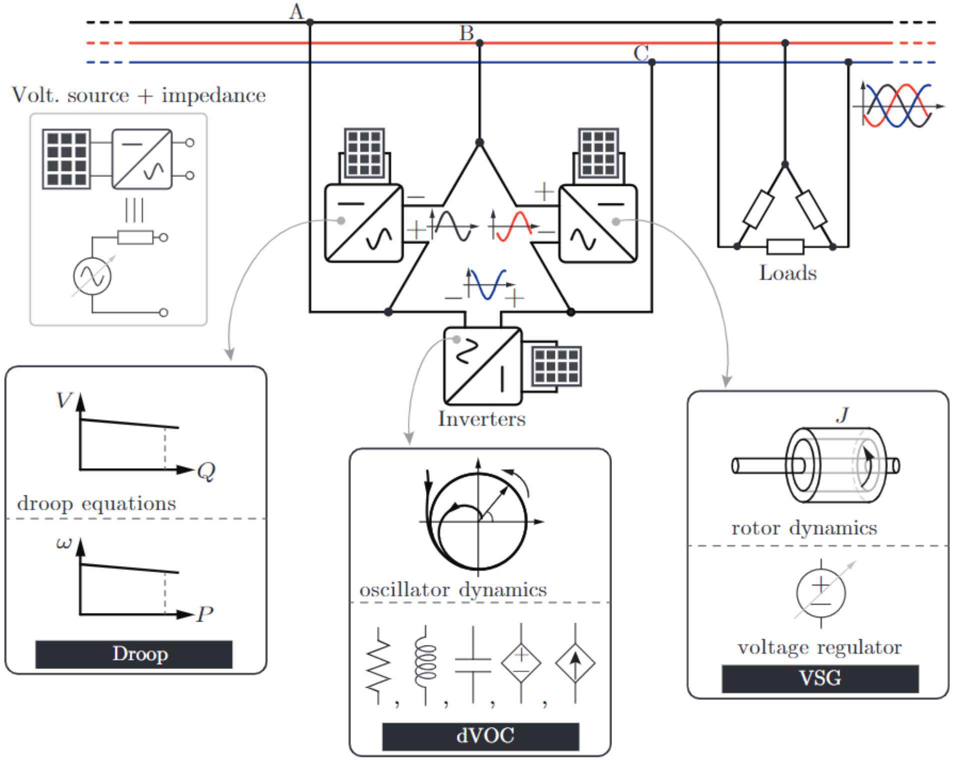
Single-phase GFM inverters in (a) wye, and (b) delta configuration across a balanced wye-connected load. For the delta-interconnection of inverters, we readily obtain phase-balanced voltages.

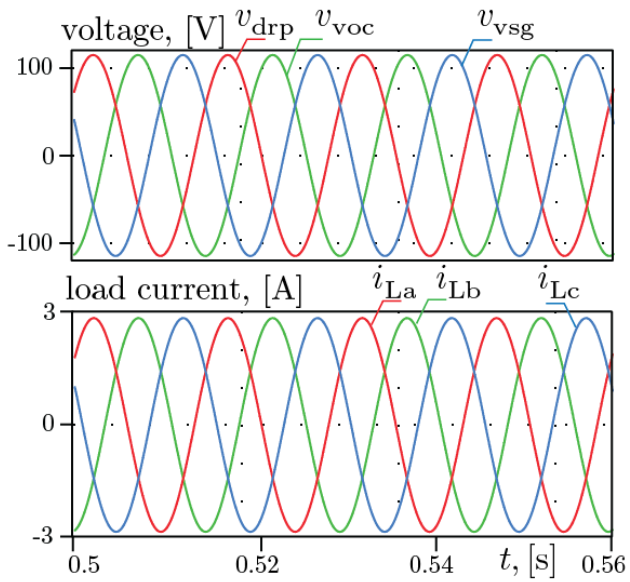


Stable equilibria, saddle points, and unstable equilibria are on offer for phase-difference dynamics. Stable equilibria correspond to phase-balanced condition.

- Single-phase GFMs exhibit phase-balanced operation in certain three-phase interconnections with no external communication.
- Complex networks with transformers, multiple parallel-connected inverters, inverters with different primary control exhibit similar behavior.

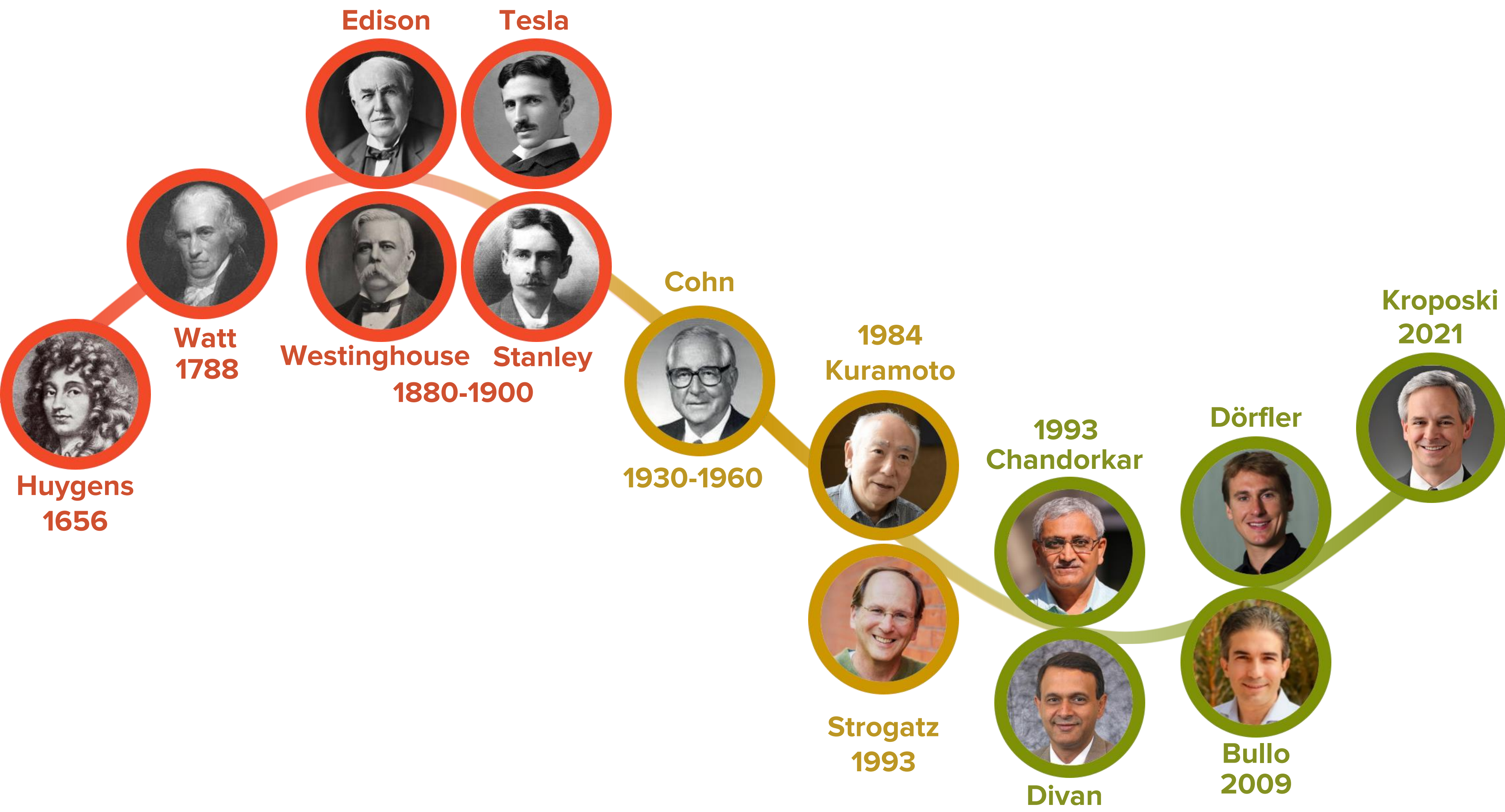
3. Resilient grids from the bottom up





Phase-balanced behavior emerges in spite of heterogenous primary controls.

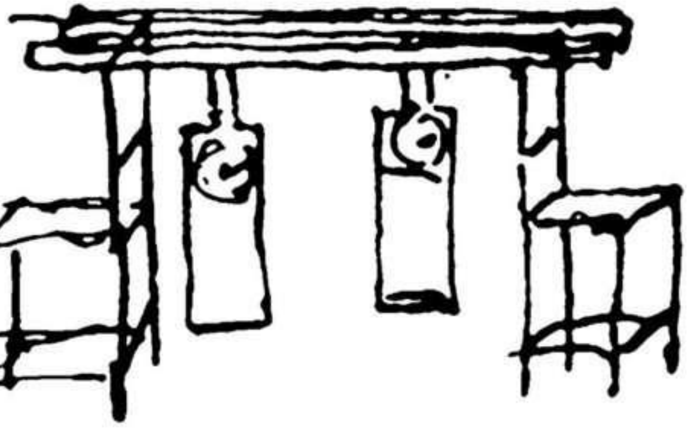
Single-phase GFM inverters with different primary controls in a delta configuration connected across a balanced delta-connected load.


Edison
Tesla
Watt
1788
Westinghouse
Stanley
1880-1900
Huygens
1656
Cohn
1930-1960
1984
Kuramoto
1993
Chandorkar
Dörfler
Kroposki
2021
Strogatz
1993
Divan
Bullo
2009

Spontaneous synchronization in inanimate objects

Huygens
1665

"an odd sympathy"



- Conceived pendulum clock in 1665 (for expeditions)
- Contraption involved a set of two (for redundancy)
- (while sick) Noticed synchronization over half hour

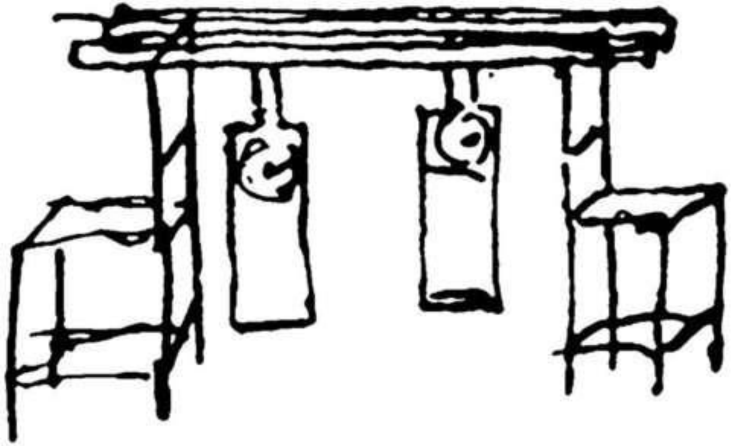
The mechanical governor

- Adopted fly-ball governor in 1788 to steam engines
- Underlies operation of synchronous generators today

Watt
1788

Huygens
1665

“an odd sympathy”



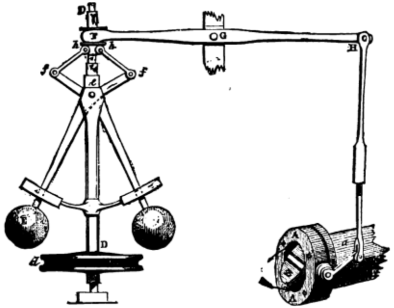
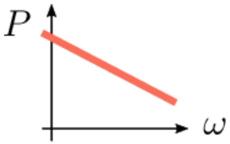


FIG. 4.—*Governor and Throttle-Valve.*



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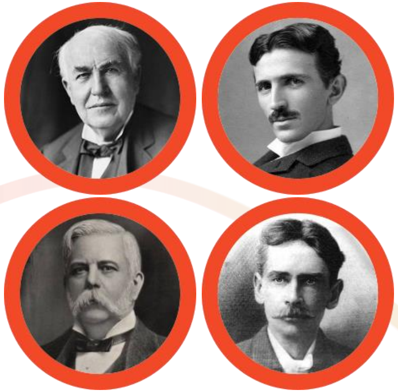
Ac Dc

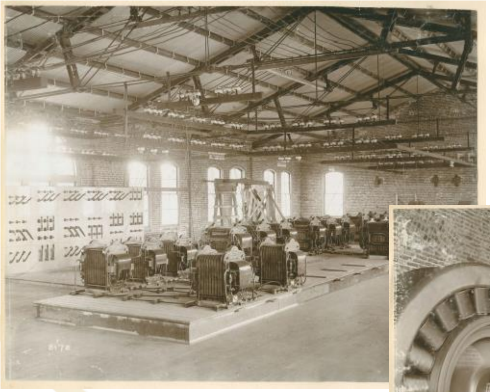
Edison Tesla

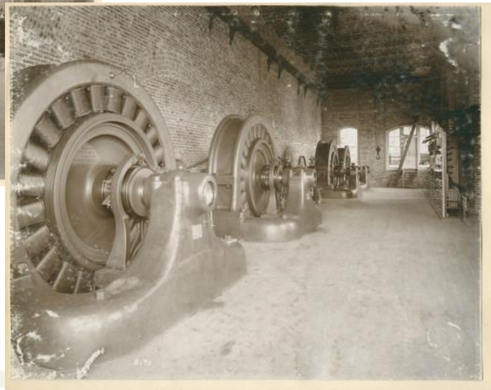


Westinghouse Stanley

1880-1900

- Big-bang moment in the history of electrification
- Suite of technologies that permitted the efficient transmission and delivery of electricity
- Contributions of Stanley
  - 1885: built first practical transformer
  - 1886: demonstrated first complete system of high voltage ac transmission: generators, transformers and high-voltage transmission lines.
  - 1890: founded Stanley Electric Manufacturing Company in MA
  - 1903: bought out by GE

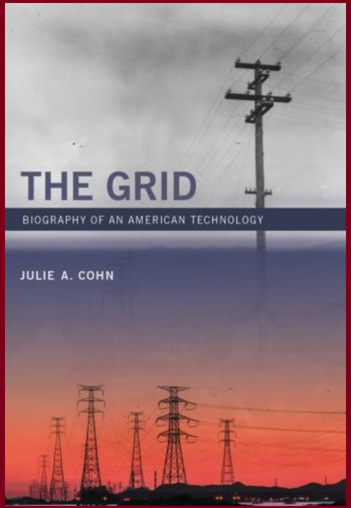




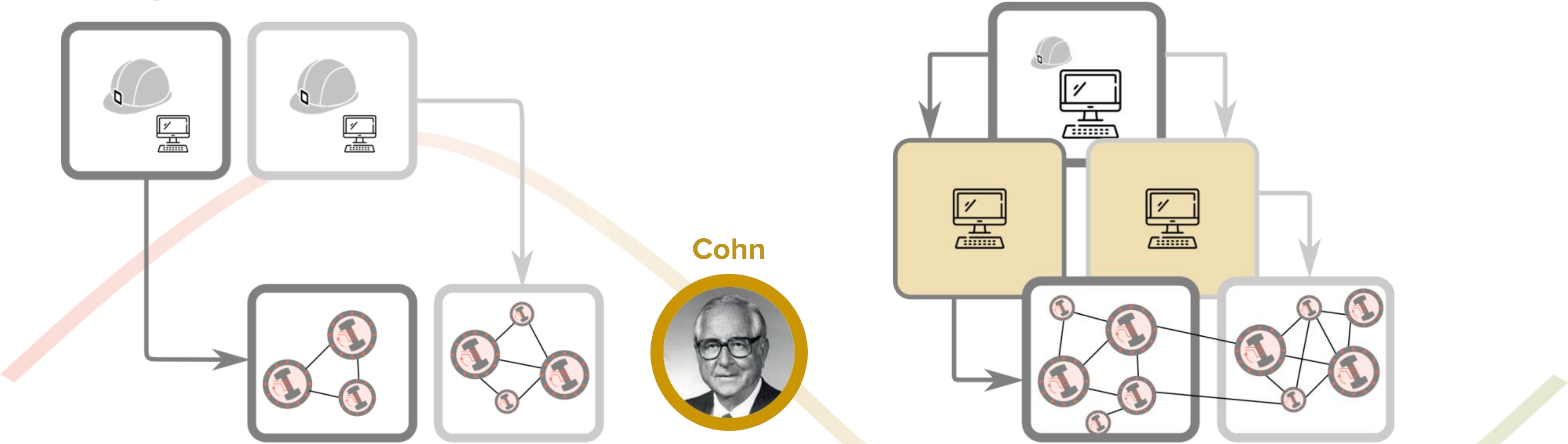
It all worked … but no one knew why

Joint meeting of Institution of Electrical Engineers
& American Institute of Electrical Engineers
(St. Louis, 9/14/1904)

"Notably, the attendees at the St. Louis meeting displayed a great deal of curiosity about the experiences of presenters who had operated stations in parallel—a requisite of interconnection."



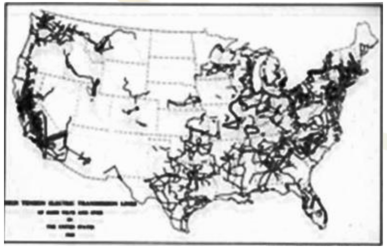
Scaling delivery with distributed control



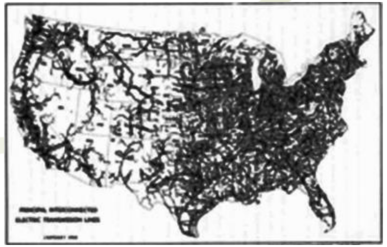
1908

1918

1940

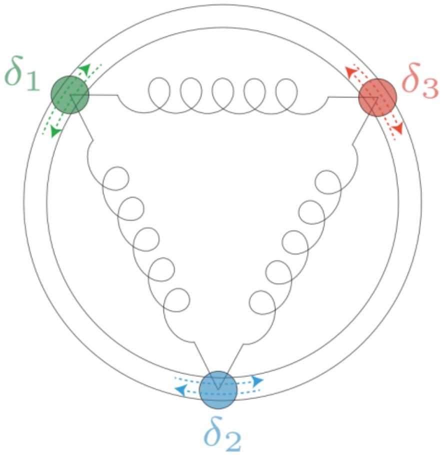


1960



- Sandwiched distributed control architecture to control flows across utilities and regulate frequency over networks
- Interoperable architecture that balanced economy and reliability
- Enabled interconnections to spread over vast scales in a short period of time

The science behind synchronization



$$\dot{\delta}_i = \omega_i - \omega_0 - \sum_{j=1}^{n} a_{ij} \sin(\delta_i - \delta_j), \quad i \in \{1, 2, \dots, n\}$$

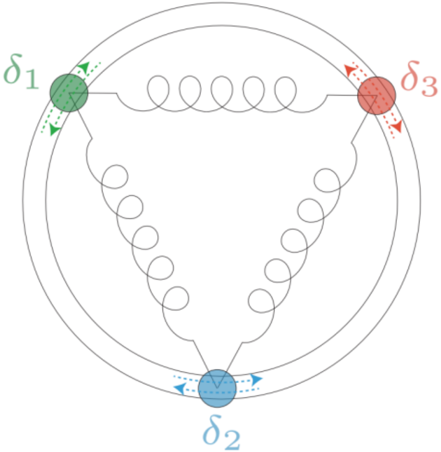


- General dynamical-system model with diverse applications
- Significant interest in conditions that guarantee phase and frequency synchronization

1984
Kuramoto

Strogatz
1993

Why do generators synchronize?



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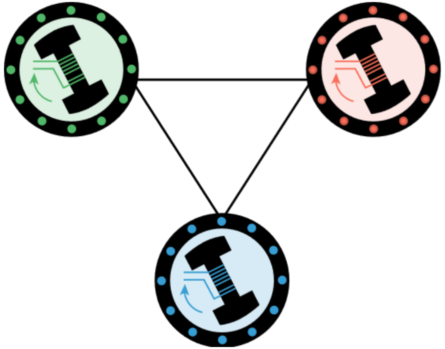

- Aligned dynamics of networks of generators with those of Kuromoto oscillators
- Established conditions for synchronization and stability

$$\dot{\delta}_i = \omega_i - \omega_0 - \sum_{j=1}^{n} a_{ij} \sin(\delta_i - \delta_j), \quad i \in \{1, 2, \ldots, n\}$$



Dörfler

Bullo
2009

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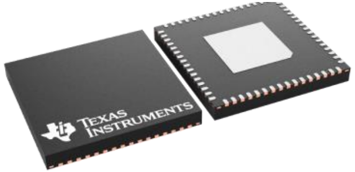
- Significant interest in conditions that guarantee phase and frequency synchronization

Governors: mechanical to software

future

software governors that mimic age-old
mechanical solution for inverters



mechanical governors regulate power delivery based on
observed speed of rotation / electrical frequency

1993
Chandorkar

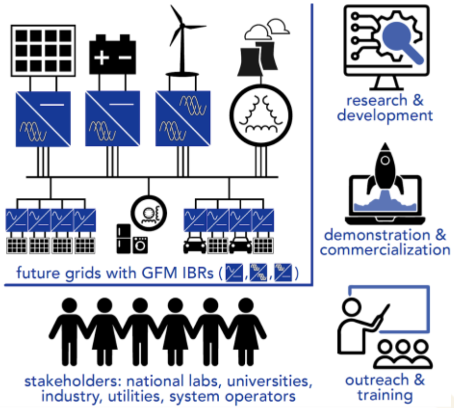
Divan

past

Driving industry forward

unifi consortium

universal interoperability for grid-forming inverters



Kroposki 2021