Sending information with converters

Josh Taylor

New Jersey Institute of Technology

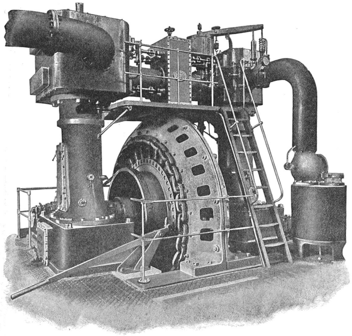
Synchronous machines

Behavior is dominated by physics:

- inertia

$$J\ddot{\theta} = P_{\text{in}} - P_{\text{out}}$$

- speed governor, power system stabilizer
- automatic voltage regulator.

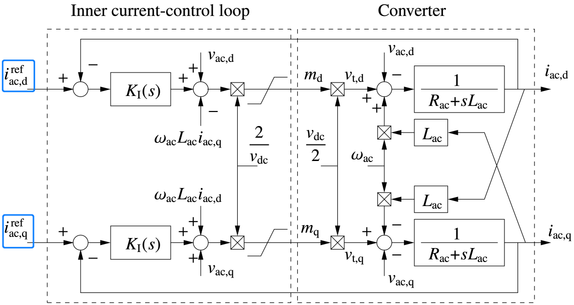


Less ‘room’ to send signals through controllers.

Voltage source converters

Behavior is dominated by controlled switching:

- inner current control
- outer voltage/power control
- more natural to send signals by perturbing controller references.



VSC current controller (Milano and Manjavacas 2019)

Comparison with power-line communications

Power-line communications—conventional transmitter/receiver sends bits through transmission line.[1]

This talk:

- Info is state of the system.
- Transmitter/receiver depends on application. (I think.)
- No new hardware.

[1] Stefano Galli, Anna Scaglione, and Zhifang Wang. "For the grid and through the grid: The role of power line communications in the smart grid". In: *Proceedings of the IEEE* 99.6 (2011), pp. 998–1027.

Applications

- **Fault protection**
- **Decentralized control**
- Unintentional islanding—distributed generator accidentally disconnects from main grid[2]
- Cybersecurity—watermarking.[3]

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[2] Houshang Karimi, Amirnaser Yazdani, and Reza Iravani. "Negative-sequence current injection for fast islanding detection of a distributed resource unit". In: *IEEE Transactions on power electronics* 23.1 (2008), pp. 298–307.

[3] Woo-Hyun Ko et al. "Robust Dynamic Watermarking for Cyber-Physical Security of Inverter-Based Resources in Power Distribution Systems". In: *IEEE Transactions on Industrial Electronics* (2023).

Fault protection

Faults—unintentional short circuits, e.g., due to tree or lightning.

In conventional grids:

- Faults cause 20$\times$ increase in current.
- Simple(r) detection logic.

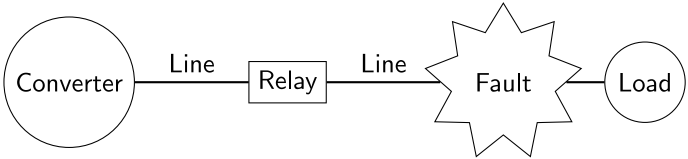
In a converter-based grid:

- Fault current as low as 5% higher than normal.
- Need more sensitive detection.

Source: `wildfiretoday.com`

Active detection

Converter adds perturbation to make faults more visible to relays.



- Harmonics[4]
- Negative sequence
  - Distance protection[5]
  - New IEEE standard[6]

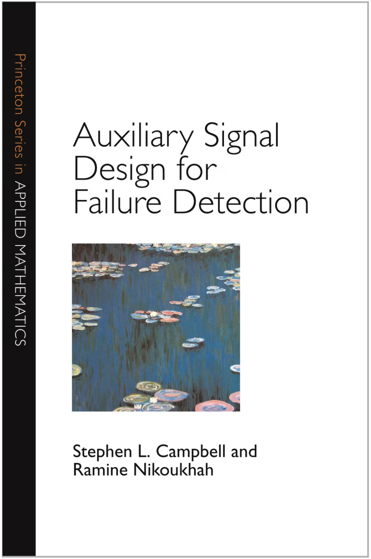
Controversial ideas … effective, but necessary?

[4] Saleh, Allam, and Mehrizi-Sani 2020.
[5] Banaiemoqadam, Hooshyar, and Azzouz 2020.
[6] *IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems* 2022.

Auxiliary signal design / active fault diagnosis

A classical problem in systems theory:

- Optimize *auxiliary signal* to ensure detection.
- Static and LTI systems.



Distance protection

Procedure:

- Relay measures voltage & current phasors.
- Computes effective impedance, Z.
- If Z is in zone of operation, switches open to clear fault.

Recent work:

- Duality-based procedure for auxiliary signals in static systems.[7]
    - Auxiliary signal = negative sequence current phasor.
- Time domain-based protection.[8]

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[7] J.A. Taylor and A.D. Dominguez-Garcia. "Auxiliary signal-based distance protection in inverter-dominated power systems". In: *European Control Conference*. Submitted. 2024.

[8] M. Pirani et al. "Optimal Active Fault Detection in Inverter-Based Grids". In: *Control Systems Technology, IEEE Transactions on* 31.3 (May 2023), pp. 1411–1417. DOI: 10.1109/TCST.2022.3207661.

Decentralized control

"... input has a *dual* purpose; communication through the system dynamics and sensors to the other controllers and direct control of the system."

—Sandell, Athans, Varaiya. *Survey of decentralized control methods for large scale systems.* IEEE T. Auto. Control (1978).

Frequency in power systems

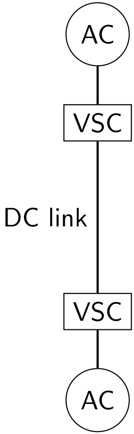
Frequency:

- $\omega < 60\text{Hz} \longrightarrow \text{load} > \text{generation}$.
- $\omega > 60\text{Hz} \longrightarrow \text{load} < \text{generation}$.

Droop:

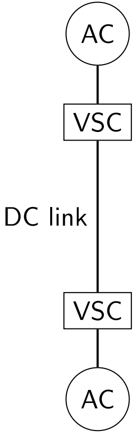
- Each generator observes ω locally,
- adjusts output to keep $\omega \approx 60Hz$.

AC/DC grids

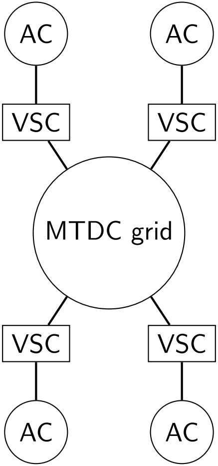


(a) Point-to-point

AC/DC grids

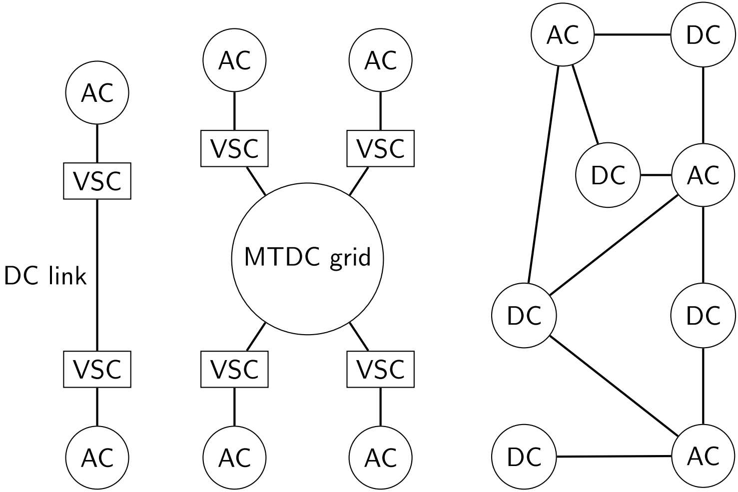


(a) Point-to-point



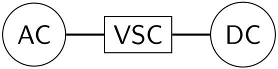
(b) MTDC grid

AC/DC grids



(a) Point-to-point (b) MTDC grid (c) Hybrid (VSCs not shown)

State decoupling



Modeling:

- $\dot{x} = f(x, u)$
- x: frequencies, currents, voltages
- u: VSC control input

Reasonable approximation:

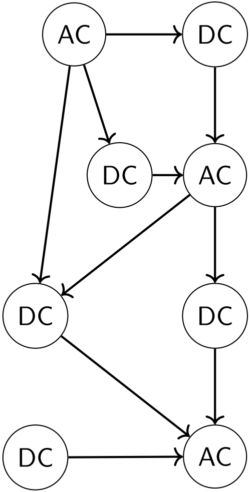
- AC and DC states only coupled by VSC controls
- In other words:
  - Electrical physics in AC & DC subgrids
  - Controllable current/power transfer across VSC.

Information structures

Information structure—which subsystems influence which?

Poset-causality[a][b]

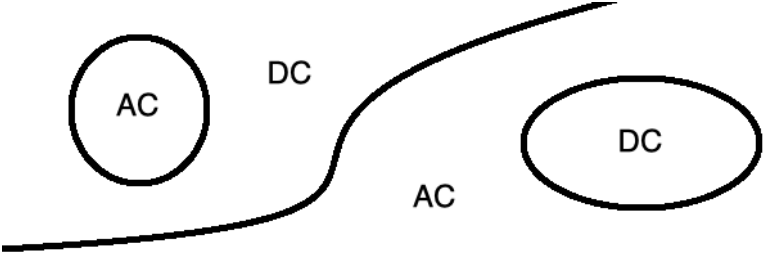
- 'Orient' converters to make directed acyclic graph
- Key to decentralized control.



[a] B. Vellaboyana and J.A. Taylor. "Optimal Decentralized Control of DC-Segmented Power Systems". In: *Automatic Control, IEEE Transactions on* 63.10 (Oct. 2018), pp. 3616–3622. DOI: 10.1109/TAC.2018.2796620.

[b] J.A. Taylor. "Information structures in AC/DC grids". In: (2023). Submitted. DOI: 10.48550/arXiv.2307.09922.

Controllable boundaries of converters



What are implications for:

- distributed and decentralized optimization and control
- pricing and markets
- sensor and communication infrastructure?

Questions

Is there value in thinking of converters in terms of information?

How to make best use of information capacity over multiple applications?

- Decentralized control
- Fault protection
- Cybersecurity
- Islanding detection