Advances in Grid-Forming Technology

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Acknowledgments

U.S. DEPARTMENT OF ENERGY

IOWA economic development

IOWA STATE UNIVERSITY
Electric Power Research Center

+ industry members

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Dr. Soummya Roy

Hoang P. Dang

Christopher Peralta

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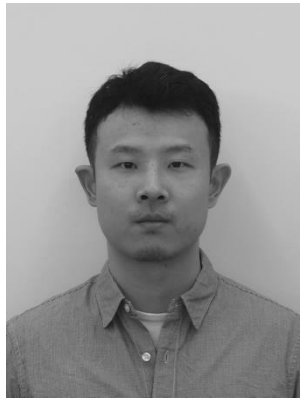

Zhenghan Zhang

Abdel M. Mannan

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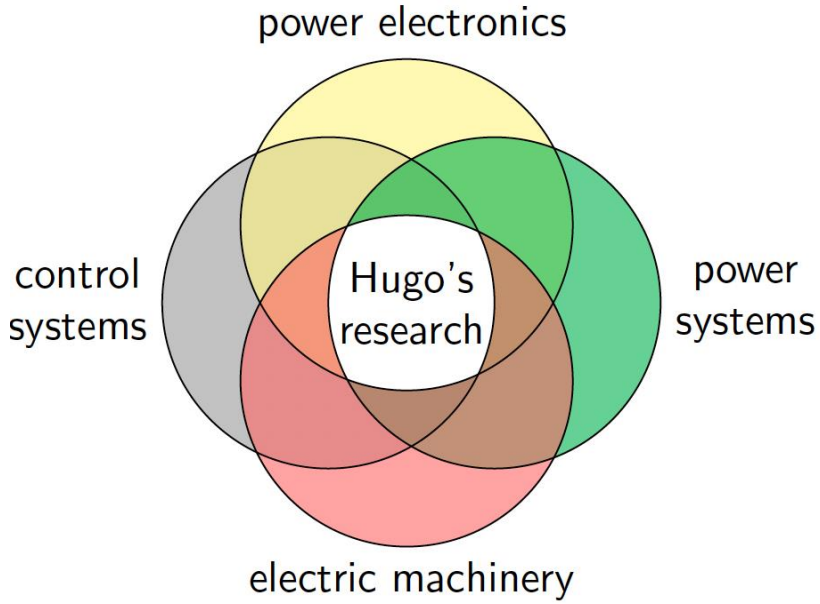
Hugo's Background

- Ph.D. ECE, Purdue University, West Lafayette, IN, 2016
- M.S. EE, Iowa State University, Ames, IA, 2011
- Supervisor of electrical maintenance, Ecuador, 2007–2009

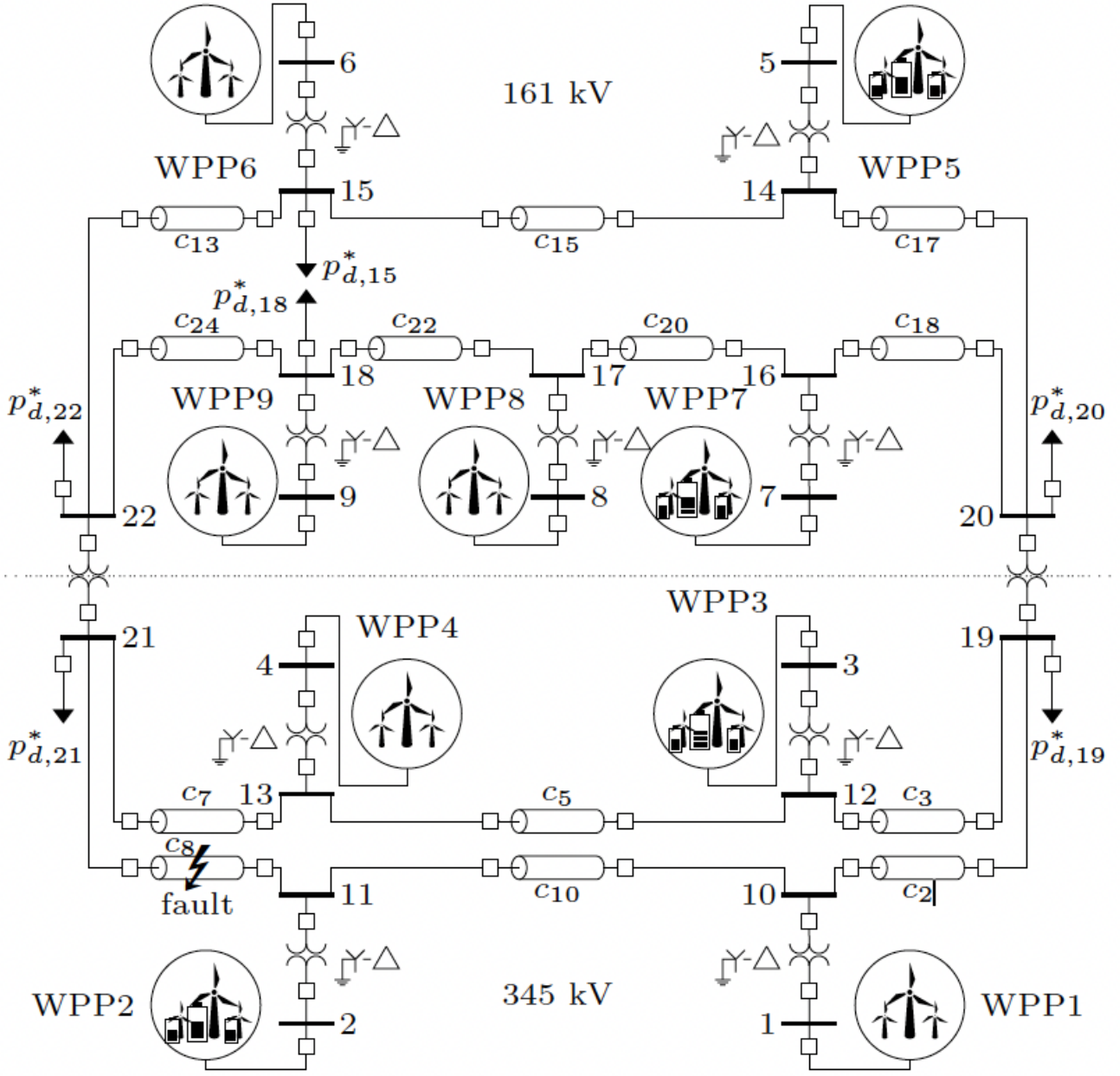


Key Problem at ISU

How to autonomously restore a wind-dominant power grid from a blackout?

Sequential energization of:

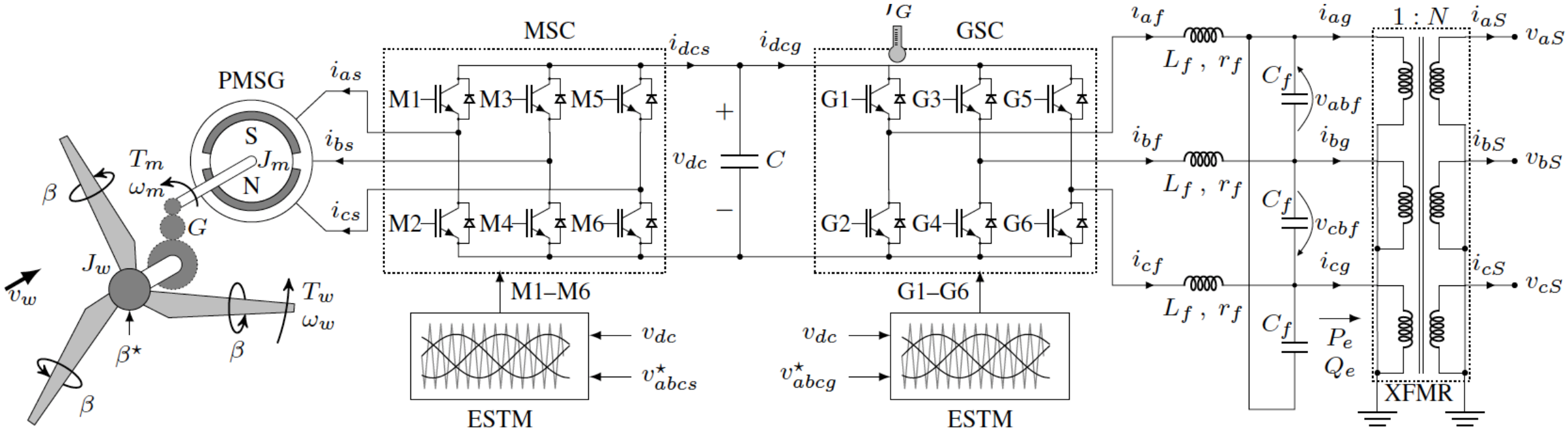
- Wind power plants (blackstart)
- Transformers
- Transmission lines
- Loads
- Meet constraints



H. P. Dang, Z. Zhang, and H. N. Villegas Pico, “Analysis of Electromagnetic Transients During the Automatic Restoration of Wind-Dominant Grids,” IEEE Trans. Sustain. Energy, vol. 16, no. 4, Oct. 2025.

Grid-Forming Technology: Type-4 Wind Turbines

GSC steers ac line-to-line voltages voltages: v_{abf} and v_{cbf}
MSC steers dc-link voltage: v_{dc}
Pitch angle β servos steers PMSG speed: ω_m
If GSC transfers more power than the wind turbine can harvest: PMSG speed and v_{dc} can collapse



H. N. Villegas Pico and Vahan Gevorgian, “Blackstart capability and survivability of wind turbines with fully rated converters,” IEEE Trans. Energy Convers., vol. 37, no. 4, pp. 2482–2497, Dec. 2022.

Grid-Forming Technology: Type-4 Wind Turbines

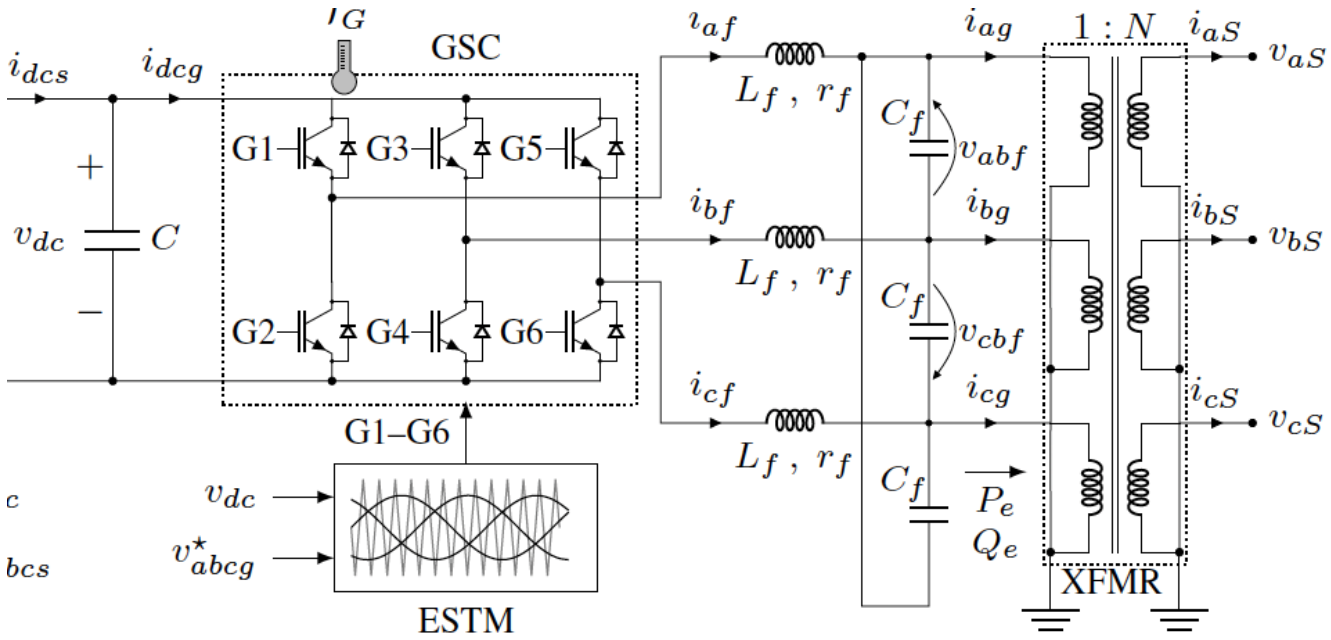
Advance: two-axis anti-windup PI regulators (series implementation)

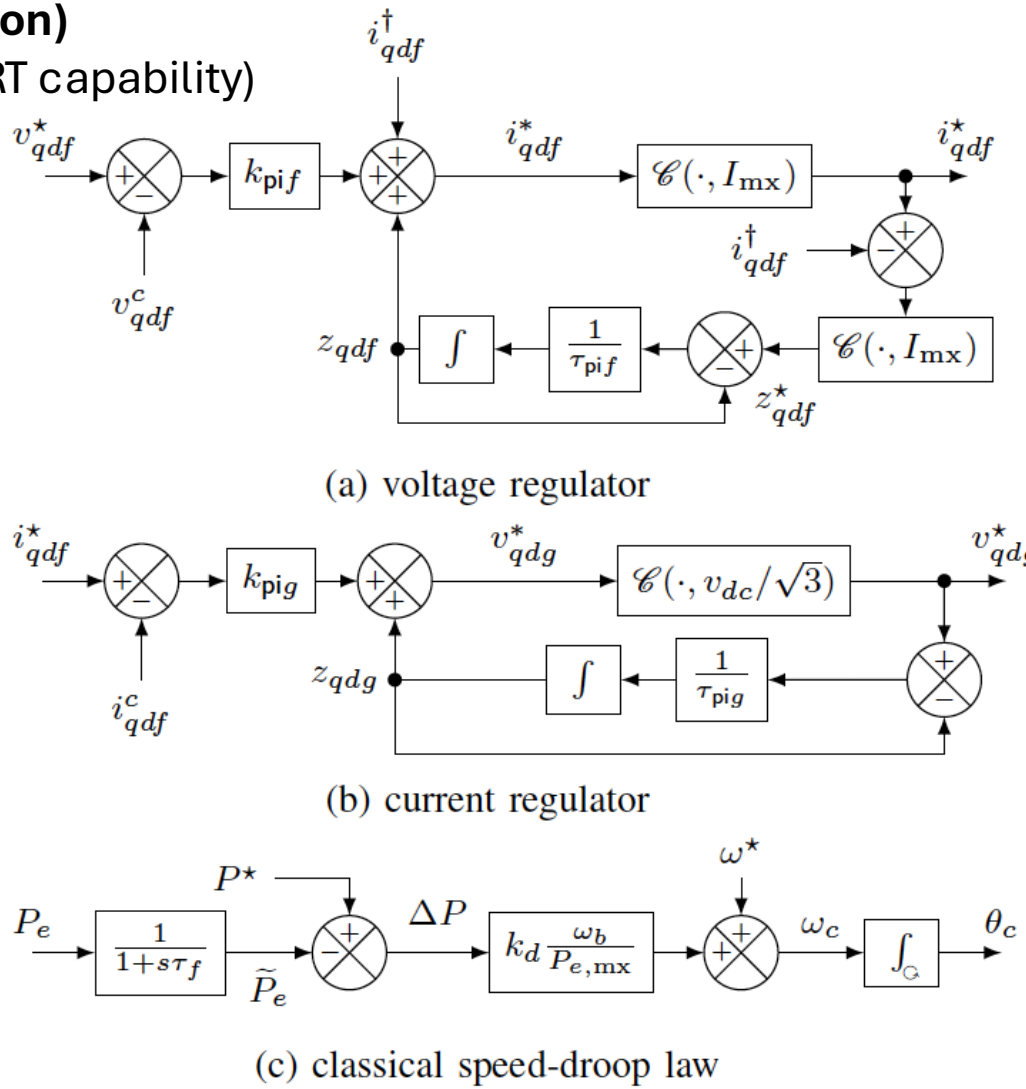
Regulate ac capacitor voltages by regulating GSC currents (built in FRT capability)

Reference frame angle/speed: θ_c, ω_c (droop law)

Voltages: $[v_{abf}, v_{bcf}] \overset{\theta_c}{\rightarrow} [v_{qf}^c, v_{df}^c]$

Currents: $[i_{af}, i_{bf}] \overset{\theta_c}{\rightarrow} [i_{qf}^c, i_{df}^c]$





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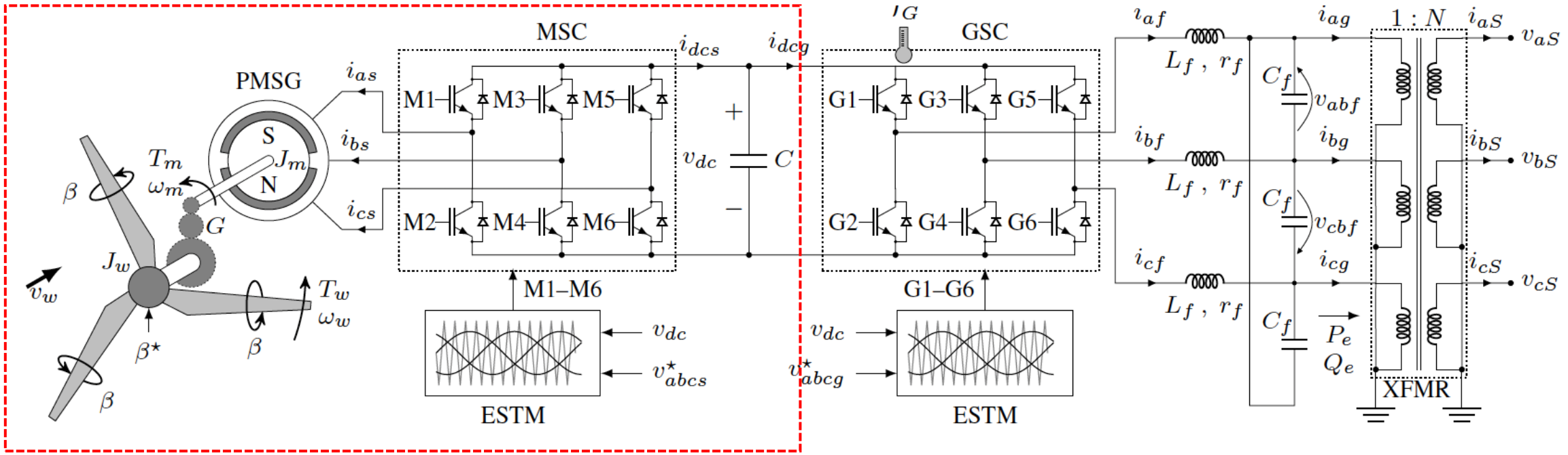
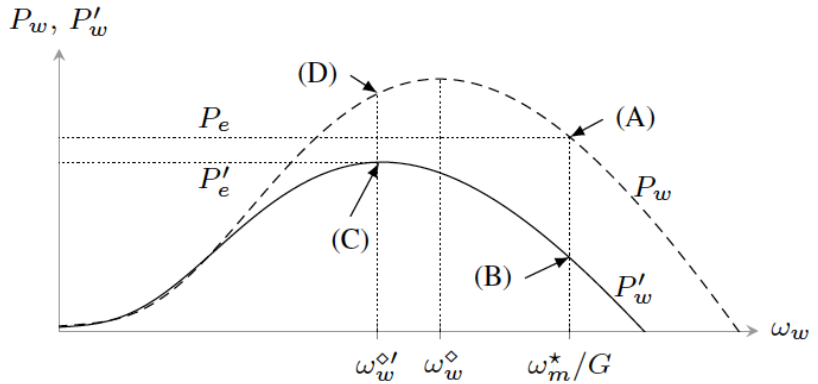
Grid-Forming Technology: Type-4 Wind Turbines



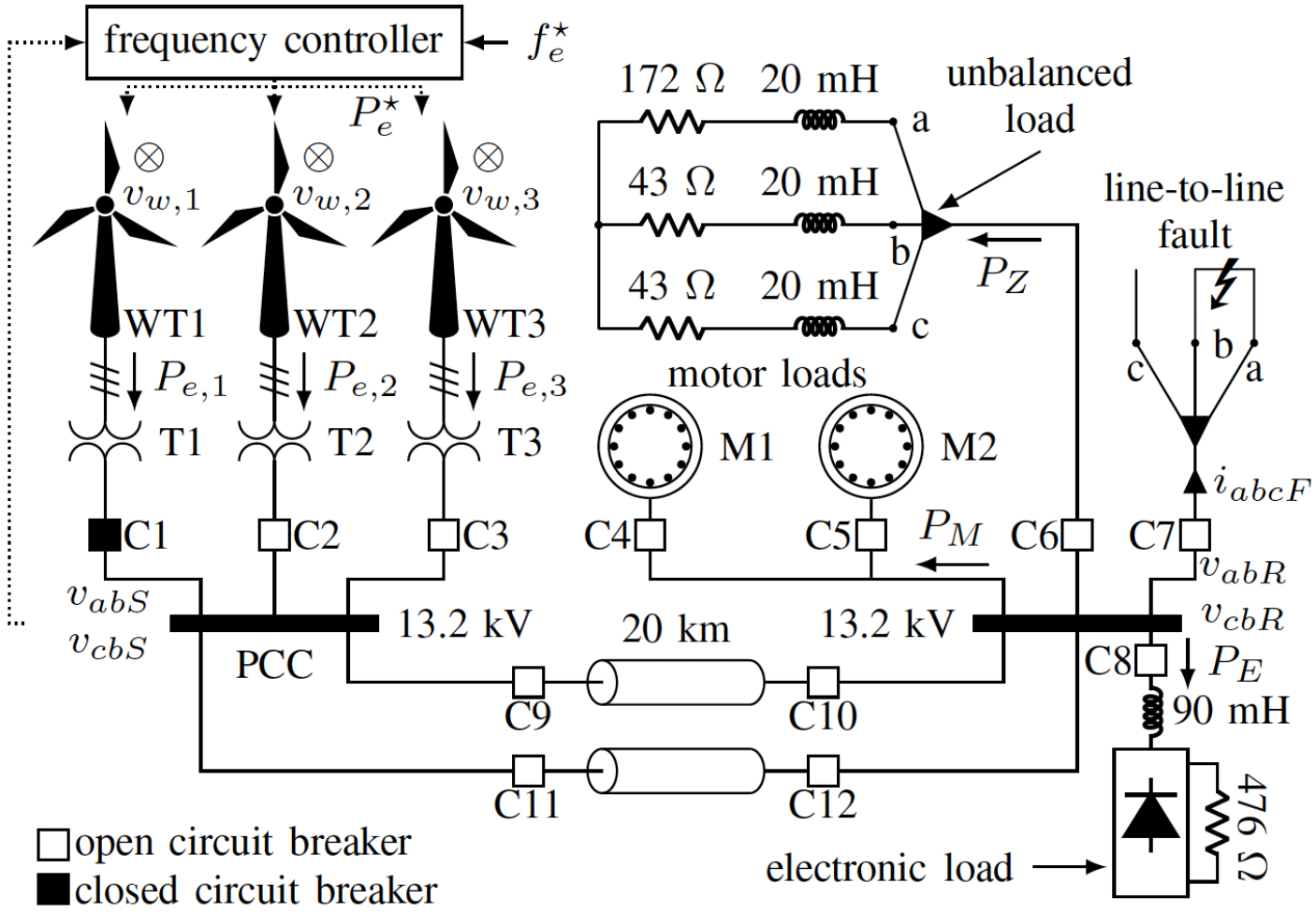


Advances:

- **Survivability method to low wind speed**
- **Anti-stalling and dc-link voltage protection**
- **Volts-per-Hertz limits (ac side)**

H. N. Villegas Pico and Vahan Gevorgian, “Blackstart capability and survivability of wind turbines with fully rated converters,” IEEE Trans. Energy Convers., vol. 37, no. 4, pp. 2482–2497, Dec. 2022.

Grid-Forming Technology: Type-4 Wind Turbines

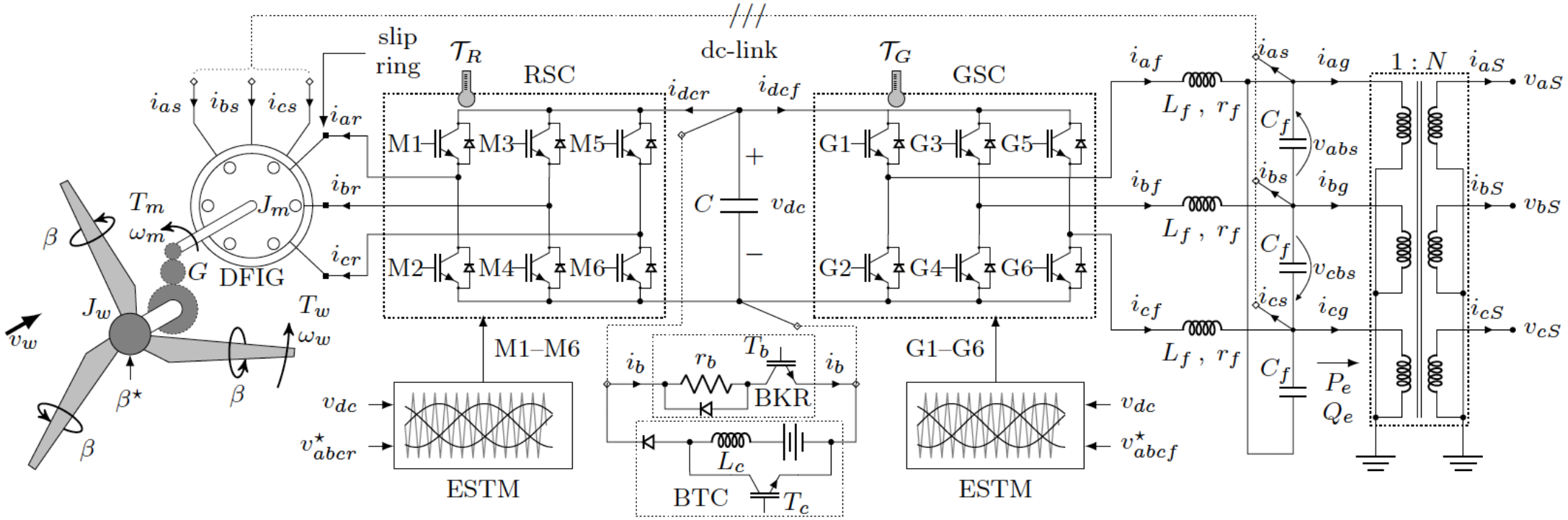


Three turbines: showcase they work in parallel
Motor loads: showcase they can start up motor
Unbalanced load: showcase unbalance operation
Electronic load: withstand non-linear impacts
Asymmetrical fault: withstand short-circuits

H. N. Villegas Pico and Vahan Gevorgian, "Blackstart capability and survivability of wind turbines with fully rated converters," IEEE Trans. Energy Convers., vol. 37, no. 4, pp. 2482–2497, Dec. 2022.

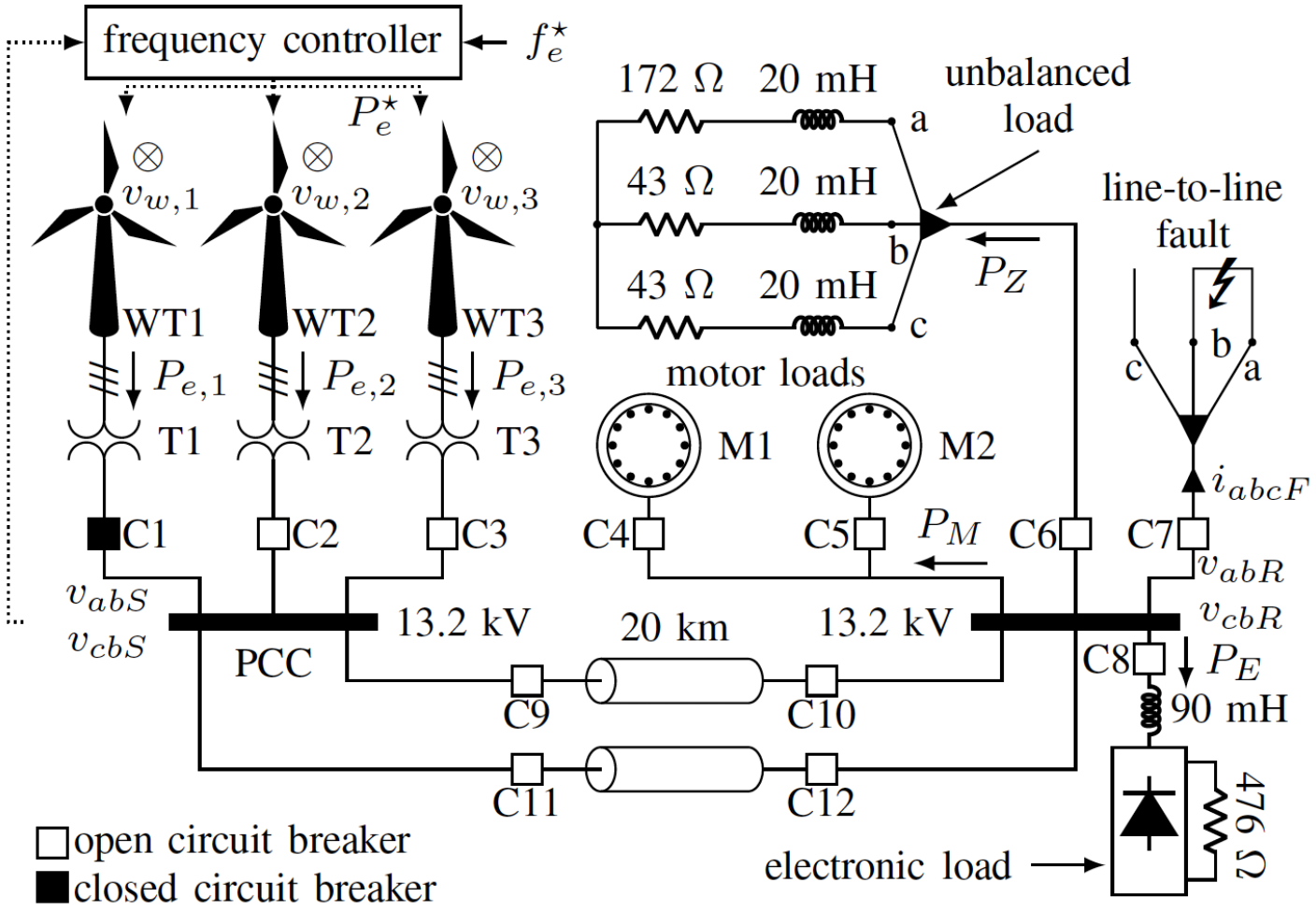
Grid-Forming Technology: Type-3 Wind Turbines

RSC steers ac line-to-line voltages voltages: v_{abf} and v_{cbf}
GSC steers dc-link voltage: v_{dc}
Pitch angle β servos stees PMSG speed: ω_m
If DFIG+GSC transfer more power than the wind turbine can harvest: DFIG speed and v_{dc} collapse
Advances: feed-forward loops to regulate ac voltages using the the RSC and sync. GSC with DFIG



H. P. Dang and H. N. Villegas Pico, "Blackstart and fault-ride through capability of DFIG-based wind turbines," IEEE Trans. Smart Grid, vol. 14, no. 3, pp. 2060 – 2074, May 2023.

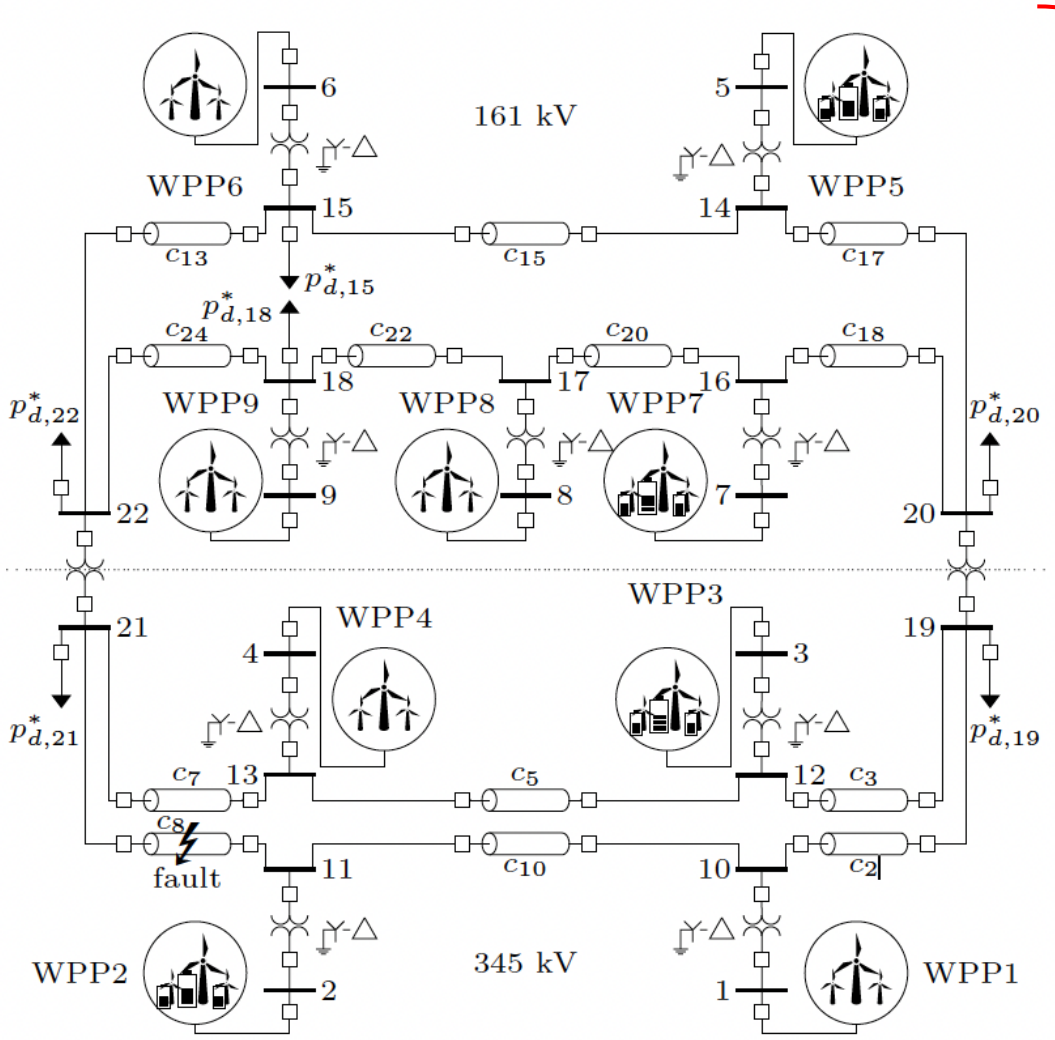
Grid-Forming Technology: Type-3 Wind Turbines



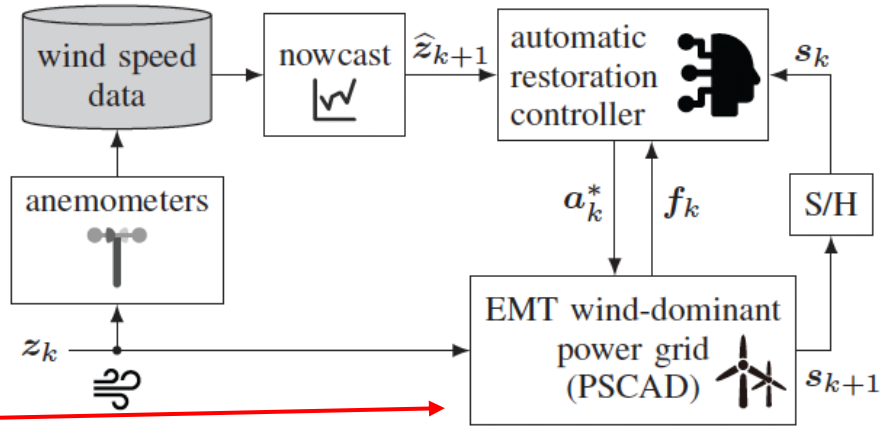
Three Type 3 turbines
Motor loads
Unbalanced load
Electronic load
Asymmetrical fault
Low wind speed
Survivability
Active Protections

H. P. Dang and H. N. Villegas Pico, “Blackstart and fault-ride through capability of DFIG-based wind turbines,” IEEE Trans. Smart Grid, vol. 14, no. 3, pp. 2060 – 2074, May 2023.

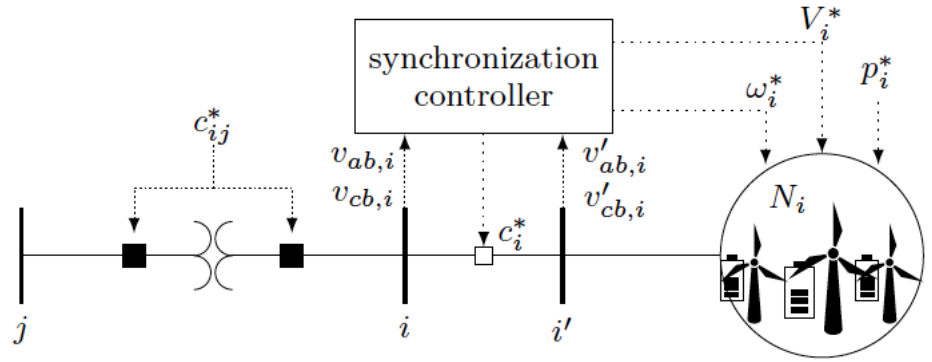
Restoration of Wind-Dominant Power Systems



Advance: automatic restoration



Advance: Stable interconnection



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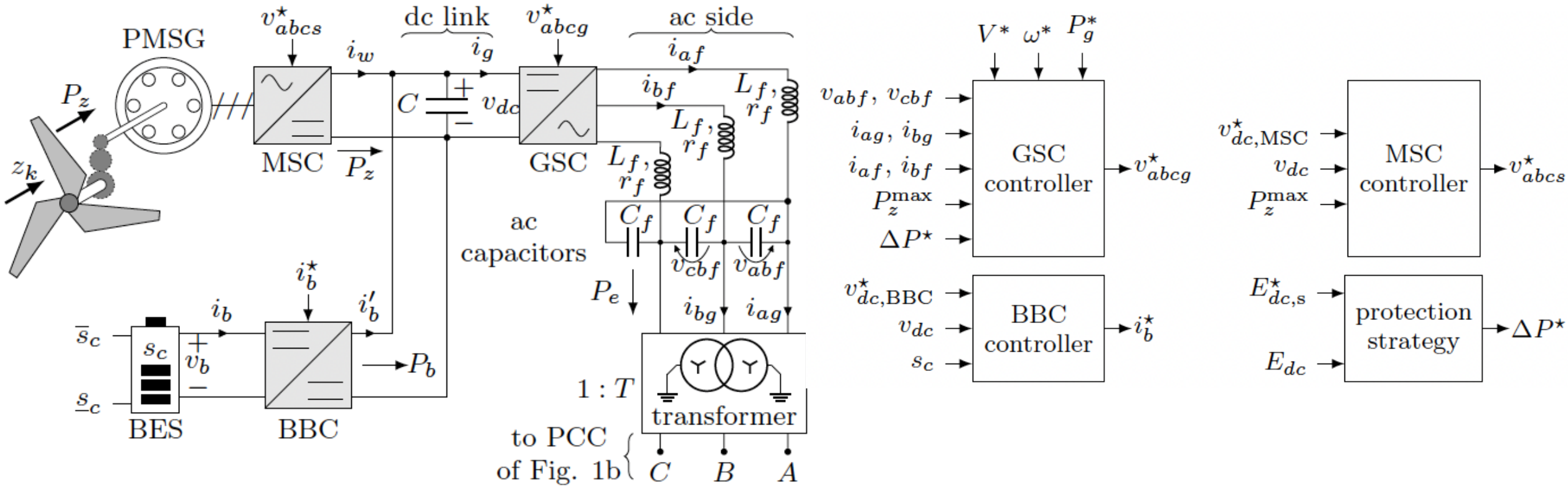
Restoration of Wind-Dominant Power Systems

Advance: hybrid grid-forming wind turbine, coordinate control MSC and BBC



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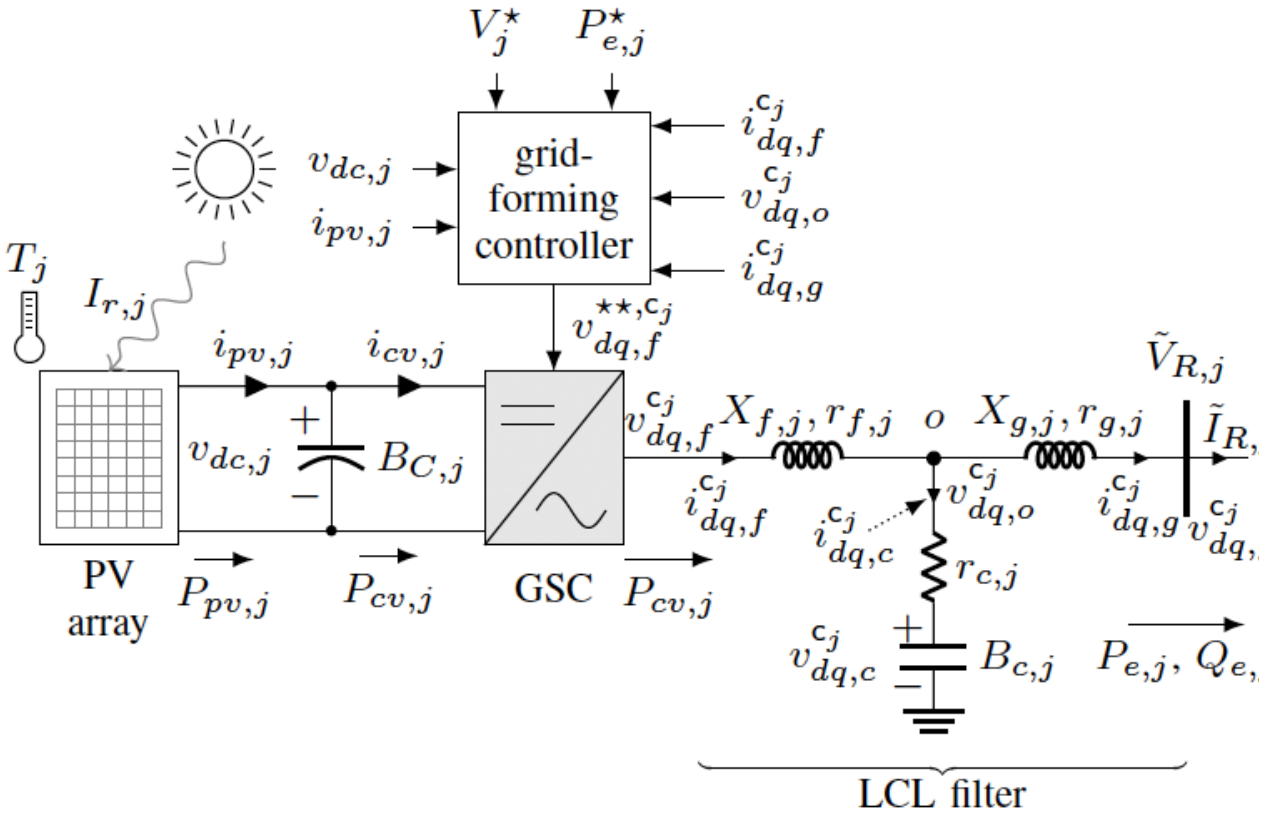
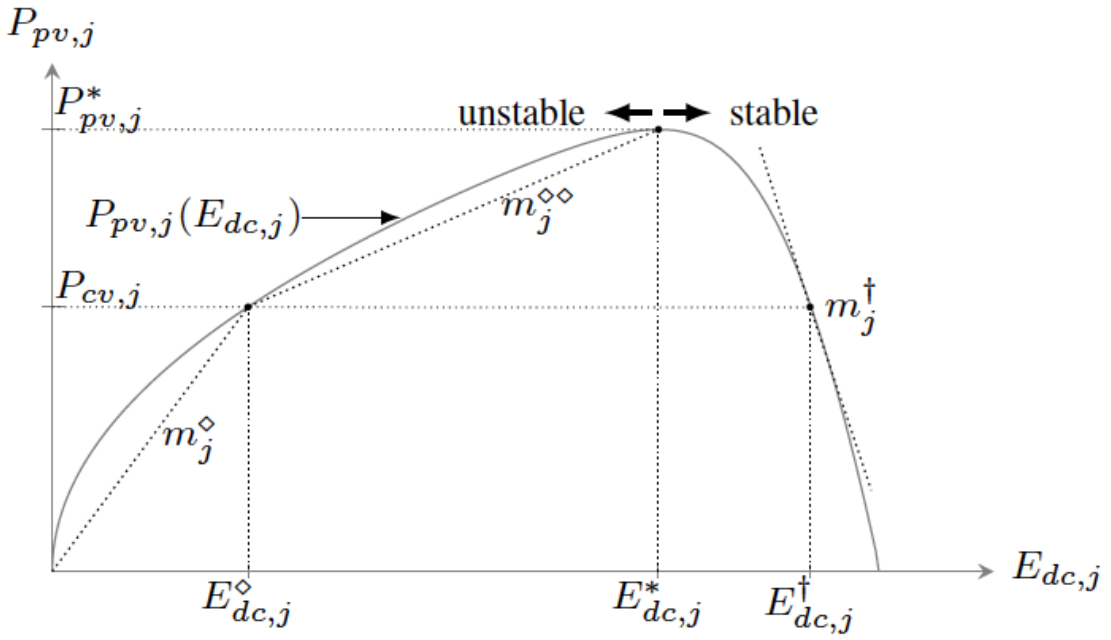
Grid-Forming Technology: Photovoltaic Solar

Advances: rigorous analysis of dc-link voltage stability, rigorous estimation of maximum power point (E^*_{dc}, P^*_{pv}), dc-link voltage protection

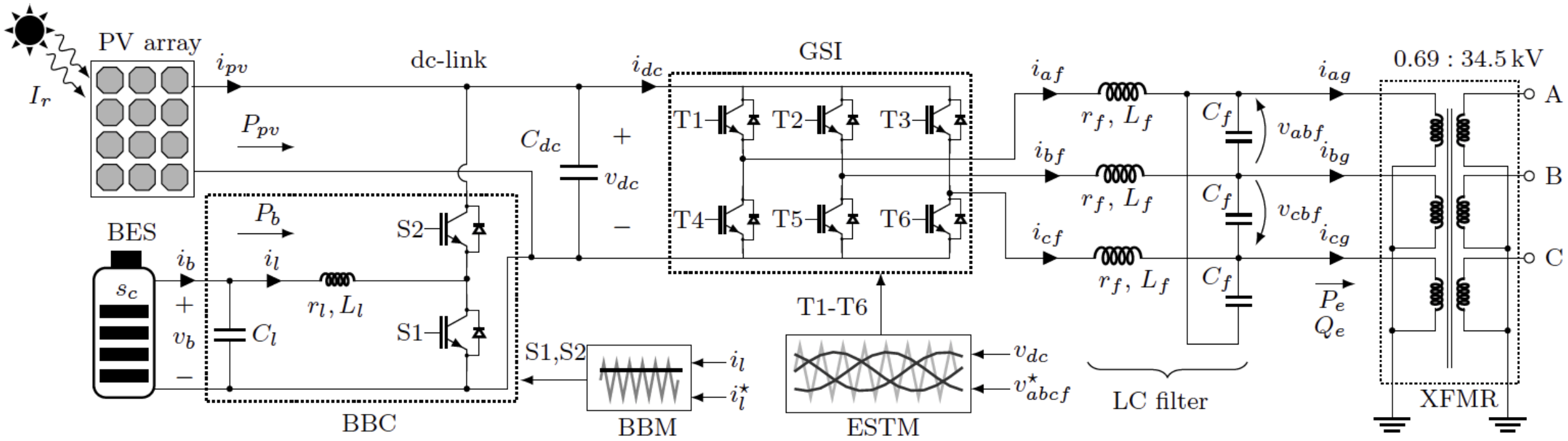




S. Roy and H. N. Villegas Pico, "Transient stability and active protection of power systems with grid-forming PV power plants," IEEE Trans. Power Syst., vol. 38, no. 1, pp. 897–911, Jan. 2023

Grid-Forming Technology: Photovoltaic Solar

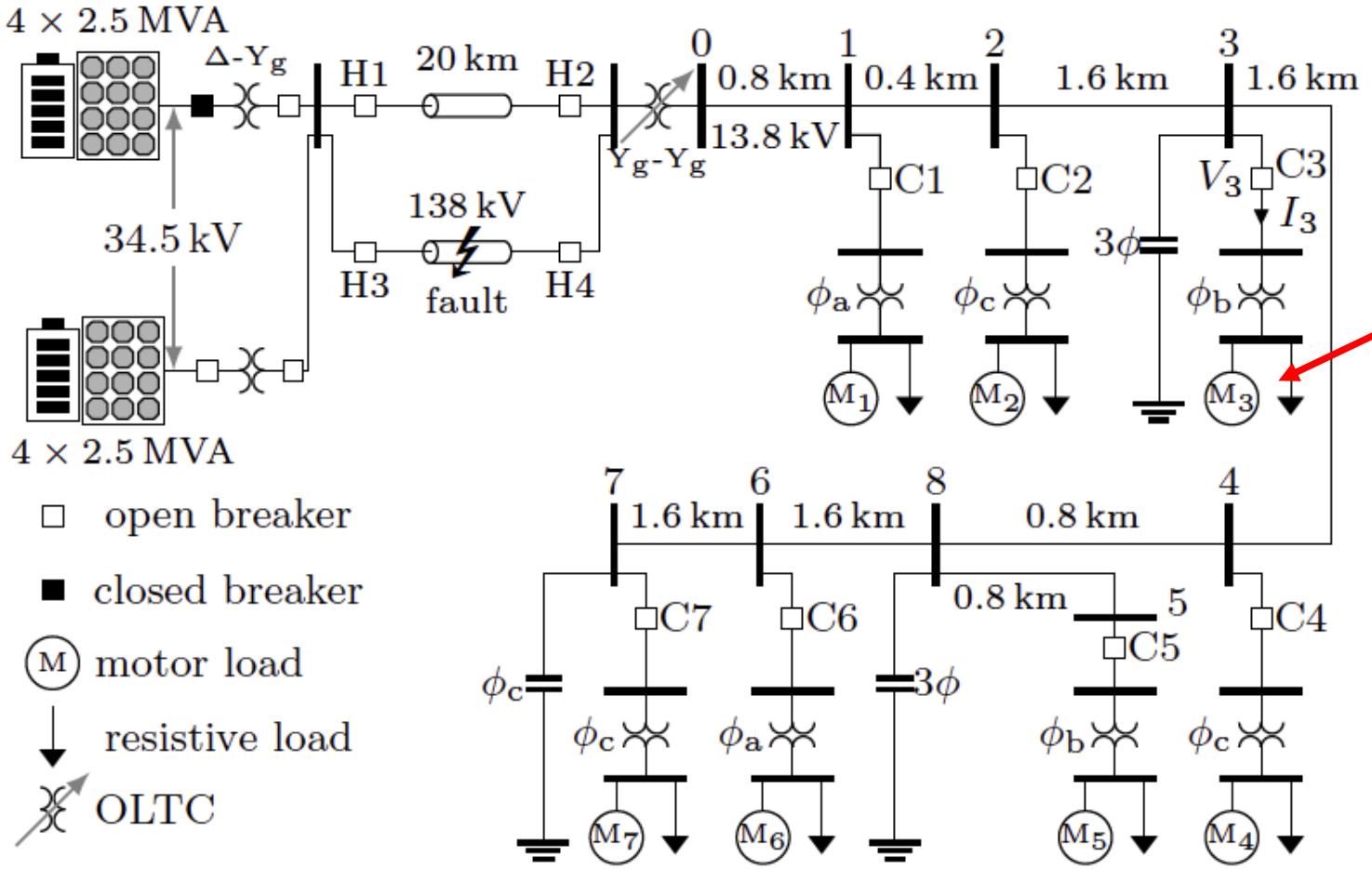
Advance: hybrid-solar grid-forming inverter

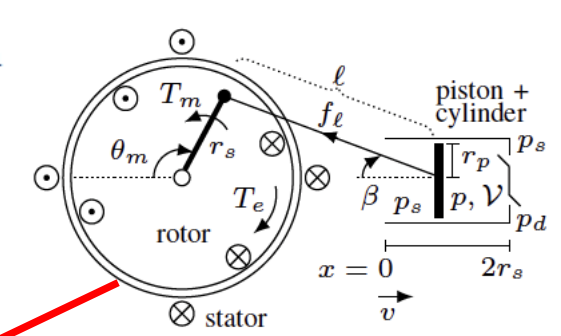


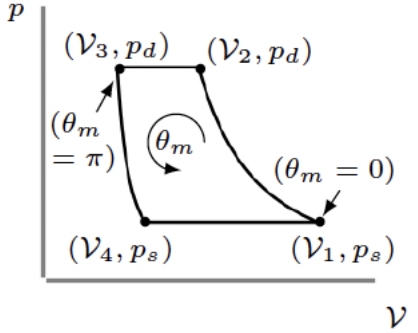
A. M. Mannan, H. P. Dang, and H. N. Villegas Pico, “FIDVR capability of hybrid grid-forming PV power plants during feeder restoration” IEEE Trans. Energy Convers., vol. 39, no. 3, pp. 1613–1629, Sep. 2024

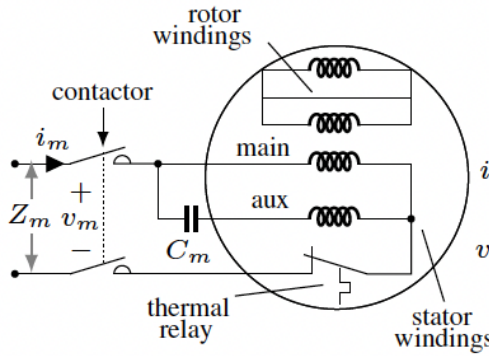
Grid-Forming Technology: Photovoltaic Solar

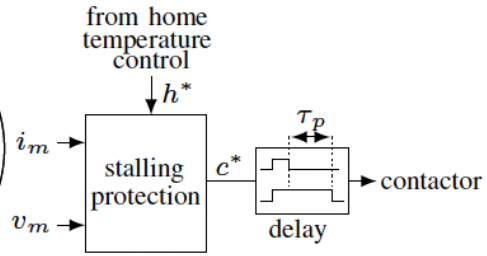
Advance: analysis and protection of of single-phase motors powered by grid-forming inverters









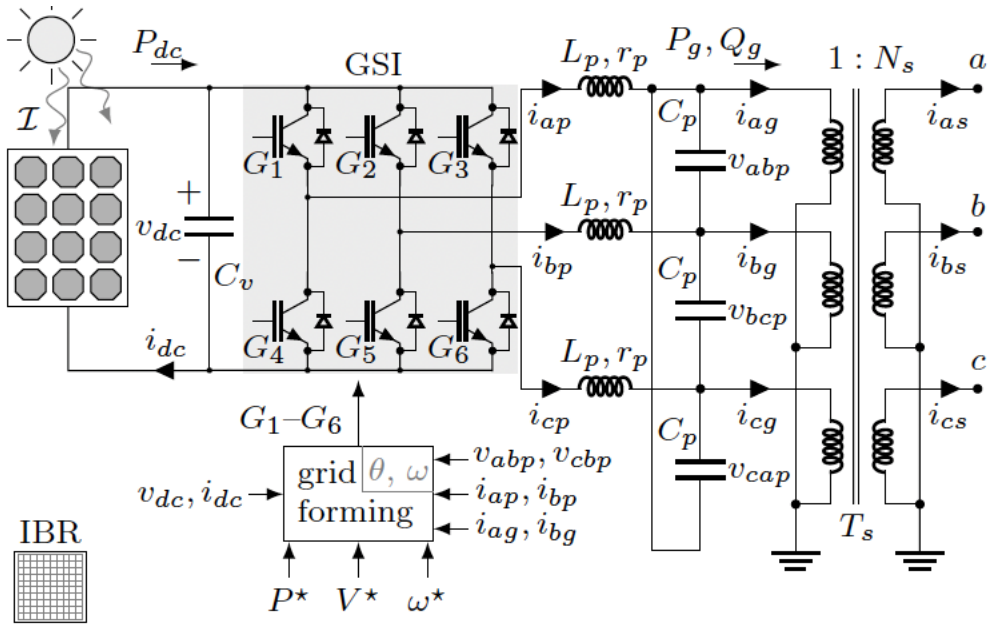


(a) AC-compressor motor wiring (b) stalling protection

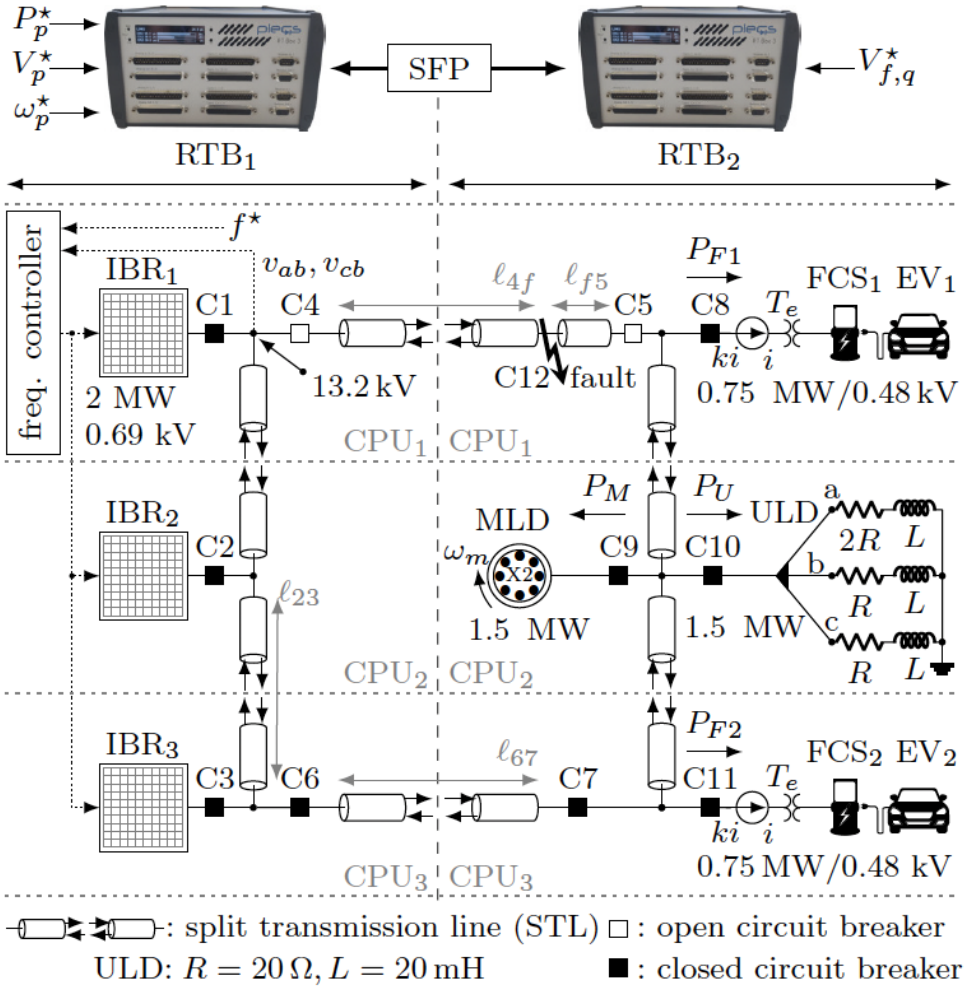
A. M. Mannan, H. P. Dang, and H. N. Villegas Pico, “FIDVR capability of hybrid grid-forming PV power plants during feeder restoration” IEEE Trans. Energy Convers., vol. 39, no. 3, pp. 1613–1629, Sep. 2024

Grid-Forming Technology: Photovoltaic Solar + EVs

Advance: fast-chargers proportionally sensitive to low voltage and frequency events



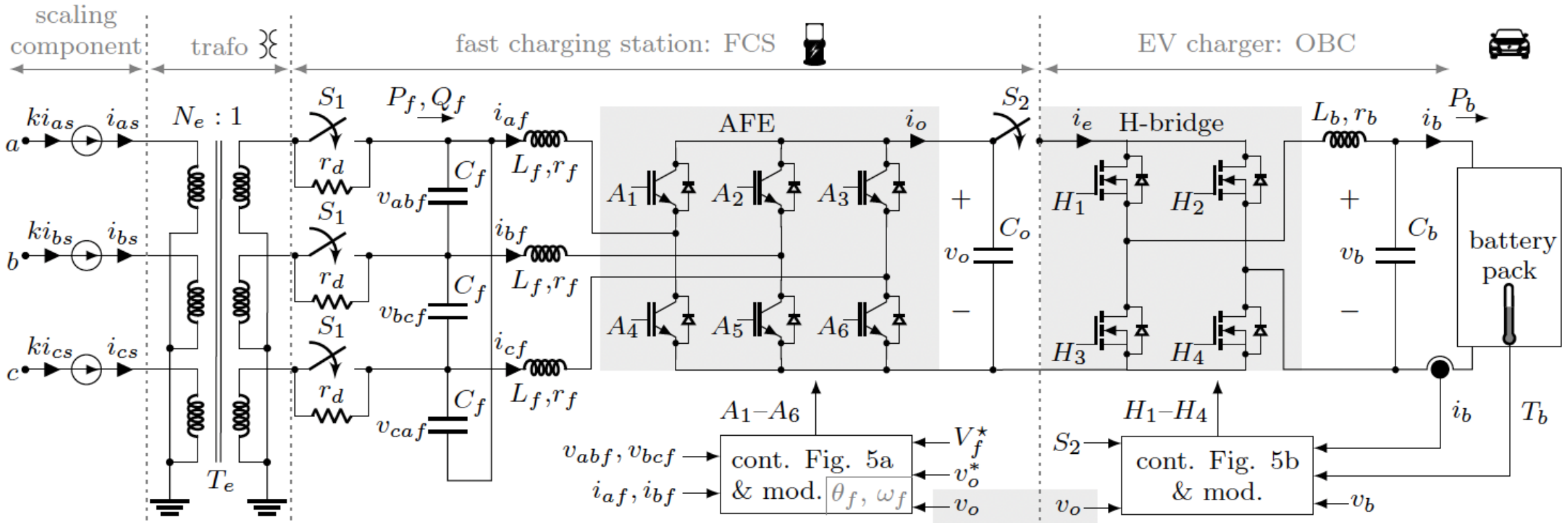
GFM equipped with dc-link voltage protection,
volts-per-Hertz control, and other standard functionalities



L. G. Guillén Montenegro and H. N. Villegas Pico, “Control and real-time simulation of microgrids with EV fast-charging and grid-forming resources,” IEEE Trans. Transp. Electrific., early access.

Grid-Forming Technology: Photovoltaic Solar + EVs

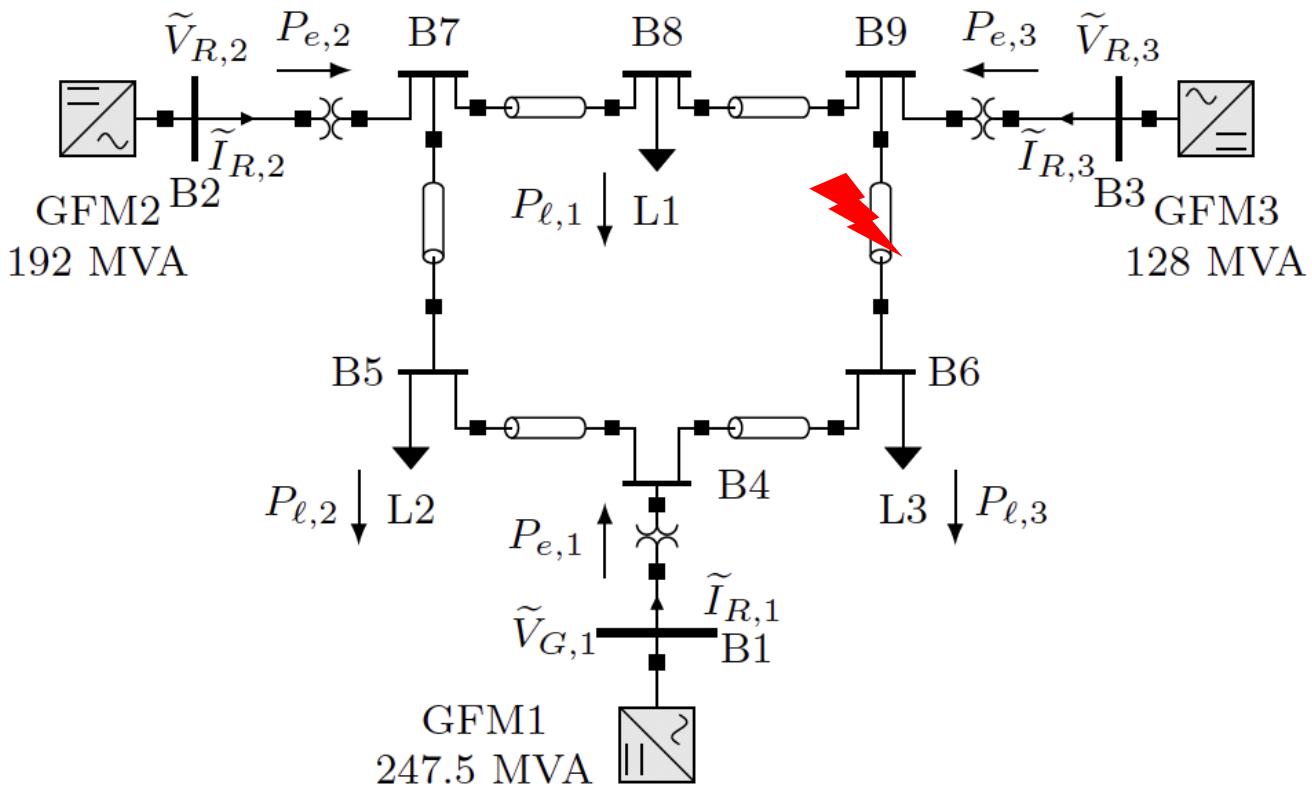
Advance: fast-chargers proportionally sensitive to low voltage and frequency events
OBC: automatically reduce withdrawn power during low voltage-frequency events

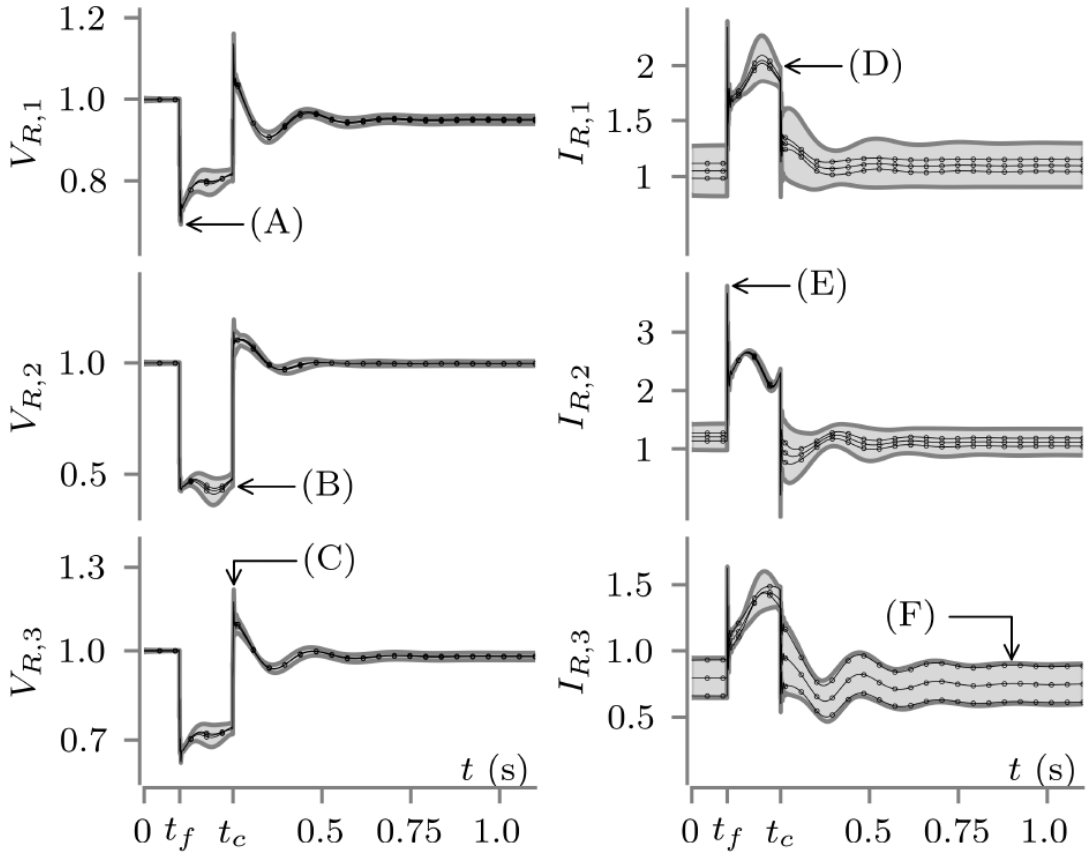


L. E. Guillén Montenegro and H. N. Villegas Pico, “Control and real-time simulation of microgrids with EV fast-charging and grid-forming resources,” IEEE Trans. Transp. Electrific., early access.

Propagation of Uncertainties

Advance: Propagation through nonlinear flows of grid-forming:
faults + high-order Taylor polynomials + saturation two-axis anti-windups PI regulators

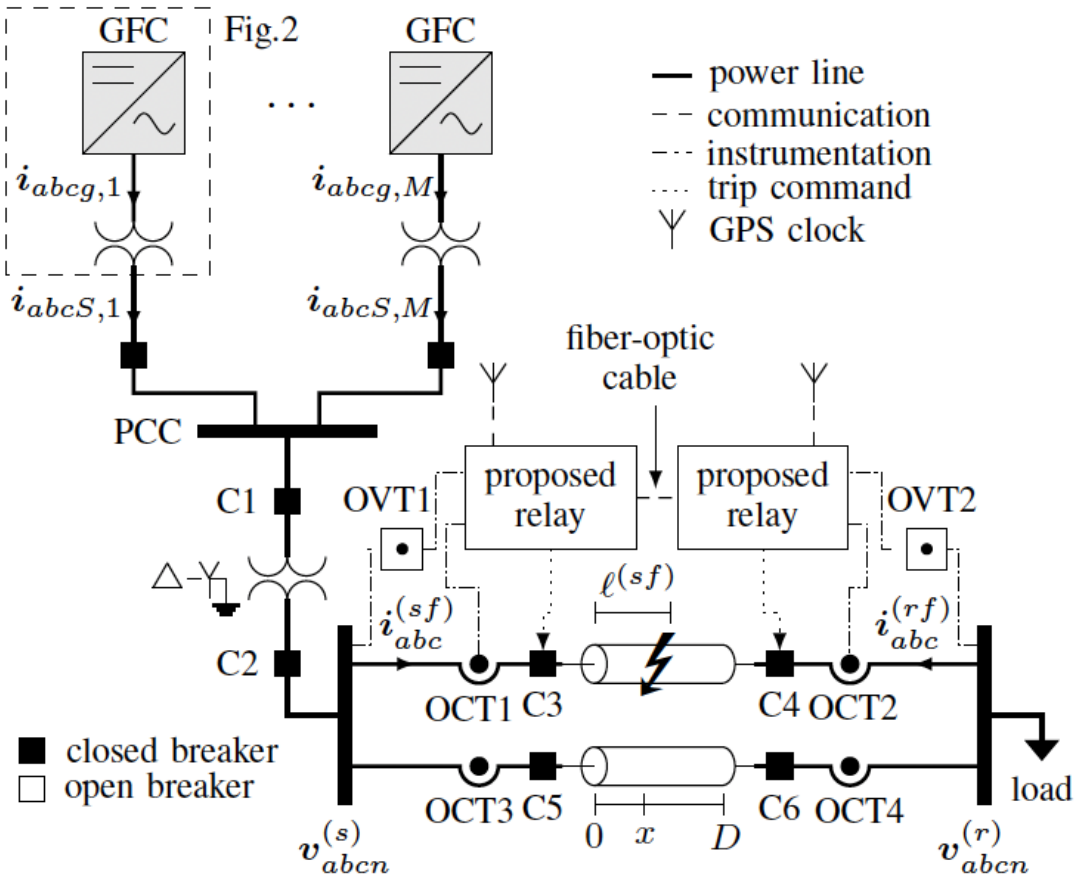


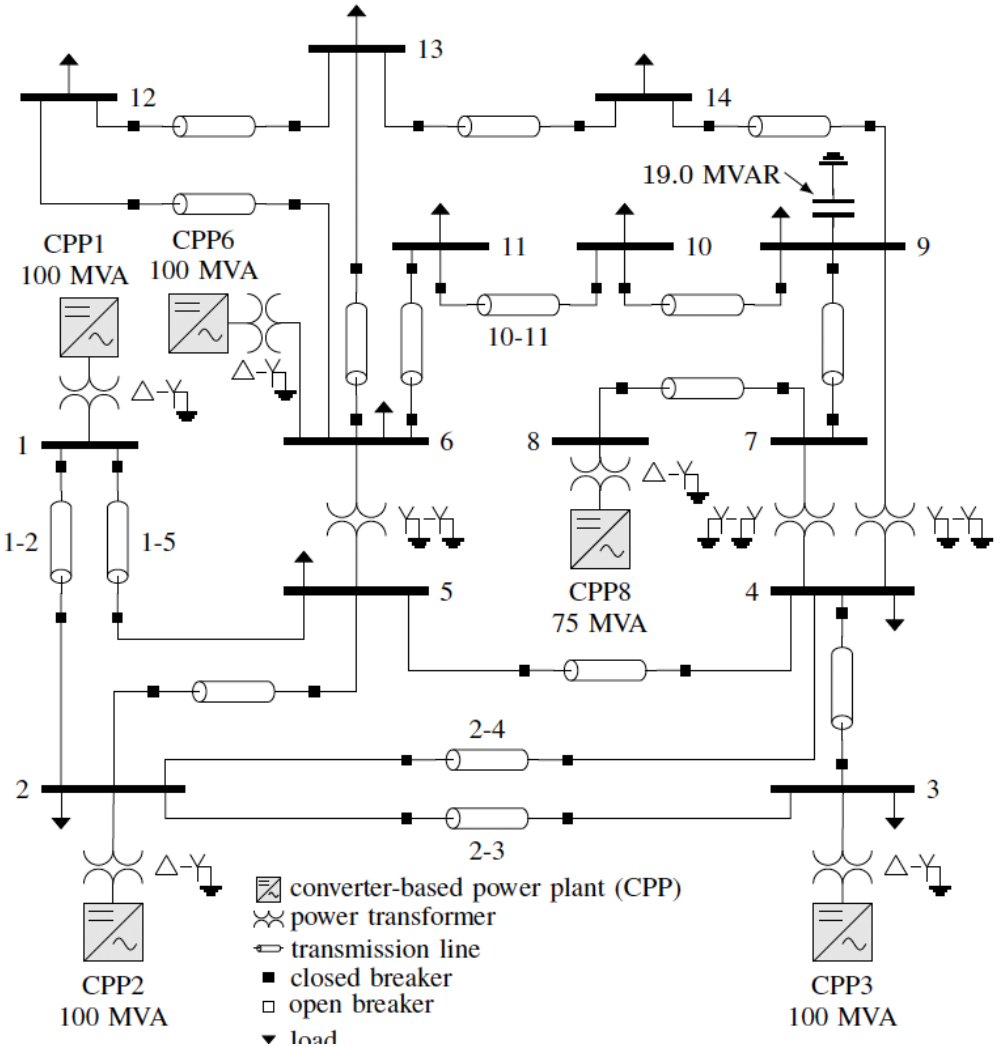


S. Roy and H. N. Villegas Pico, "Uncertainty propagation through nonlinear flows of grid-forming exclusive power systems," IEEE Trans. Power Syst., vol 40, no. 6, pp. 4493–4509, Nov. 2025

Grid-Forming Technology: Protection

Advance: time-domain protection agnostic to generation class

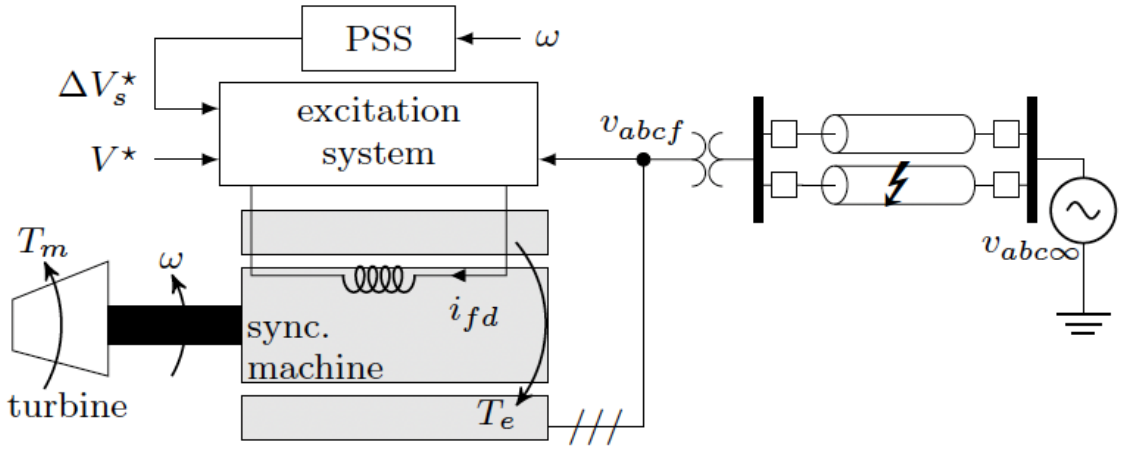


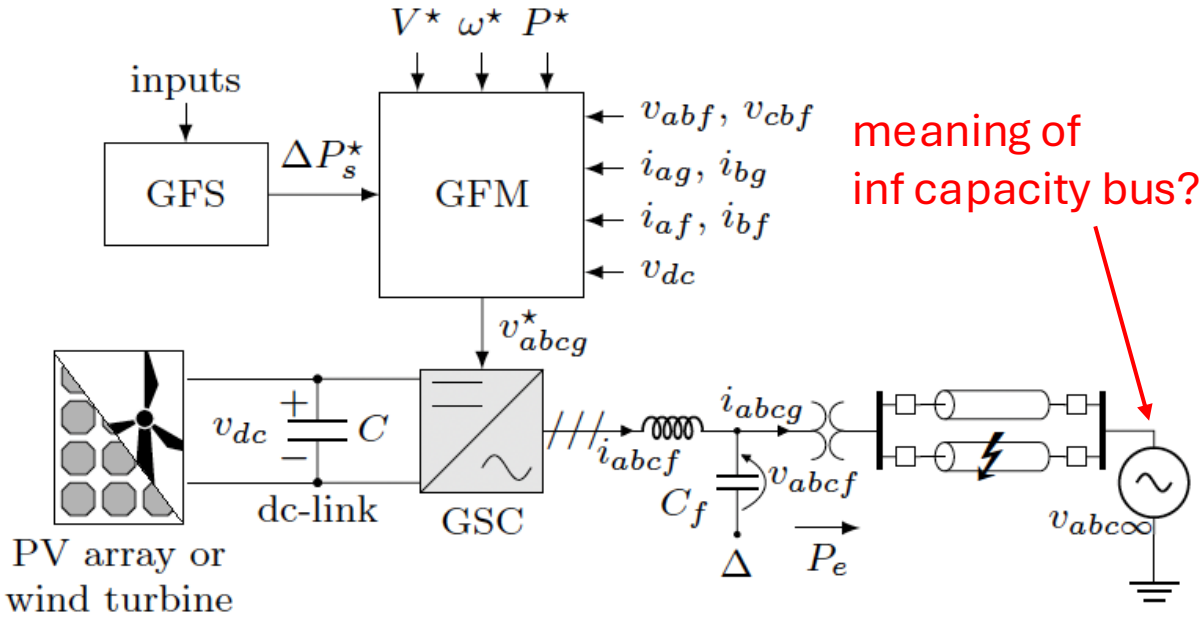


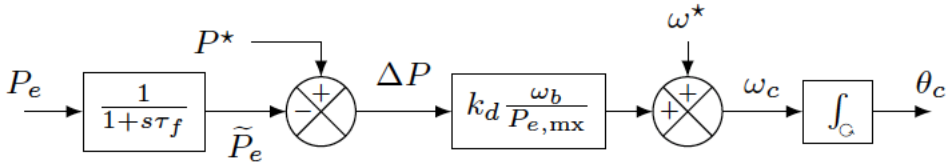
C. L. Peralta and H. N. Villegas Pico, “A time-domain protection approach for ac transmission systems with grid-forming resources” IEEE Trans. Instrum. Meas., vol. 73, Art. no. 9000318, Nov. 2023

Grid-Forming Technology: Stabilizer

Problem: grid-forming technology with modified droop control law may not be able to re-synchronized after faults





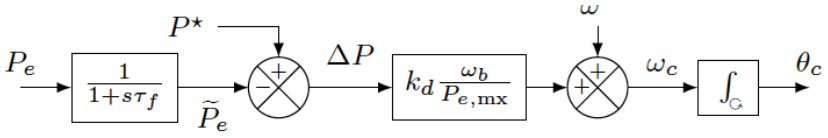


(c) classical speed-droop law

H. P. Dang and H. N. Villegas Pico, “Stabilizers for grid-forming inverters to regain synchronism after fault clearing,” presented at IEEE Energy Convers. Congress Expo., Philadelphia, PA, Oct. 19–23, 2025

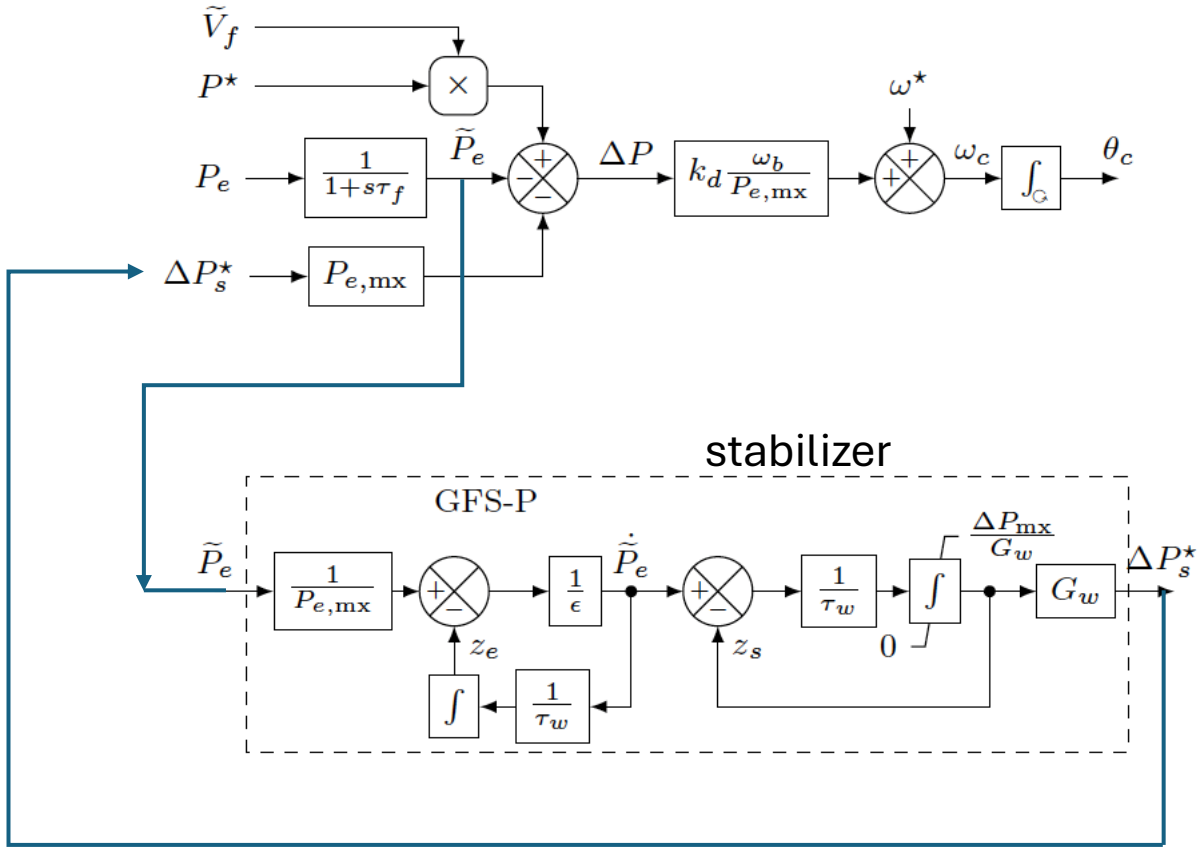
Grid-Forming Technology: Stabilizer

Advance: modified droop control law and stabilizer for grid-forming inverters



(c) classical speed-droop law

advance



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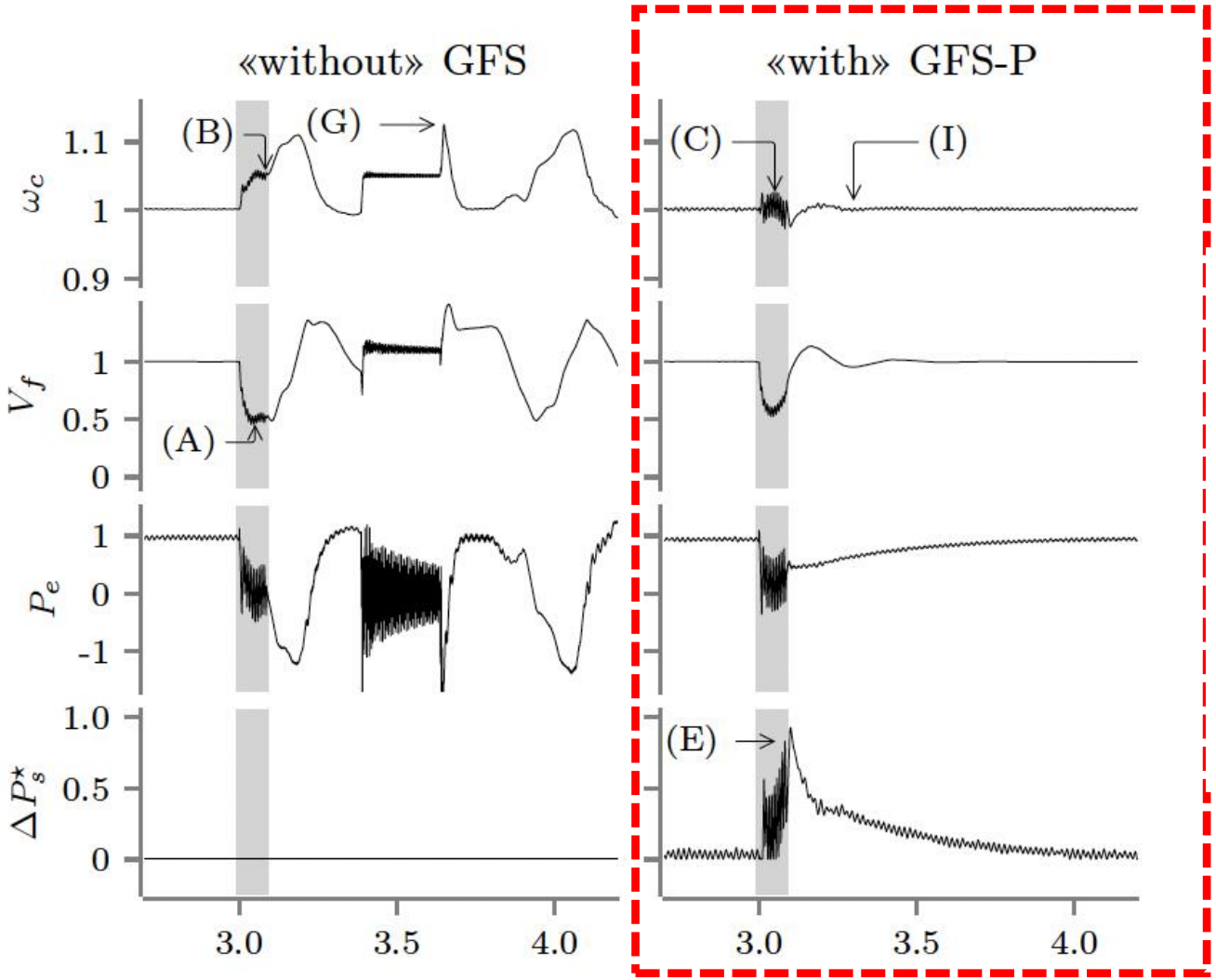
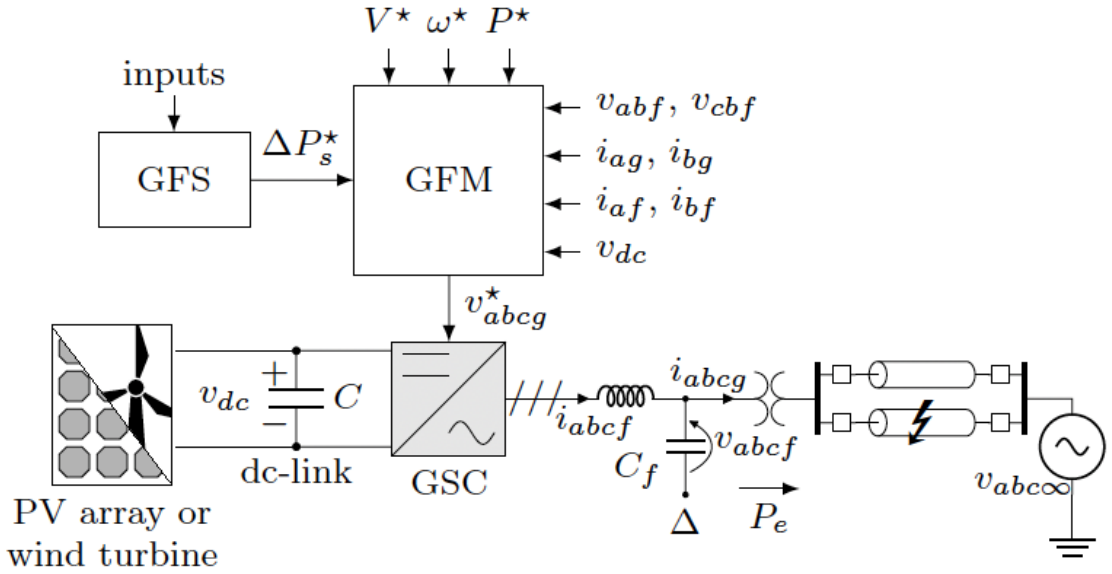
Grid-Forming Technology: Stabilizer





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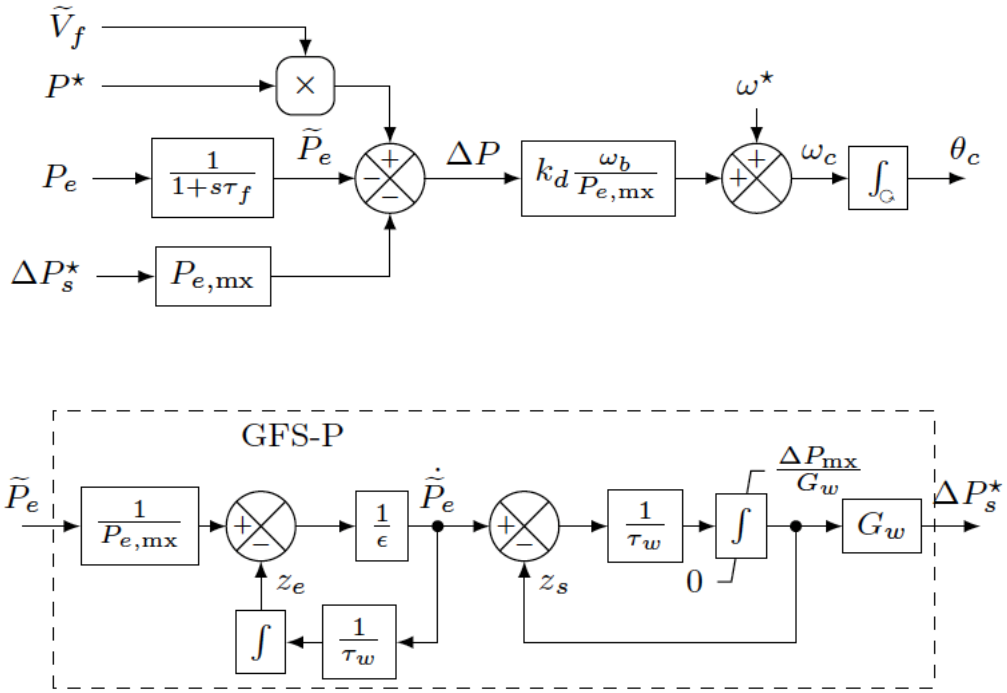
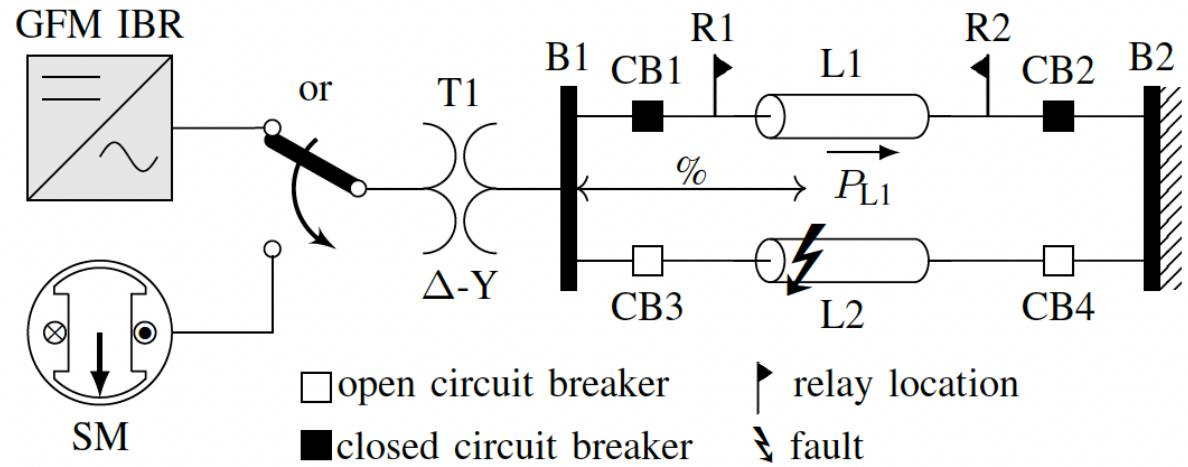
Grid-Forming Technology: Stabilizer + Power Swing

Study: impact of stabilizer of grid-forming inverter on power swing blocking



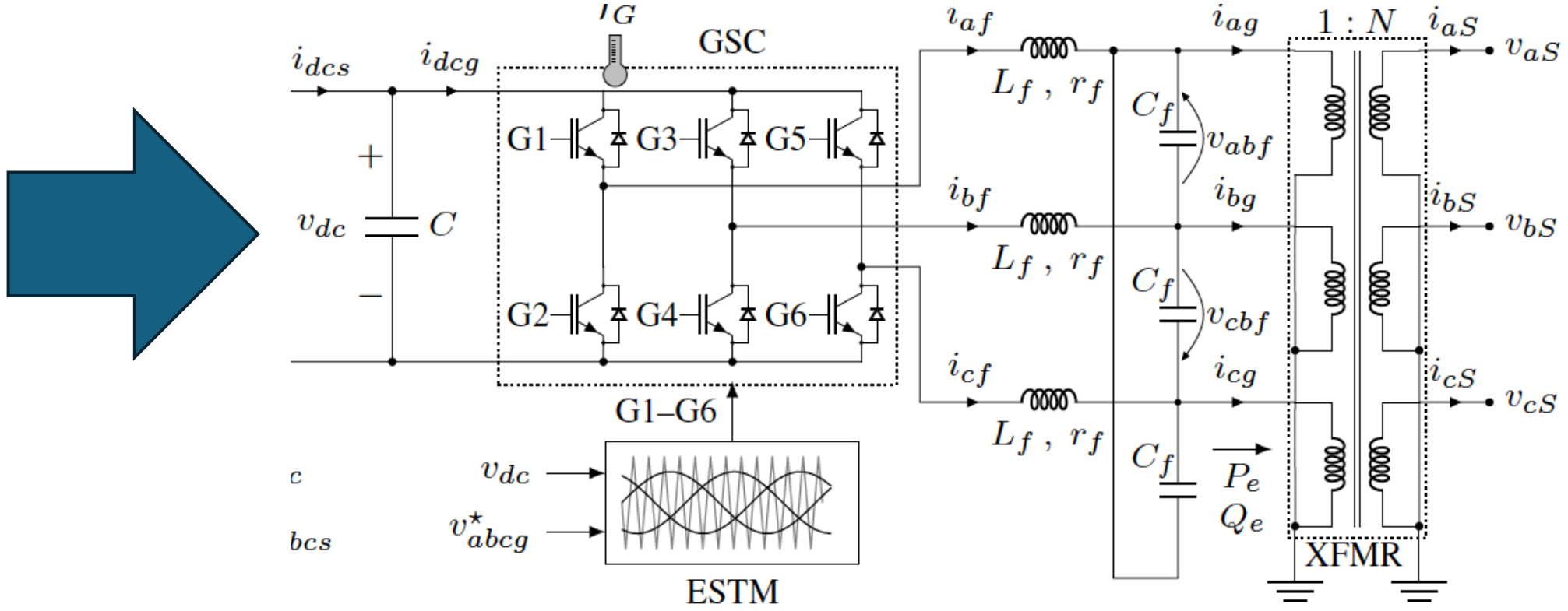


C. L. Peralta and H. N. Villegas Pico, "Impact of a Grid-Forming Inverter with Stabilizer on the Dual-Quadrilateral Power Swing Blocking," to be presented at the 2026 IEEE PES Transmiss. Distribution Conf. Expo., 4-7 May 2026, Chicago, IL, USA.

Grid-Forming Technology: Energy Resource

- Volatile primary energy resource to power grid-forming inverters
- **Grid-forming technology does not create energy that is transferred per unit time to power inverters**

Wind
Solar
Battery



Grid-Forming Technology: Energy Resource

Energy storage capacity: Rated Power Generation x Time

nuclear, years

natural gas, years

hydro, months

coal, months

batteries, hours

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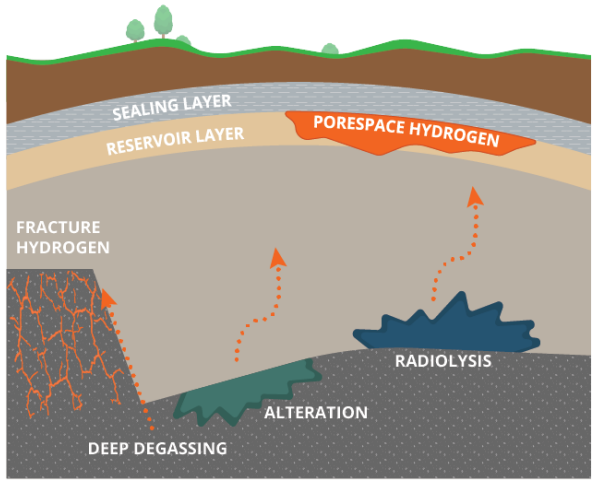
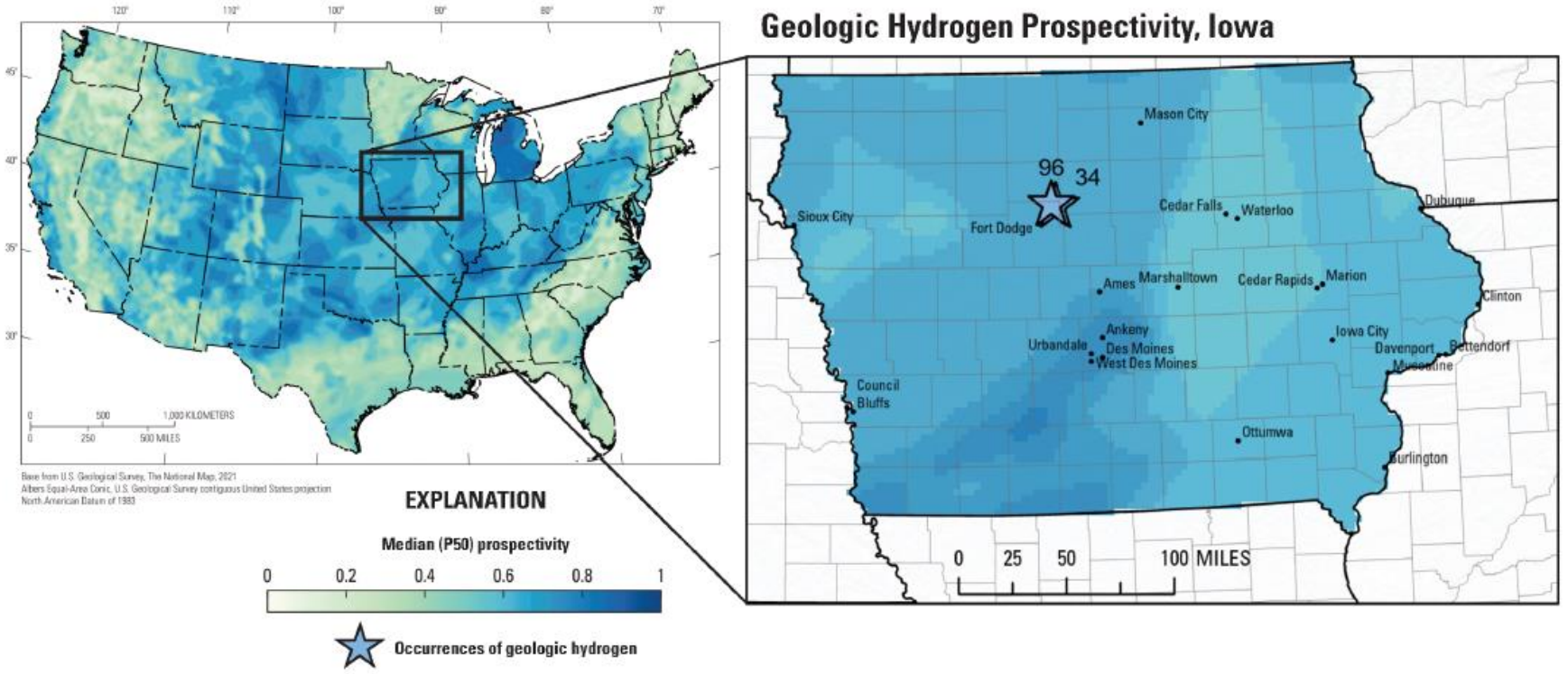
Grid-Forming Technology: Energy Resource

Geologic hydrogen: no need to convert from electricity to hydrogen



Natural H2 production:

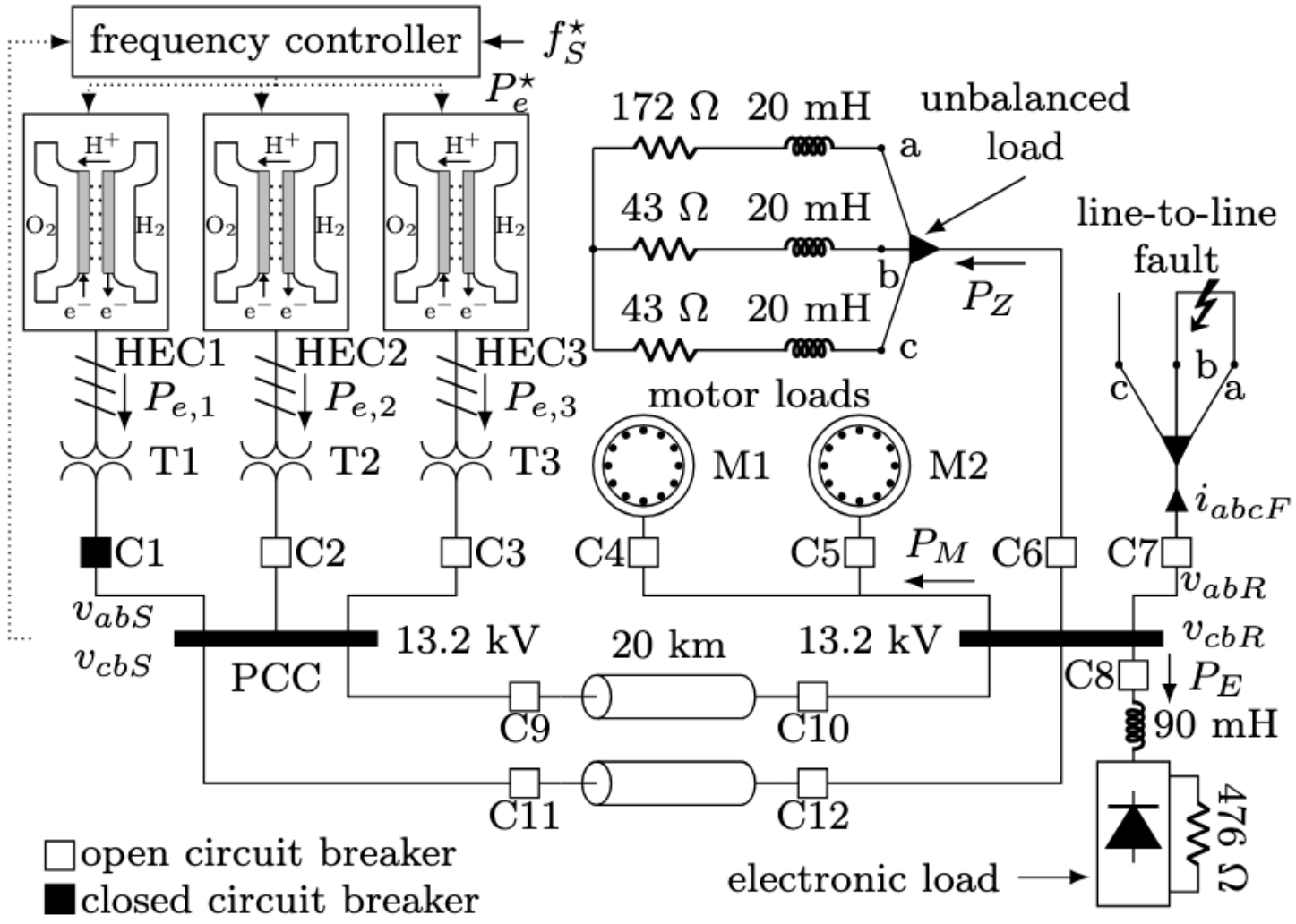
1. hydrothermal alteration
2. Radiolysis
3. Deep mantle degassing



https://energy.sandia.gov/programs/fossil-energy/subsurface-storage/geologic-hydrogen-capabilities/geologic-hydrogen/

U.S. Geological Survey, "Potential of geologic hydrogen as a next-generation," energy resource, Apr. 2023, https://certmapper.cr.usgs.gov/data/apps/hydrogen/

Grid-Forming Technology: Energy Resource



HFC: Hydrogen fuel cells

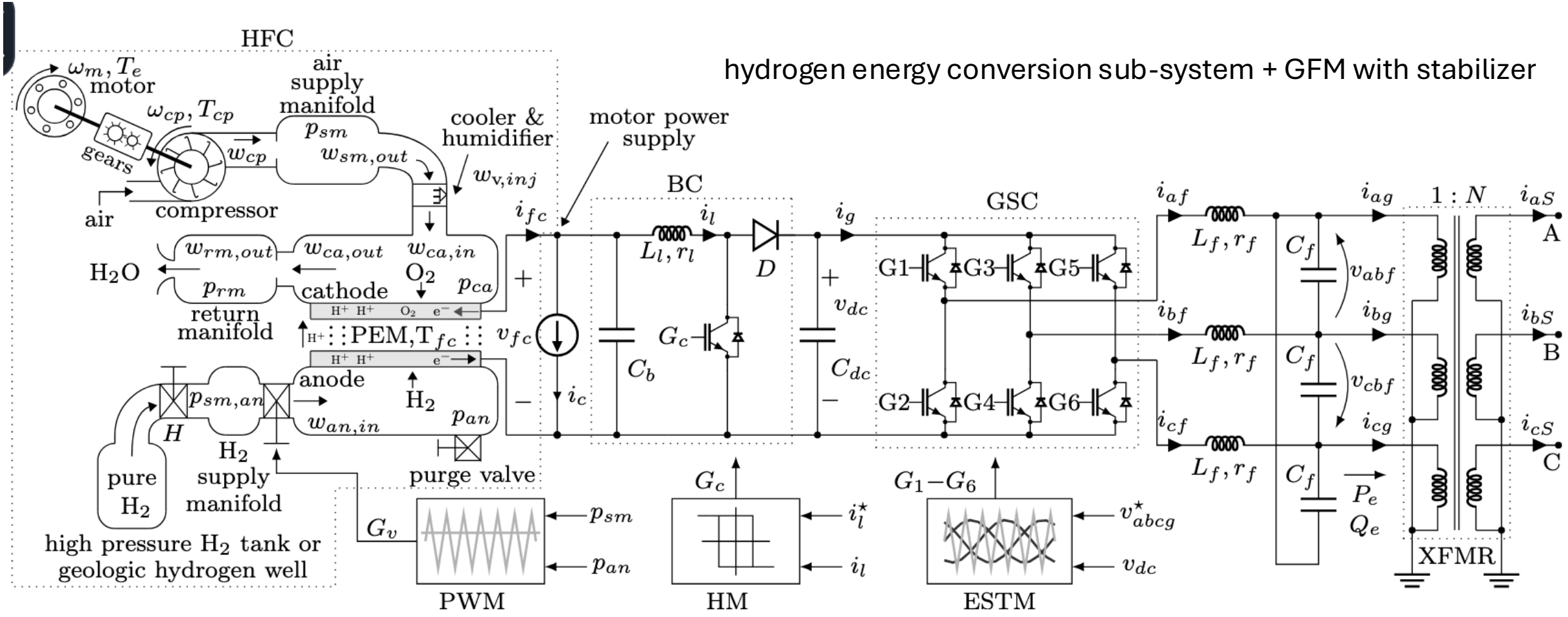
HFC can face oxygen starvation and Fuel cell membrane hot spots during sudden load pickup

HEC: hydrogen energy conversion

M. E. Tesfamichael and H. N. Villegas Pico, “Simulation of grid restoration using hydrogen fuel cells and grid-forming inverters,” presented at IEEE Energy Convers. Congress Expo., Philadelphia, PA, Oct. 19–23, 2025

Grid-Forming Technology: Energy Resource

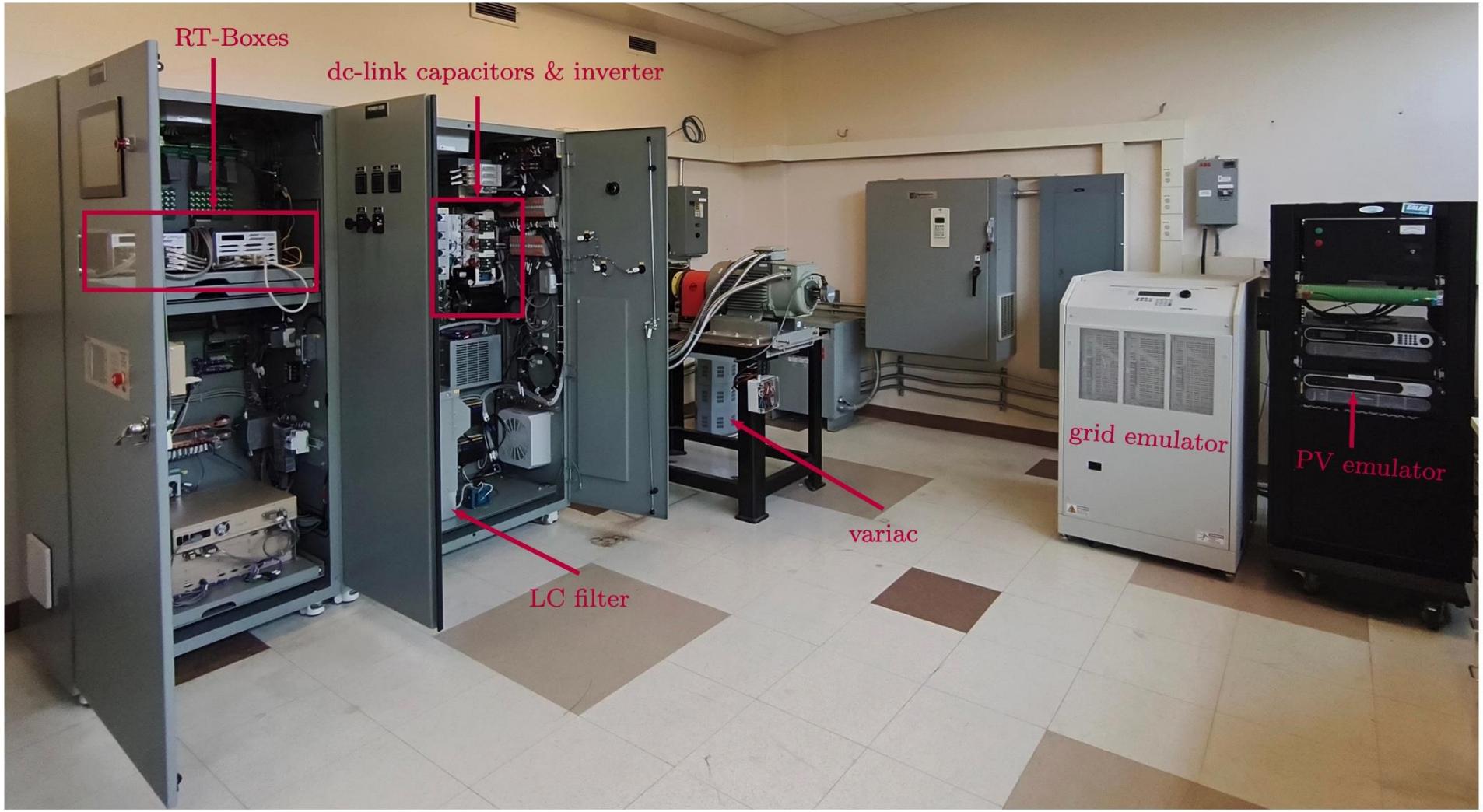
Advance: Air-control of hydrogen fuel cells for swift and long-term operation of grid-forming inverters



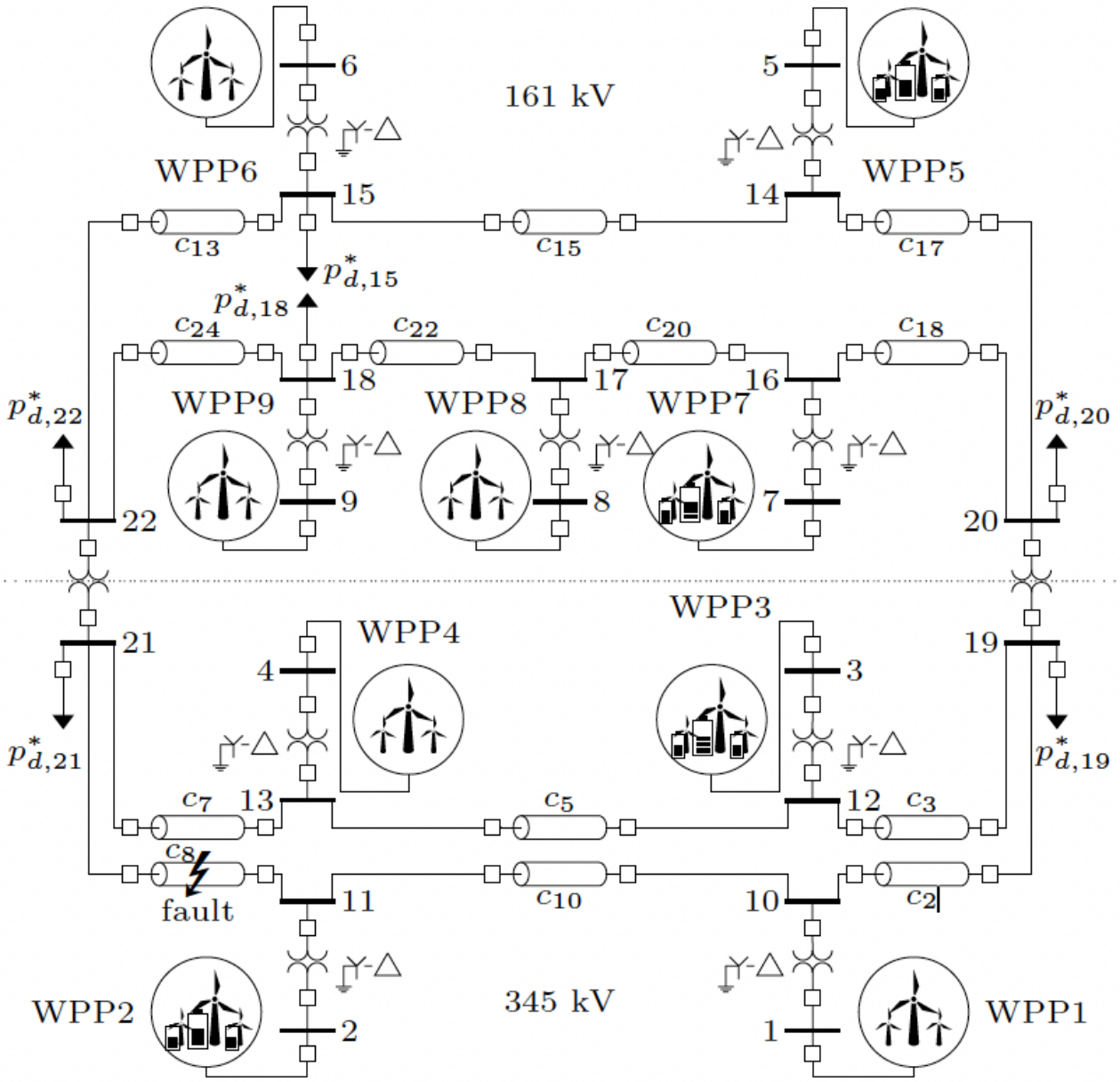
M. E. Tesfamichael and H. N. Villegas Pico, “Air control of hydrogen fuel cell stacks for swift and long-term operation of grid-forming inverters,” under review

Grid-Forming Technology: PHIL Tests

Designed a grid-forming control panel and integrated within a PHIL setup



Advanced Energy Systems Laboratory at Iowa State University

Conclusion

- A set of stablished advances to grid-forming and related technologies
- Firming the primary energy resource for grid-forming inverters is a problem that is beyond controlling inverters
- Natural hydrogen could be a game changer to firm energy for power generation over long horizons: weeks to months