Energy Storage Systems for AC Interconnected Wind and Hydrogen Systems

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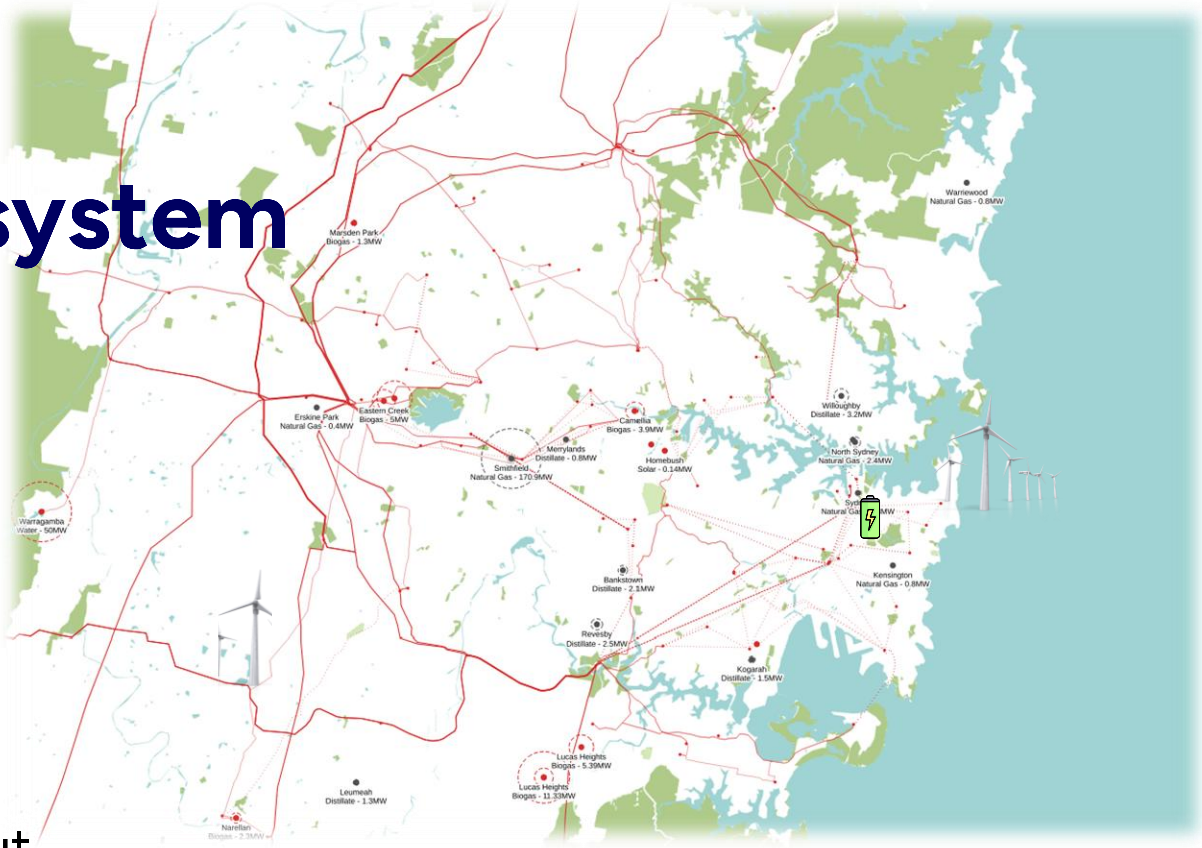
Distributed hybrid energy system

Co-located at a point of interconnection:

- Generation sources
- Energy storage – BESS and H_2
- Local loads



Functions:

- Smooth-out varying wind and solar power output
- Ability to provide dispatchable energy and grid services
  - Inertial support
  - Grid-forming
- Use electrolysers to store energy for use in local industrial services

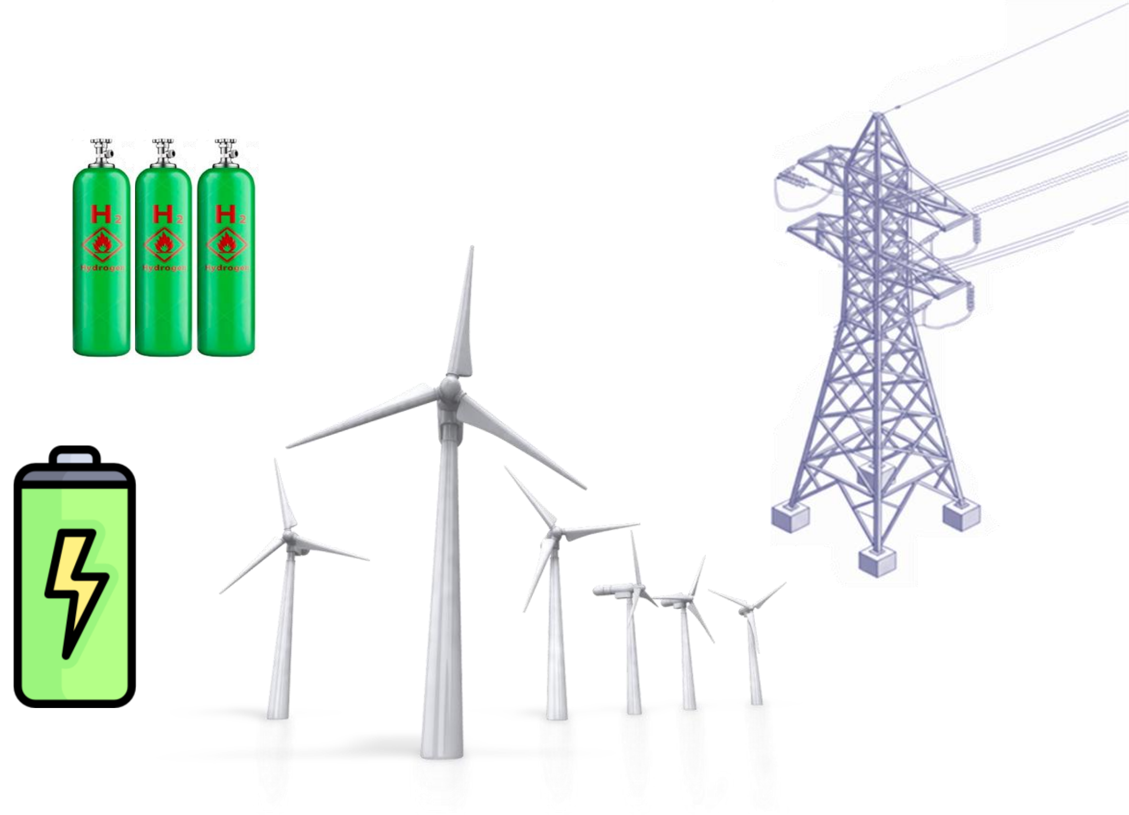
[Hybrid Distributed Wind and Battery Energy Storage Systems] Jim Reilly, Ram Poudel, Venkat Krishnan, Ben Anderson, Jayaraj Rane, Ian Baring-Gould and Caitlyn Clark, NREL/TP-5000-77662, June 2022

Distributed hybrid energy system (2)

Requires careful technical and economic system modelling, planning, and dimensioning of components

Important to maximize system benefits based on:

- The application – local industry H_2 usage
- Expected load
- Viable grid services
- Local grid conditions
- Weather conditions



Hybrid Distributed Wind and Battery Energy Storage Systems Jim Reilly, Ram Poudel, Venkat Krishnan, Ben Anderson, Jayaraj Rane, Ian Baring-Gould and Caitlyn Clark, NREL/TP-5000-77662, June 2022

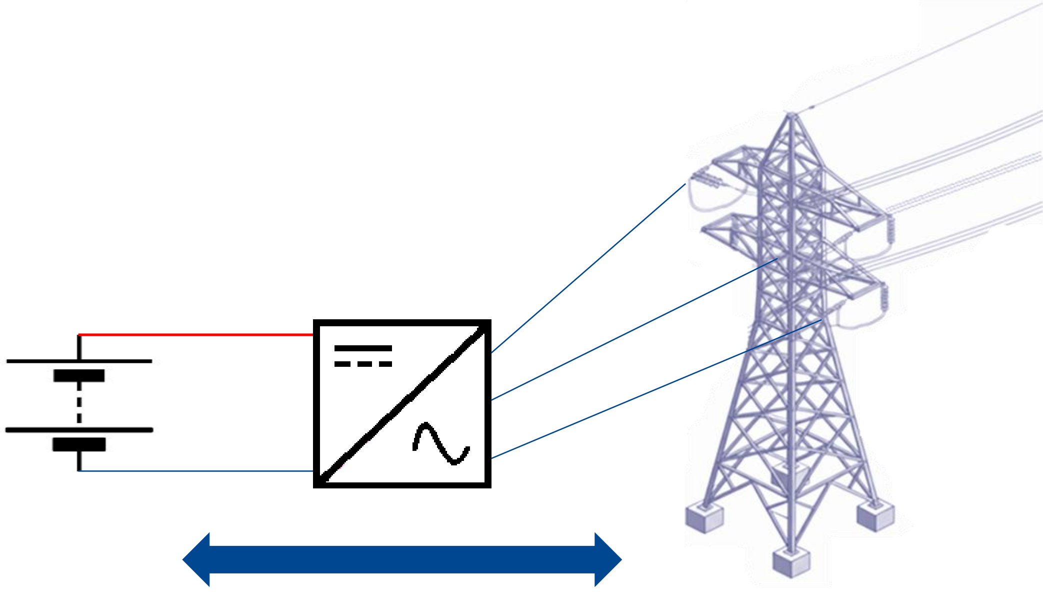
Battery energy storage

Grid-scale batteryenergy storage systems (BESS) are becoming less expensive

Bi-directional and immediately dispatchable

Ability to provide dispatchable energy and grid services

- Inertial support
- Grid-forming



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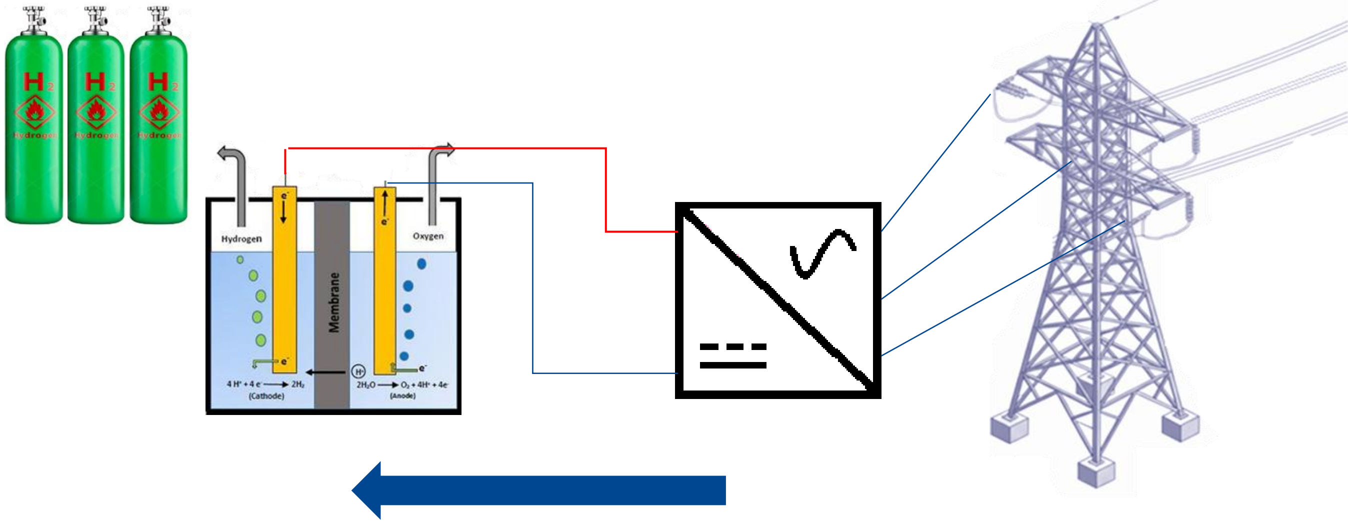
Hydrogen energy storage

"[There is] currently a lack of safe, effective, as well as affordable hydrogen storage makes industrial-scale hydrogen application impractical. "

Alternatives for hydrogen storage:

- Compressed hydrogen
- Liquefied hydrogen
- Chemical storage
- Metal hydrides
- Conversion to chemical compounds

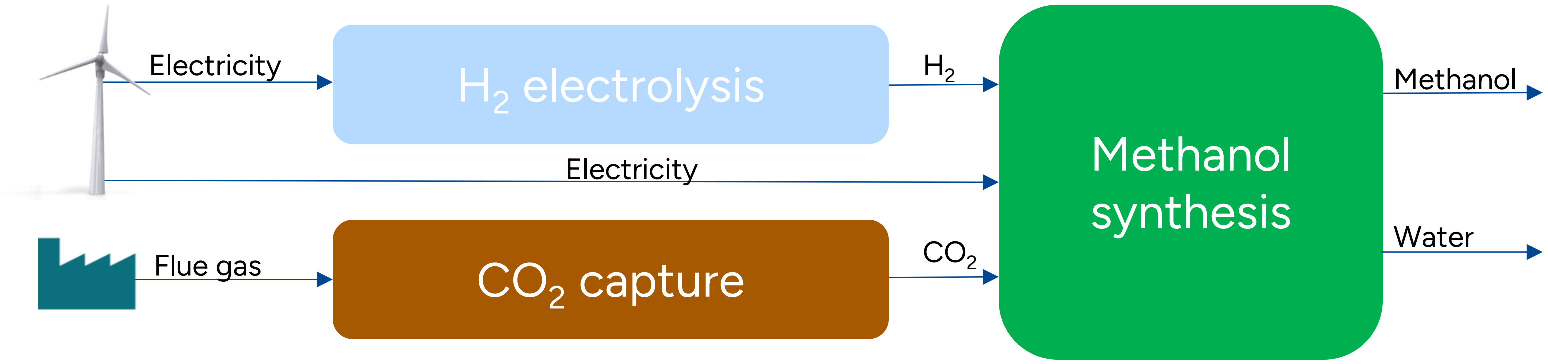


An overview of hydrogen storage technologies – Key challenges and opportunities , Mulky *et al*, Elsevier: Materials Chemistry and Physics Volume 325, 1 October 2024

Hydrogen applications

Applications:

- Metals production e.g. Stegra green steel and aluminium production
- Transport – fuel cell EV and combustion engine
- Synthetic fuels – Fischer-Tropsch synthesis (FTS)
- Methanol – precursor for paints, plastics, construction materials and vehicle parts
- Ammonia - Haber-Bosch process - fertilizers
- Pharmaceuticals
- Liquid H_2 aviation fuel



An overview of hydrogen storage technologies – Key challenges and opportunities , Mulky *et al*, Elsevier: Materials Chemistry and Physics Volume 325, 1 October 2024
The role of hydrogen in synthetic fuel production strategies - Mohammed Alsunousi, Erhan Kayabasi, Elsevier: International Journal of Hydrogen Energy Volume 54, 7 February 2024

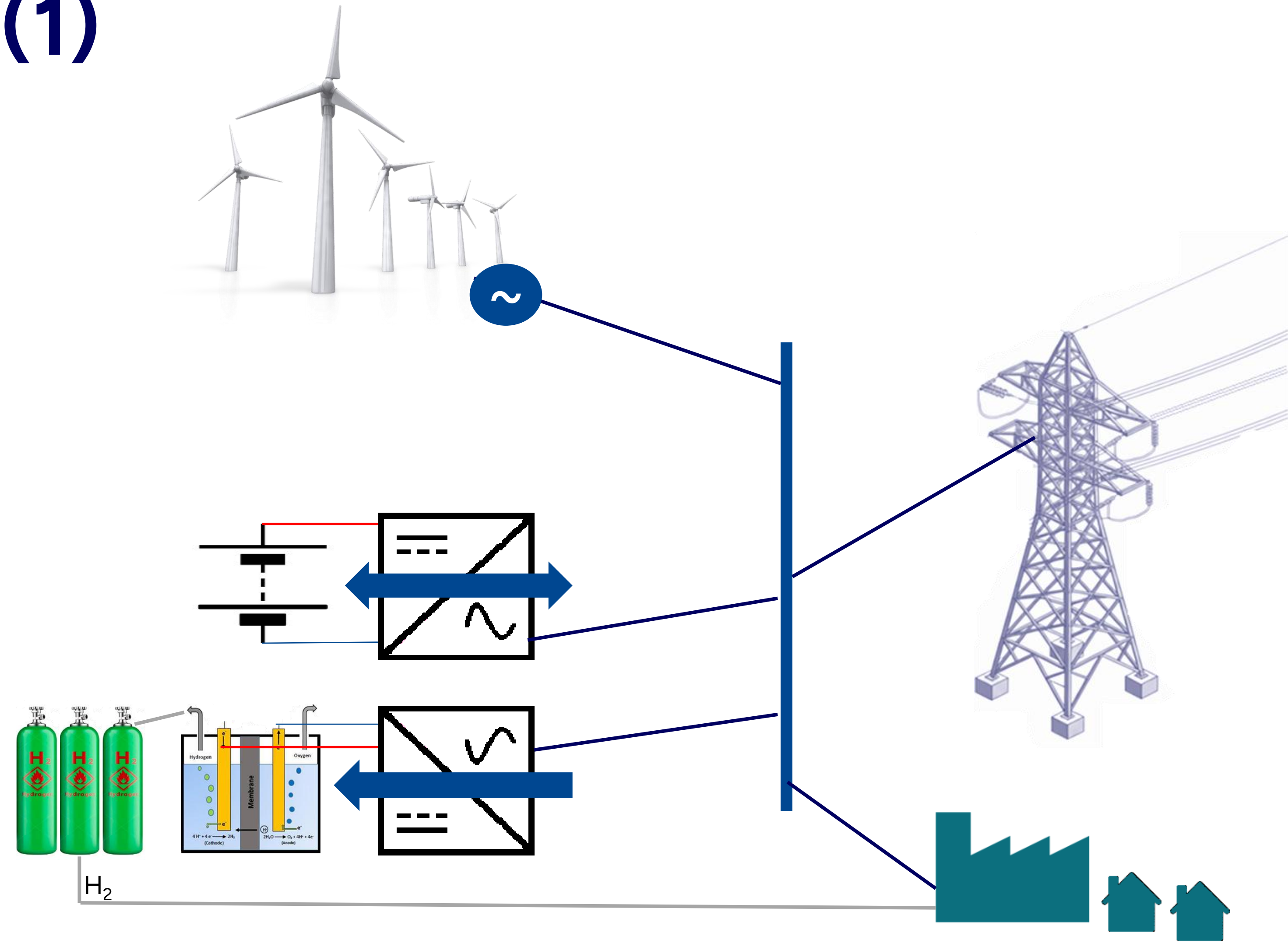
Hybrid system types (1)

AC-Coupled Wind-Storage Hybrid Systems

Easier integration into legacy systems

Underutilize BESS converter investment?

Combined total output of wind and BESS



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Hybrid system types (2)

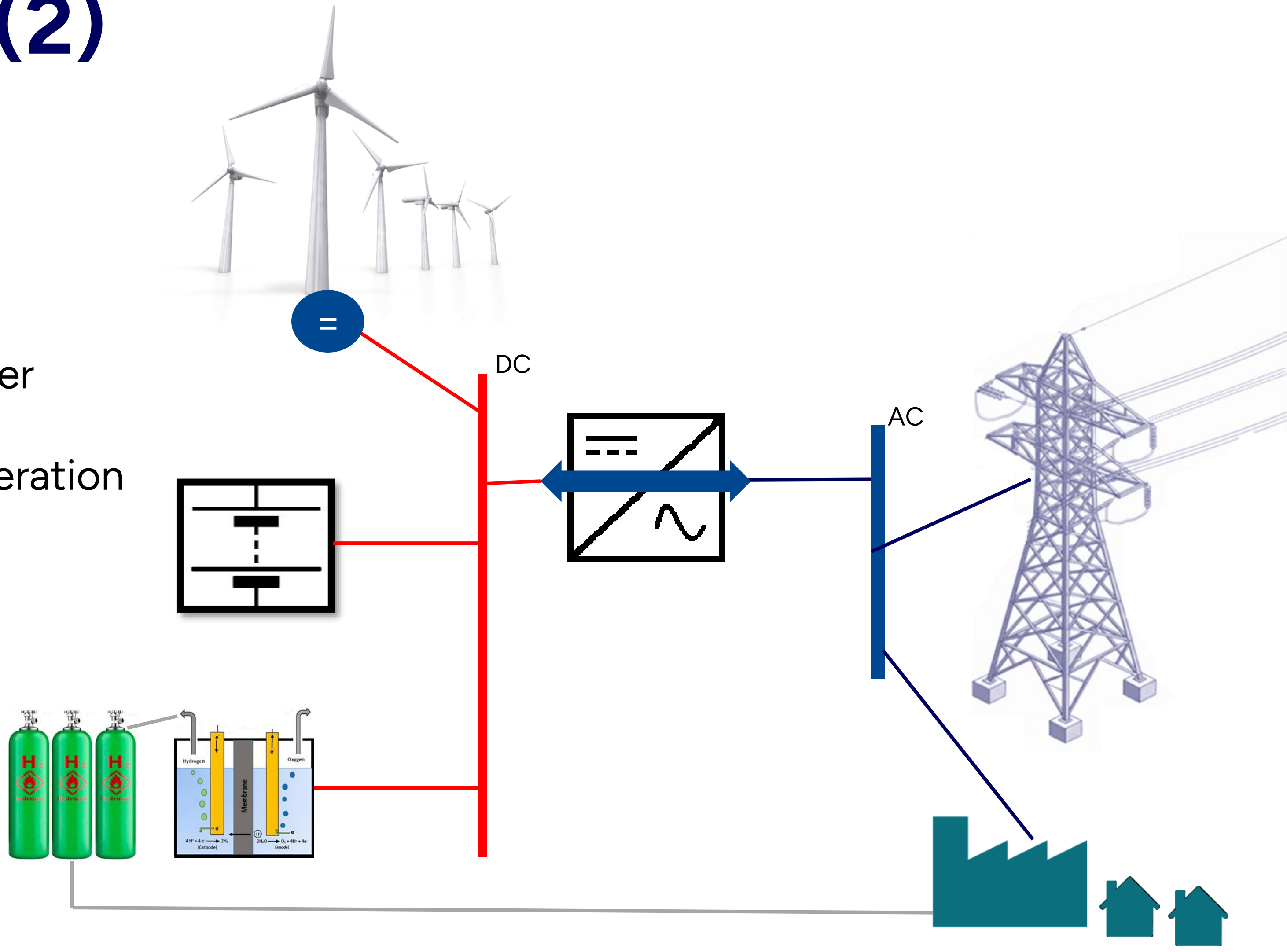
DC-Coupled Wind-Storage Hybrid Systems

Common converter/inverter from DC link

Needs DC-DC converter for BESS & electrolyser

Simplifies connection of other on-site DC generation

DC coupling not common



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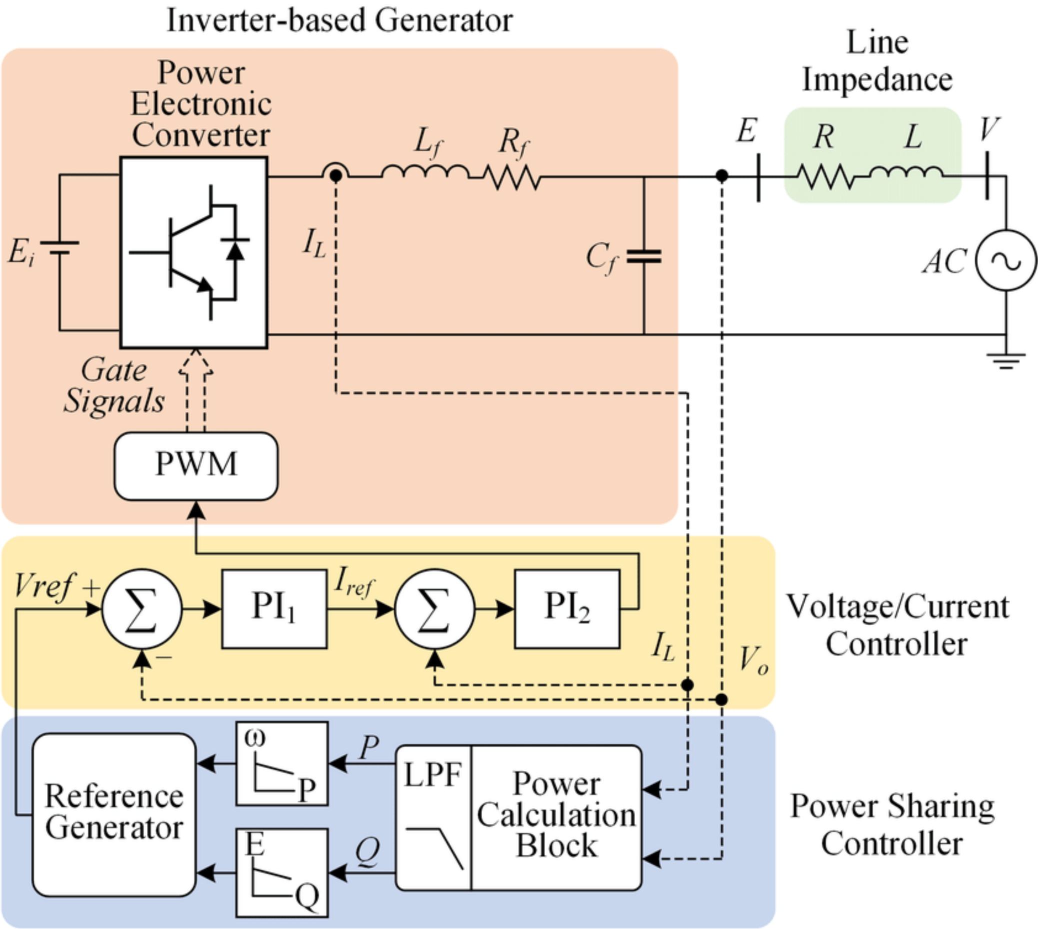
Inverters and power conversion



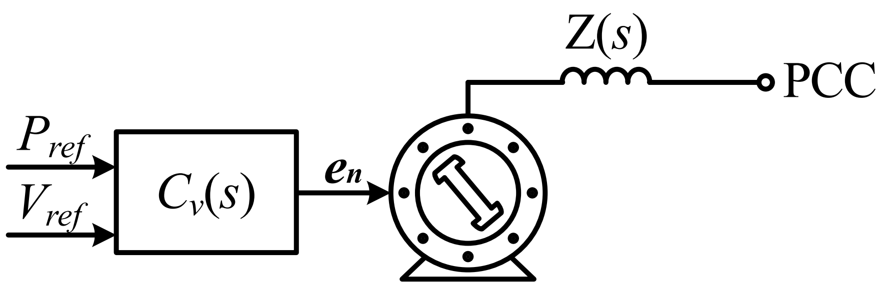
Review of Dynamic and Transient Modeling of Power Electronic Converters for Converter Dominated Power Systems – Shah et al, *IEEE Access*, vol. 9, pp. 82094-82117, 2021

Inverters and power conversion

Grid-Forming (GFM) Technology

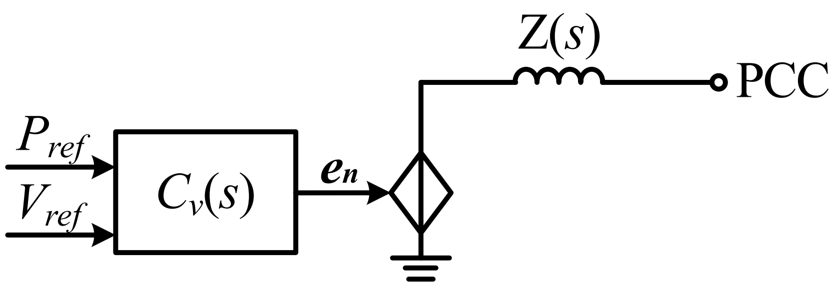
- **Synchronous machines are being replaced by grid-forming converters for frequency and voltage forming**

Synchronous Machine (SM)



- **Synchronization** governed by electromechanical swing, decoupled with electromagnetic transients
- **Inertia**, **damping**, governor (droop), automaticvoltage regulators, power system stabilizers

Grid-forming (GFM) Converter

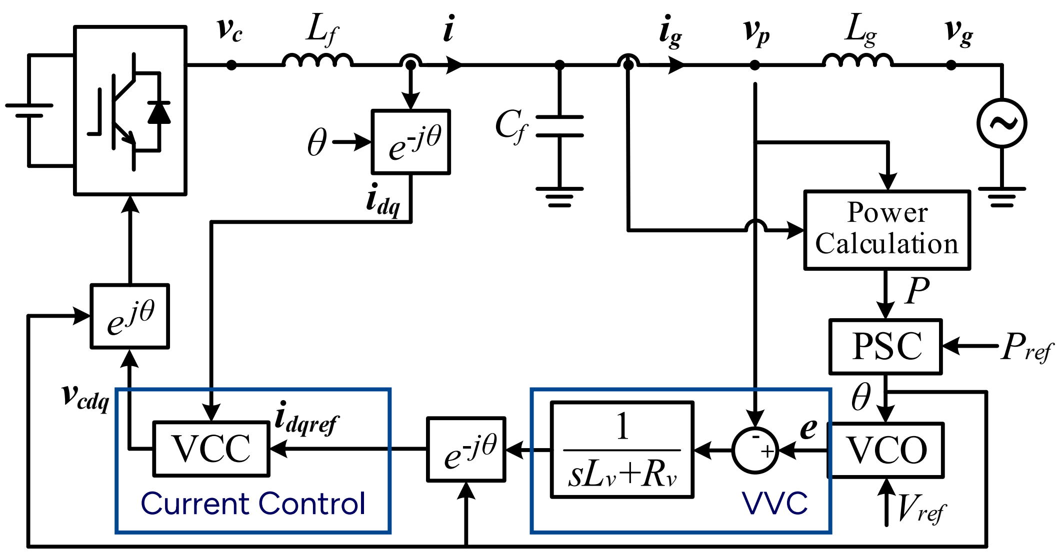


- **Synchronization** based on power/current flow, not rely on external frequency measurement
- **Inertia provision** through second-order power synchronization control

Inverters and power conversion

Grid-Forming (GFM) Technology

- **An Internal Voltage Source (IVS) behind an impedance**
  - Vector voltage control for voltage regulation
  - Second-order power synchronization control (PSC) for inertia provision



Current control is much fast, i.e. $\boldsymbol{i}_{dqref}=\boldsymbol{i}_{dq}$

Vector Voltage Control

$$\frac{\boldsymbol{e}-\boldsymbol{v}_p}{sL_v+R_v}=\boldsymbol{i}$$

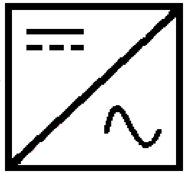
Virtual Admittance

Second-order PSC

$$J\ddot{\theta}+D\dot{\theta}=P_{ref}-P$$

Virtual Synchronous Generator (VSG)

Inverters and power conversion

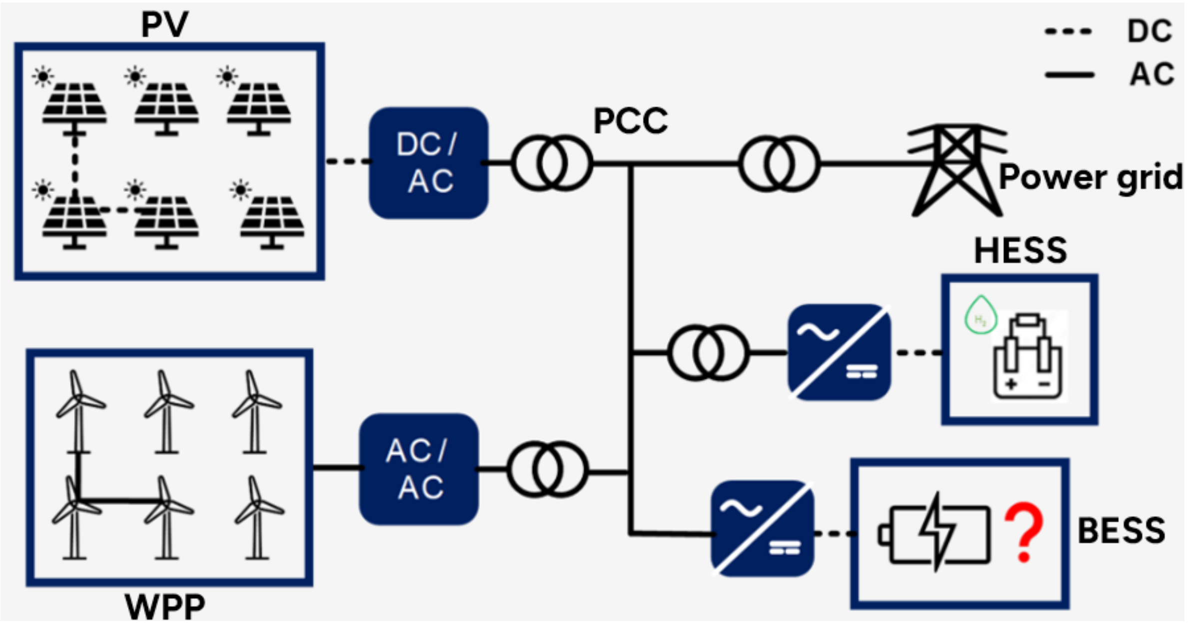


Dynamic Response Modeling and Analysis of Battery Energy Storage Systems for AC Interconnected Power Plants

- **PhD student:** Haowen Wang
- **Supervisors:** Xiongfei Wang and Ilka Jahn
- **Funding:** Hitachi & Shell
- **Project Description:**

This project will exploit **battery energy storage systems** to enhance the **AC interconnections** of **integrated hydrogen and wind power plants**. More specifically, this project will develop modeling and analysis methods for **identifying the dynamics challenges** with the integrated **wind and hydrogen power plants** under a wide range of grid conditions and exploring the potential of BESS in **addressing the identified challenges**.

Inverters and power conversion



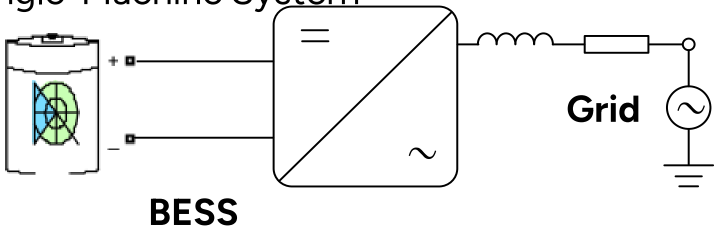
Main Researches Goals

How GFM-BESS provides damping and stability support during transient dynamics

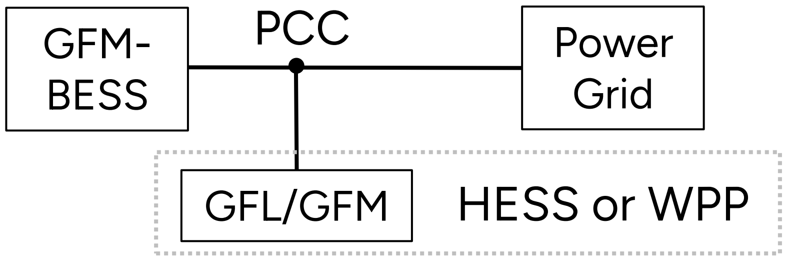
- Dynamic response analysis (disturbance-to-output & reference-to-output) of multi-machine parallel system.
- Transient stability assessment method.

Project timeline

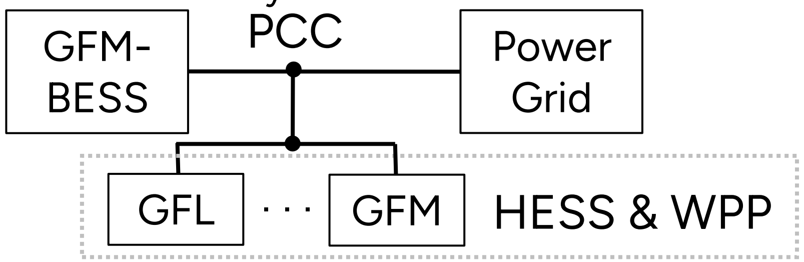
Period 1
Single-Machine System



Period 2
Dual-Machine System

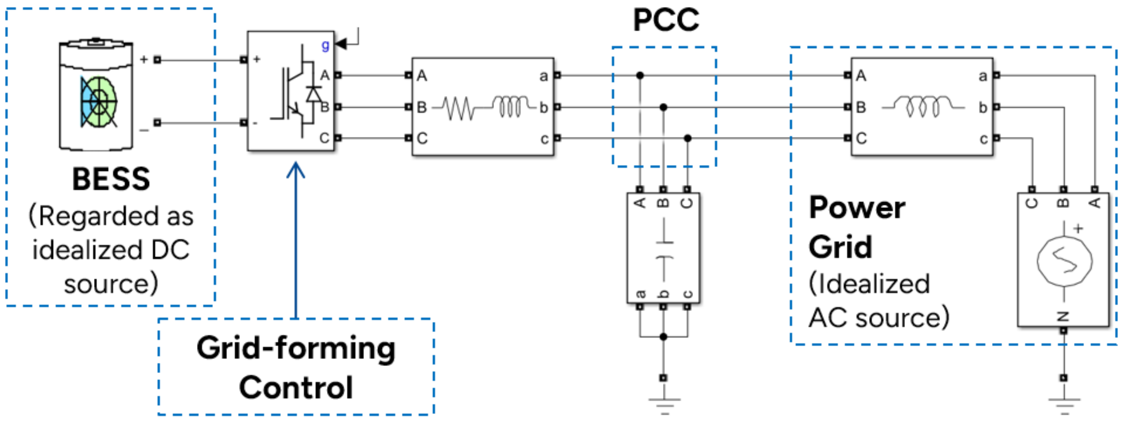


Period 3
Multi-Machine System



Current Work

Interation between GFM-BESS and Power Grid under Large Disturbance



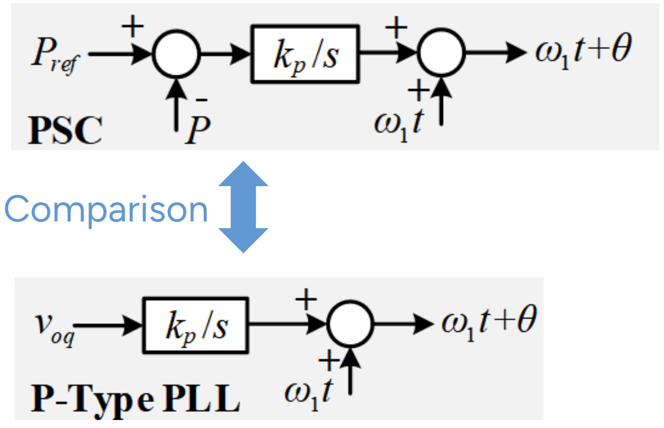
Type of Large Disturbance of Grid

- Voltage dip
- Phase jump
- Short/Open circuit, etc.

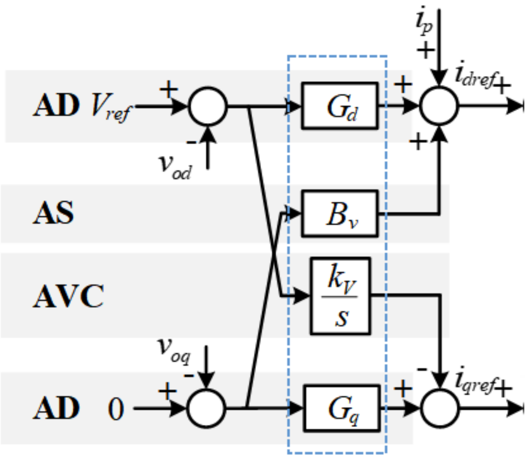
Details

- Derive the large-signal model combining synchronization and voltage loop, based on which the influences of parameters on dynamic behavior are able to be analyzed.

1. Comparison of PSC and PLL

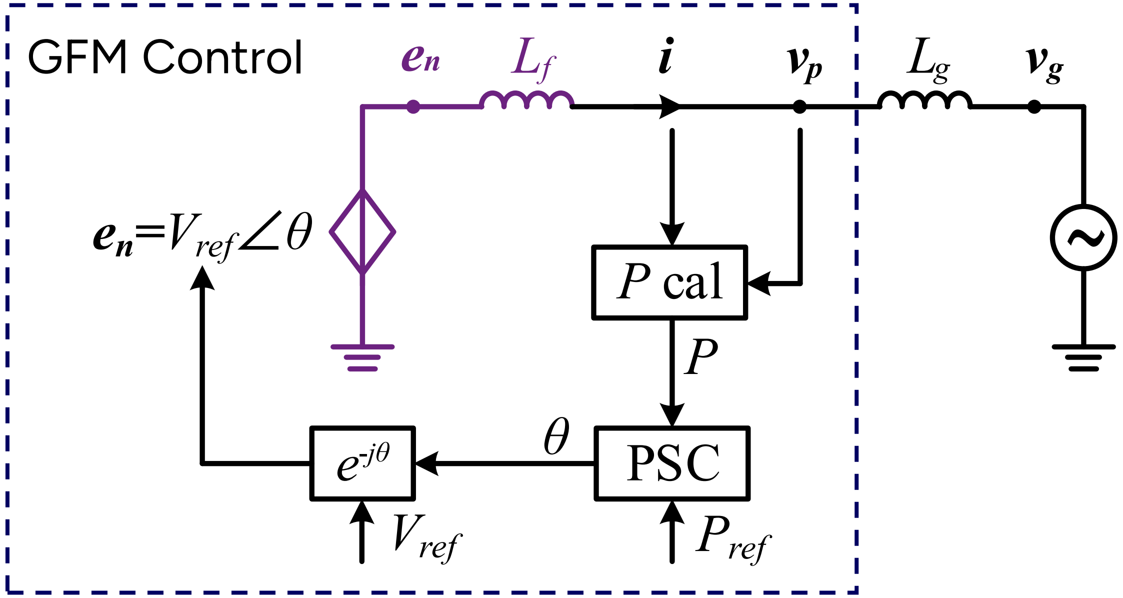


2.Influence of Parameters



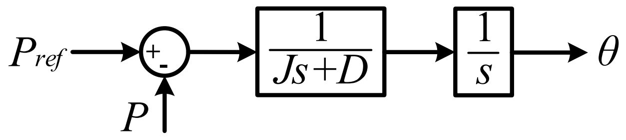
Transient Stability Issue

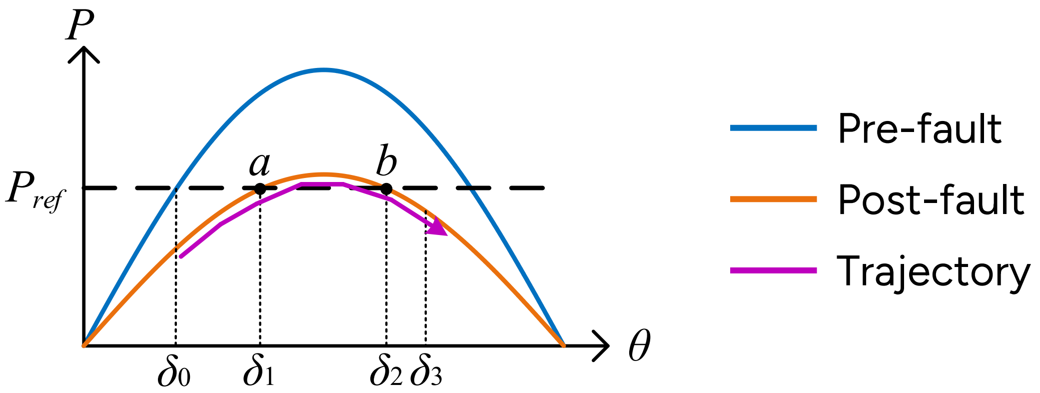
- **An Internal Voltage Source (IVS) behind an impedance**
  - Transient instability problem even if the equilibrium exists



PSC Loop

$$J\ddot{\theta} + D\dot{\theta} = P_{ref} - \underbrace{\frac{V_{ref}V_g}{X_g + X_f}\sin\theta}_{P}$$





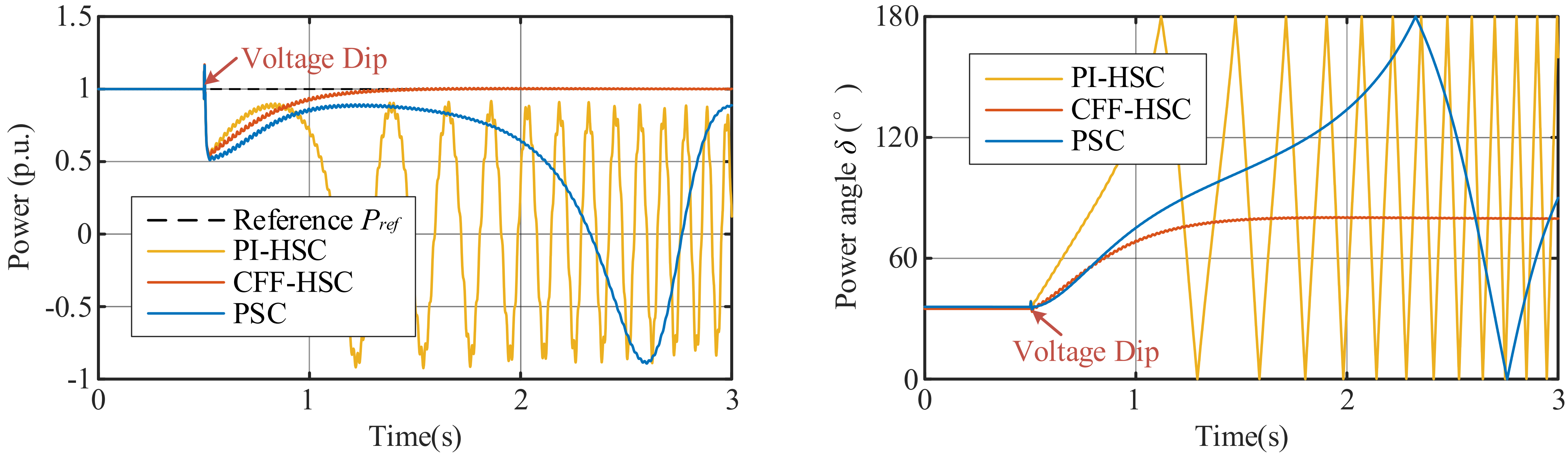
Angle reaches δ_3, losses synchronization.

- The capacitor's influence on the transient process is limited
- R_v is relatively small to be ignored

F. Chen *et al.*, "A Cascaded Hybrid Synchronization Control for Grid-Connected Inverters," in *IEEE Transactions on Power Electronics*, vol. 41, no. 1, pp. 137-142, Jan. 2026, doi: 10.1109/TPEL.2025.3603944

Simulation Results

- **Voltage disturbance with 48% voltage dip, SCR=2**



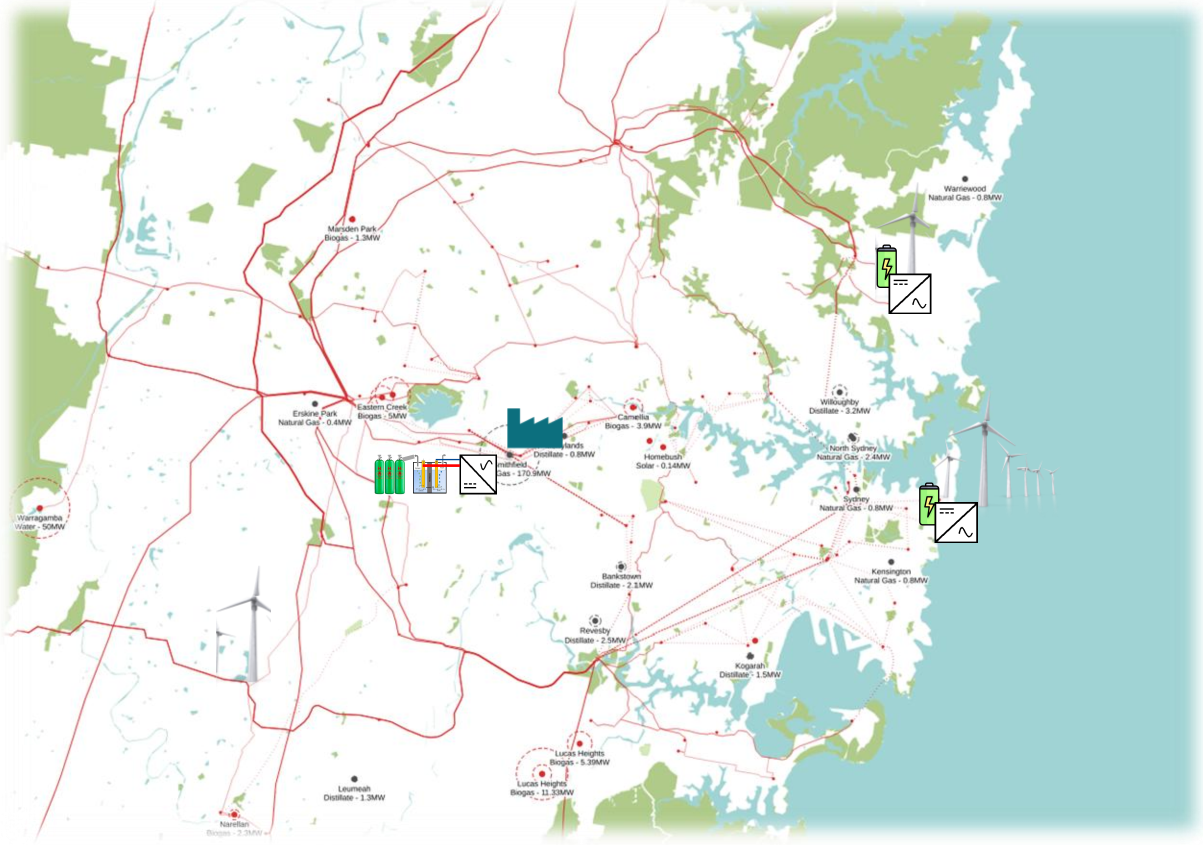
Conclusion: CFF-HSC maintains synchronization after fault.

"Current-Feedforward-Based Hybrid Synchronization Control for Transient Stability Enhancement" H. Wang, X. Wang, I. Jahn, 24th Wind & Solar Integration Workshop, Berlin, Germany, 7–10 Oct 2025

AC Interconnected Wind and Hydrogen Systems

Summary:

- System efficiency and cost
- System design trade-offs
- Technical and equipment considerations
- Grid services and flexibility
- Economic value and business case
- Market integration and modelling



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