HyLeit WS: Grid forming in Electrolysis Plants

Grid-forming for Network Resilience: A System Restoration Case Study

Dr. Abdulrahman Alassi, Power Systems Manager, Iberdrola Innovation Middle East
Dr. Zhiwang Feng, Research Associate, University of Strathclyde

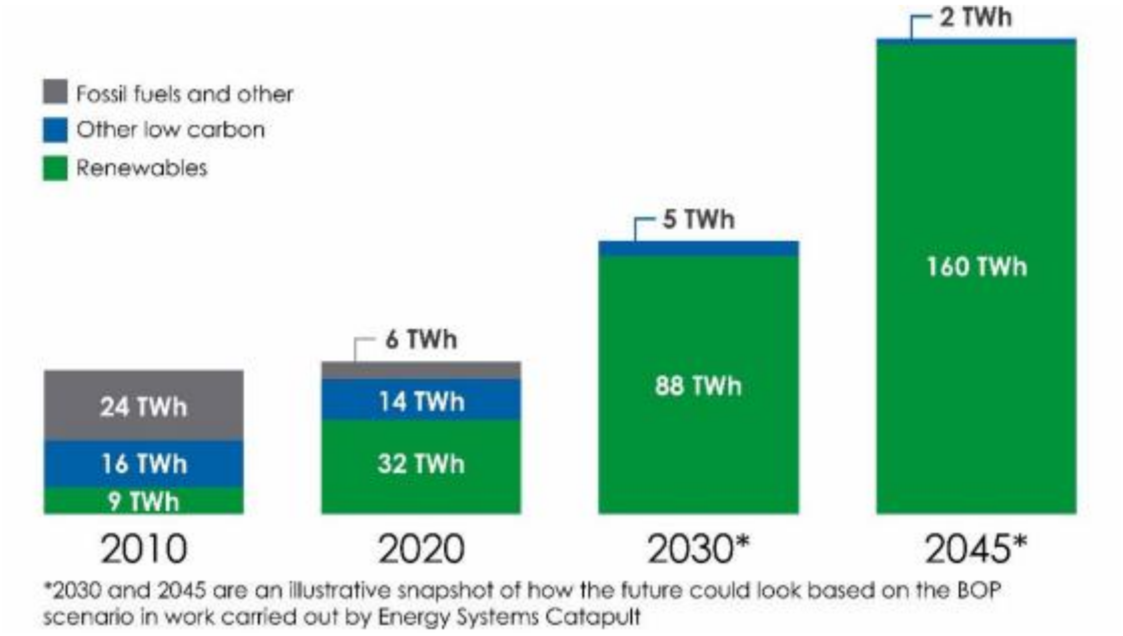
Outline of the presentation

- **Ancillary Services from Inverter-Based Resources**
- Grid-forming for Network Restoration
- Control Considerations
- Experimental Validation
- Takeaway Messages

Ancillary Services from Inverter-Based Resources

❑ Power Grid Transformation

- GB power system set to operate with net-zero by 2050
- Significant progress in decarbonising electricity grid



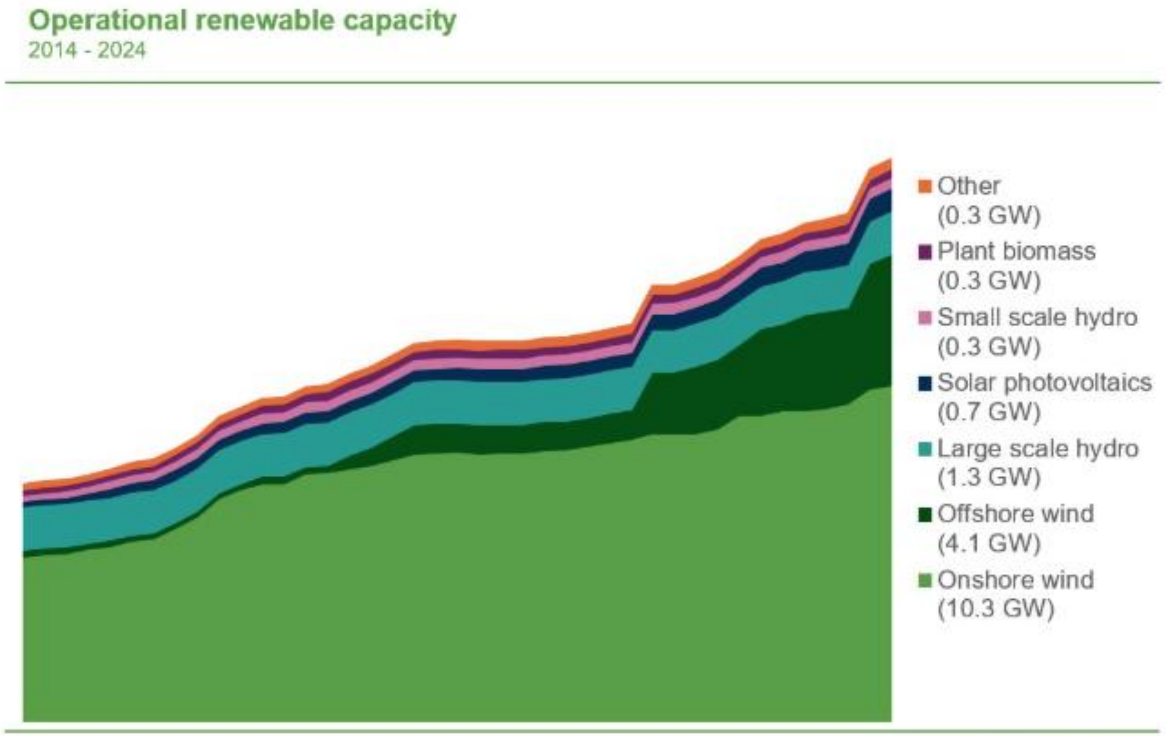
Electricity generation in Scotland – past, present and future

Source: Scottish Energy Statical Hub and Scottish whole energy system scenarios
Source: https://www.gov.scot/publications/draft-energy-strategy-transition-plan/documents/

Ancillary Services from Inverter-Based Resources

❑ Power Grid Transformation

- GB power system set to operate with net-zero by 2050
- Significant progress in decarbonising electricity grid
- Significant penetration of renewable electricity generation
- High penetration of power electronics interfaced distributed renewable resources



Scotland's electricity generation from renewable sources

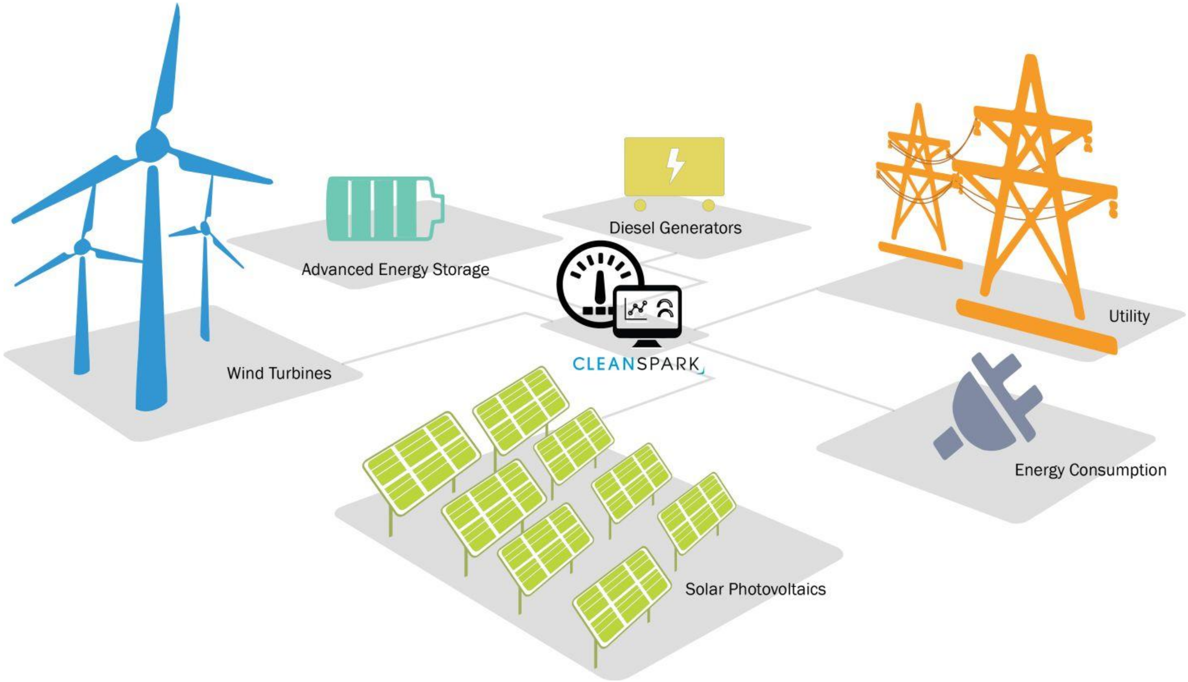
Note - 'other' includes the following technologies: shoreline wave/tidal; landfill gas; sewage sludge digestion; energy from waste; animal biomass; and anaerobic digestion

Source: Energy Statistics for Scotland – Q4 2024 https://www.gov.scot/publications/energy-statistics-for-scotland-q4-2024/pages/renewable-electricity-capacity/

Ancillary Services from Inverter-Based Resources

❑ Ancillary Services from IBRs

- Frequency and inertia support
- Synchronized regulation
- Contingency reserve
- Black-start regulation
- and more ….



Source: Yu, Z.-X.; Li, M.-S.; Xu, Y.-P.; Aslam, S.; Li, Y.-K. Techno-Economic Planning and Operation of the Microgrid Considering Real-Time Pricing Demand Response Program. Energies 2021, 14, 4597. https://doi.org/10.3390/en14154597

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Grid-forming for Network Restoration

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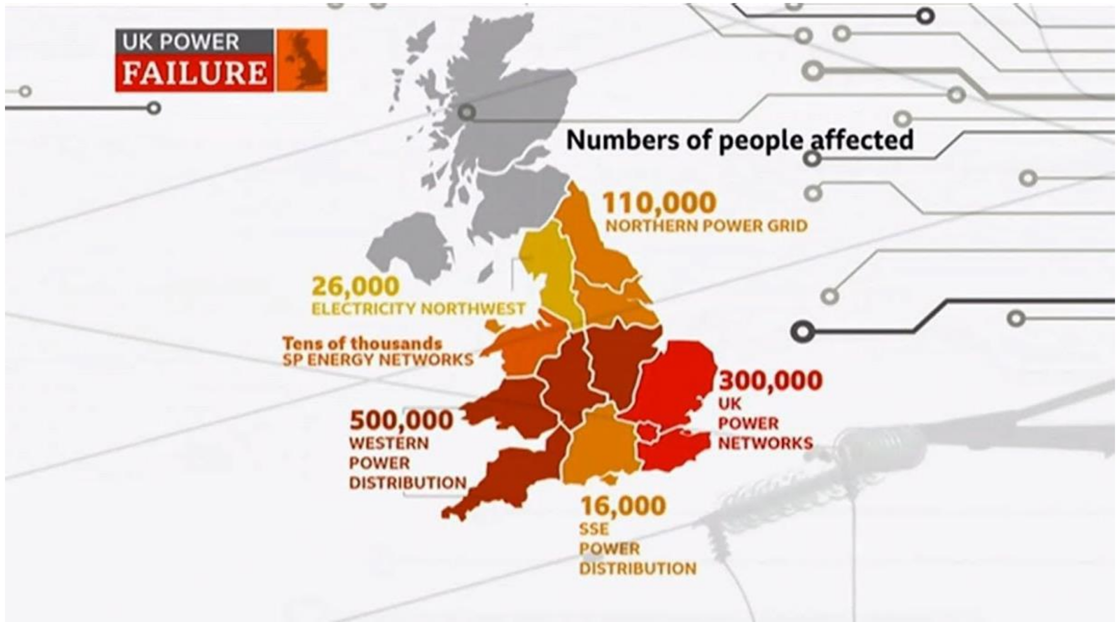
❑ Significance of Network Restoration

"Distributed ReStart was a world-first initiative. The project explored how distributed energy resources (DER) such as solar, wind and hydro, can be used to restore power to the transmission network in the unlikely event of a blackout - a process known as black start." – National Grid



SP Energy Networks tnei NESO National Energy System Operator

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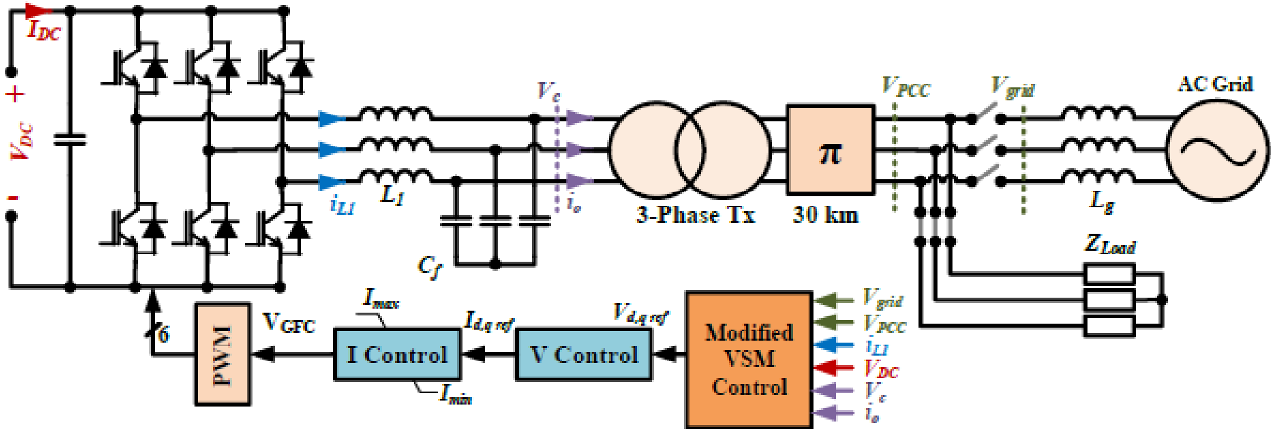
Grid-forming for Network Restoration

❑ Relevant Capabilities

- Flexible voltage control
- Self-synchronization
- Self-generated reference

❑ Implication

- Ability to anchor network restoration following blackouts



Power network with grid-forming converter for network restoration

A. Alassi, Z. Feng, K. Ahmed, M. Syed, A. Egea-Alvarez, C. Foote, *Grid-forming VSM control for black-start applications with experimental PHiL validation,* International Journal of Electrical Power and Energy Systems, volume 151, 2023, 109119, Doi: 10.1016/j.ijepes.2023.109119.

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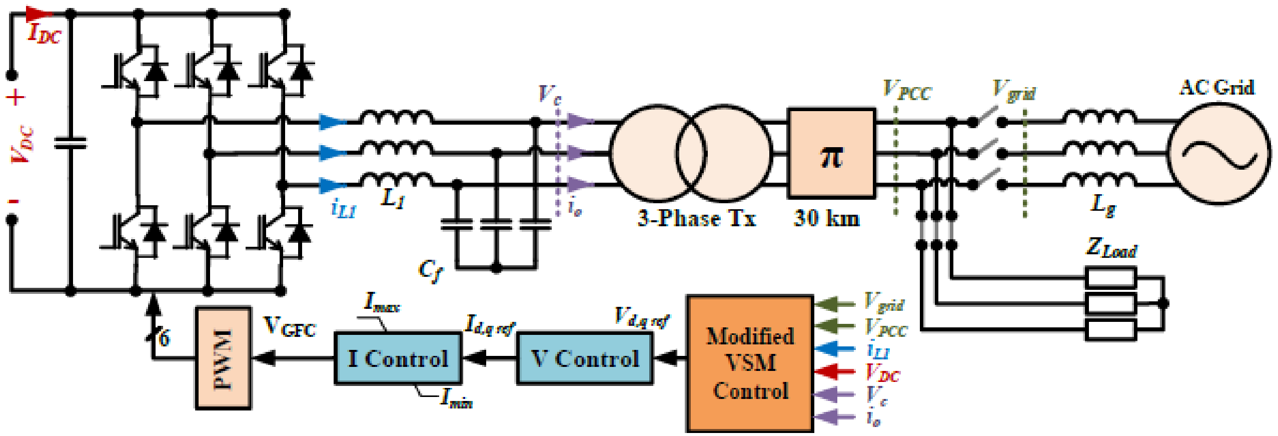
Grid-forming for Network Restoration

University of Strathclyde Engineering

❑ Grid-forming Converter for Network Restoration – Key Challenges

- Inrush current mitigation for power transformers energization during network restoration
- Network energization of critical loads and its associated transient and reliability issue
- Synchronization between energized network and the main grid after receiving the restoration command from network operator



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Control Considerations (GFM Selection)

Controllers Benchmark Strategy

Define Performance-Robustness Testing Disturbances
- Load Step (0.5 pu)
- V_{DC} Reference Step (0.2 pu)
- P_{ref} Step (0.5 pu)

⬇

Define Common Testing Conditions (common-ground benchmark)
- Unified PI Tuning
- Unified P-f slope
- Unified DC Control

⬇

Define Benchmark Parameters
- Frequency & RoCoF
- P & Q
- DC and AC Voltages

⬇

Define Soft Energization Testing Conditions
- Define load P and Q
- T_{ramp} = 10 s
- Observe *P, Q, V and f*

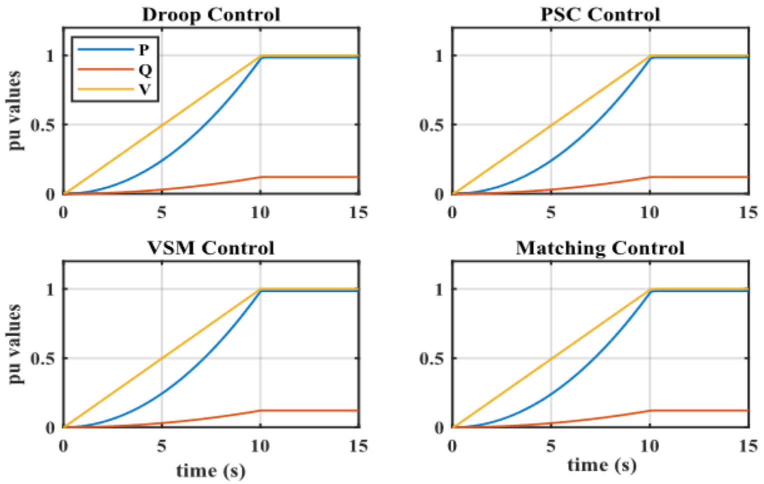
⬇

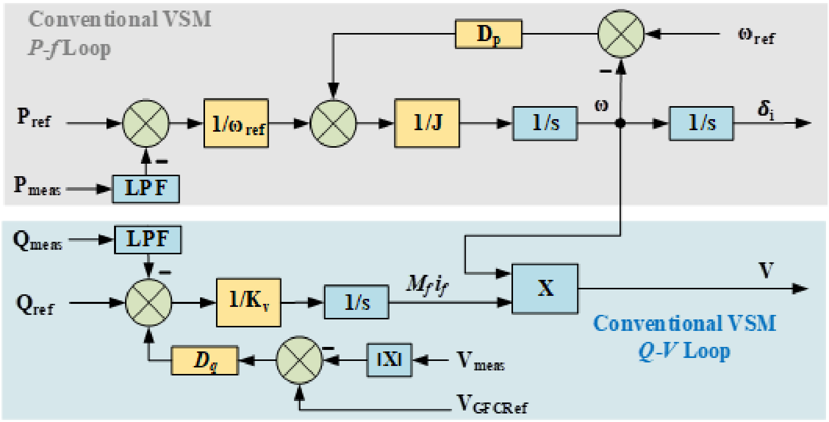
Execute the automated scripted simulations under the various operating conditions

⬇

Ranking and Suitable Techniques Selection
- Grid code compliance
- Performance rank
- Outliers identification

Sample Results





Key Observations

- Performance similarity between different grid-forming control techniques
- Persistent observation under transient, steady-state and ramping conditions

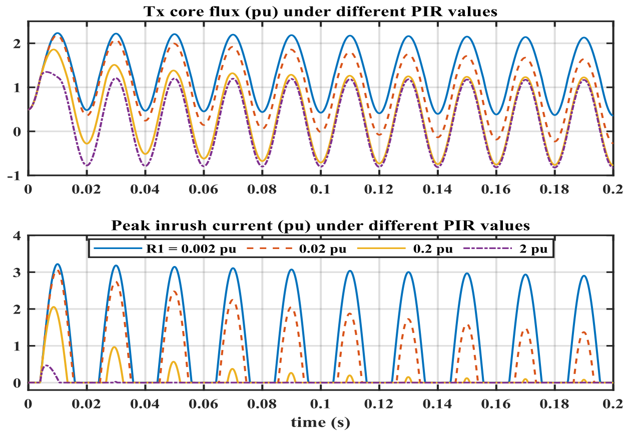
VSM is selected, but is not the only compatible control technique

A. Alassi, K. Ahmed, A. Egea-Alvarez, O. Ellabban, *Performance evaluation of four grid-forming control techniques with soft black-start capabilities*. In ICRERA 2020, the 9th International Conference on Renewable Energy Research and Application, Glasgow, UK, doi: 10.1109/ICRERA49962.2020.9242758.

Control Considerations (Inrush Current Mitigation)

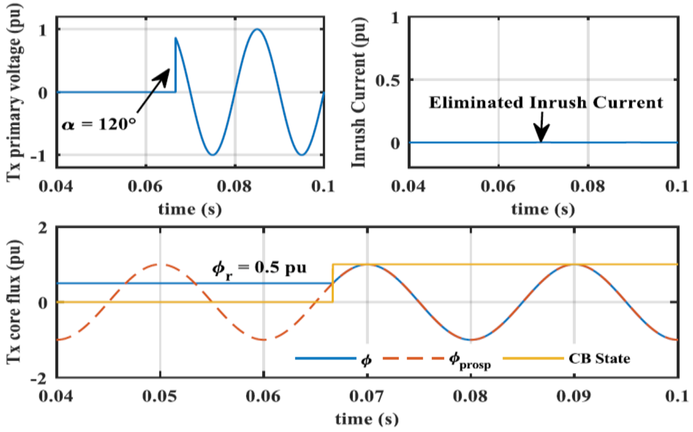
Pre-Insertion Resistor

- Requires the temporary connection of external resistor(s) – *complexity/cost*
- Limited reliance on unit measurements
- Classically independent of VSC control
- Recent proposals to mimic its behavior using VSC control (virtual impedance)



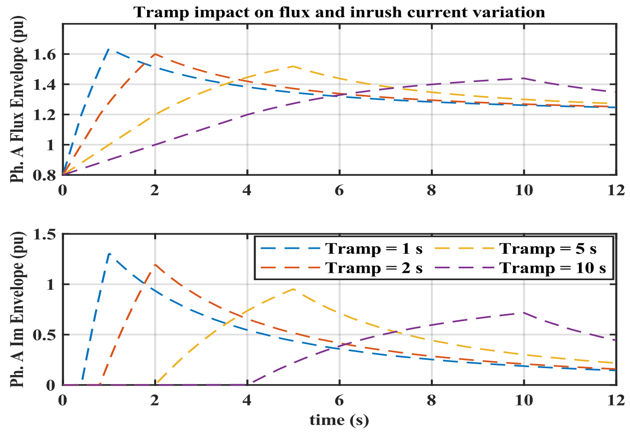
Controlled Switching

- Requires switching-angle control
- Single-Pole vs. Three-Pole CB considerations
- Dependent on transformer measurements
- Preliminary simulations show compatibility with VSCs switching



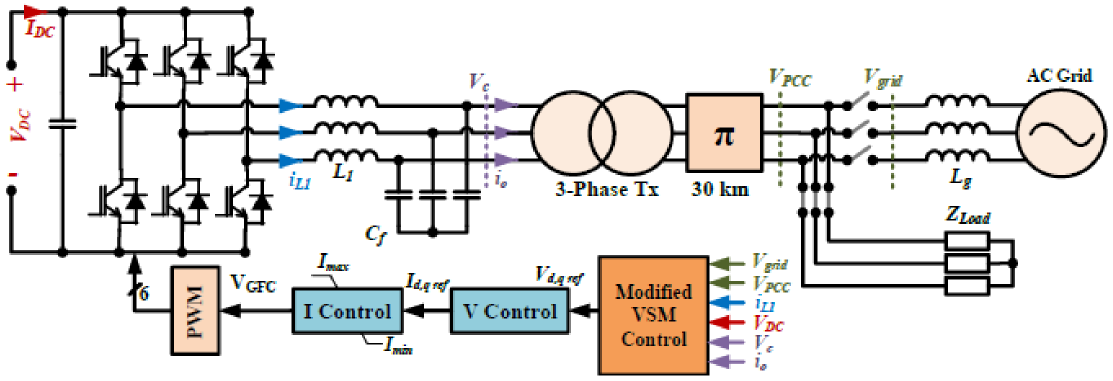
Soft Energization

- Exploits VSCs voltage control flexibility
- Gradual voltage ramp to the setpoint
- Dependent performance on flux initial point
- **Key question:** how to design adequate ramp-rates?

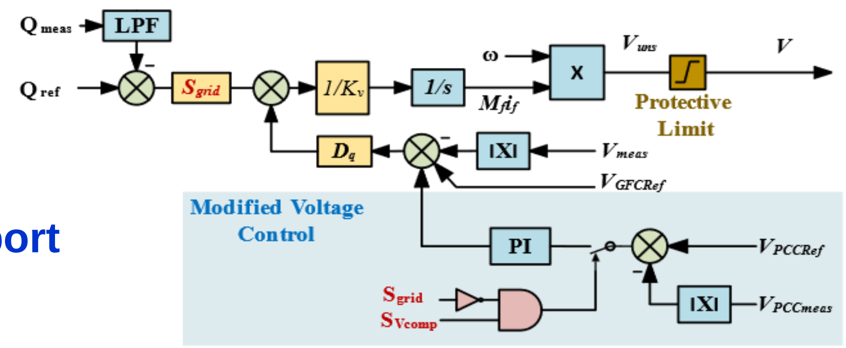


A. Alassi, K. Ahmed, A. Egea-Alvarez, C. Foote, *Transformer Inrush Current Mitigation Techniques for Grid-forming Inverters Dominated Grids,* IEEE Transactions on Power Delivery, volume 38, 2022, DOI: 10.1109/TPWRD.2022.3218923.

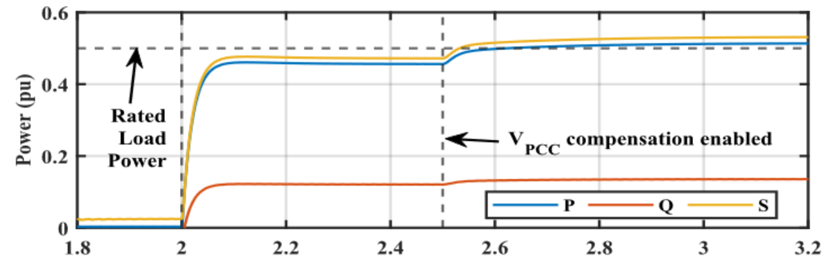
Control Considerations (Voltage Support)

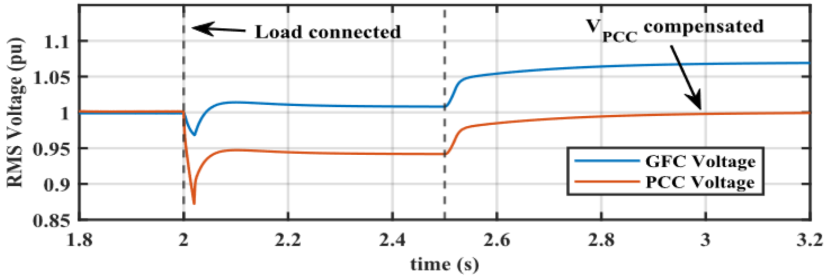


- **Objective**: compensate for voltage drops resulting from block loading
- Saturates at GFM protective voltage limits
- Can be incorporated with PCC voltage estimators in case of lacking communication links



Voltage Support Control





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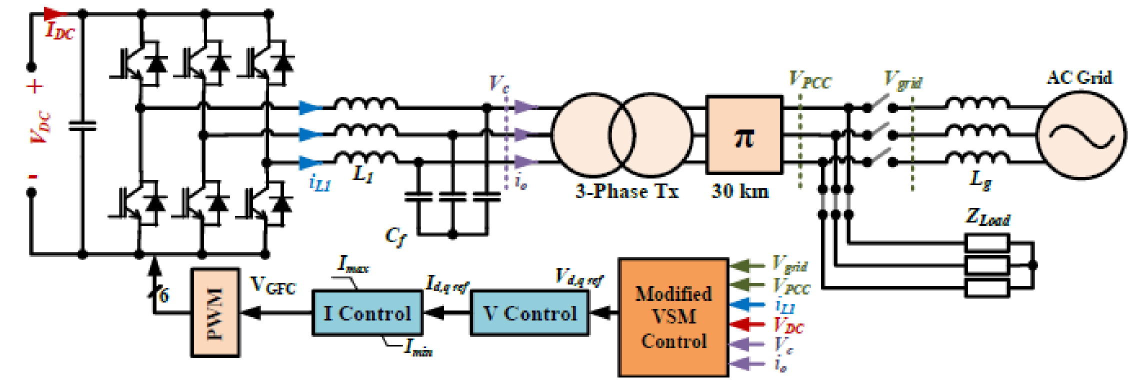
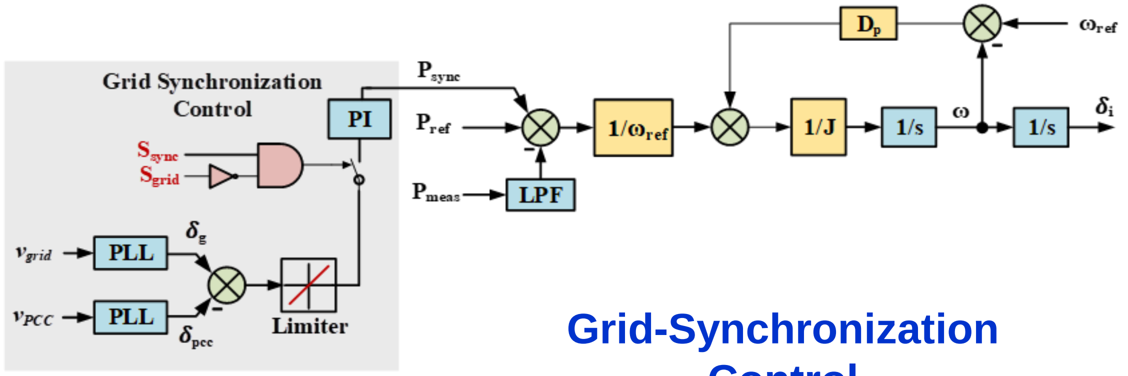
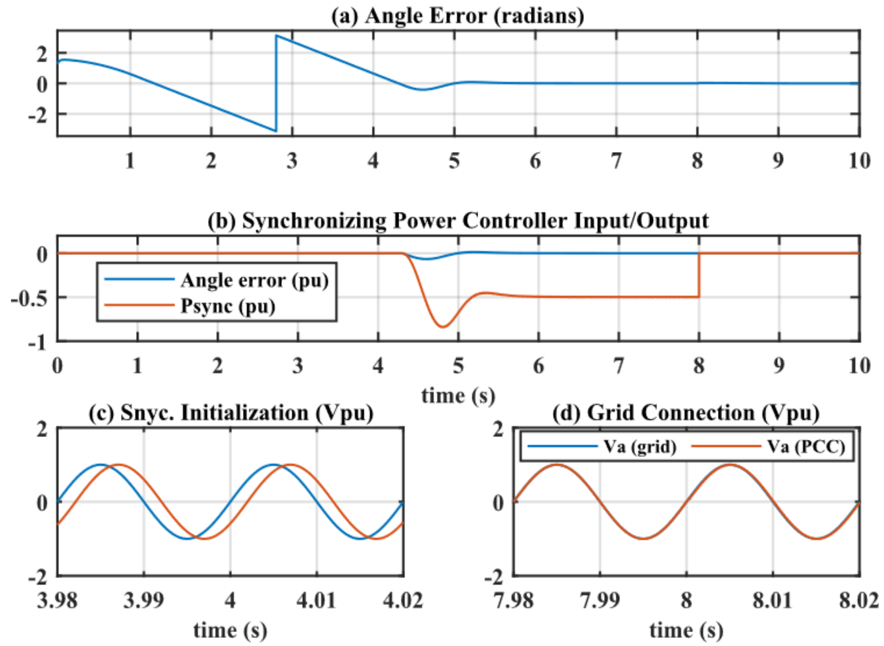
Control Considerations (Grid Synchronization)





Grid-Synchronization Control

- **Objective**: synchronize to the neighbouring 'island' or grid
- Inserts a virtual power reference to the power loop for angle matching
- Extendable to multi-converter systems



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- **Experimental Validation**
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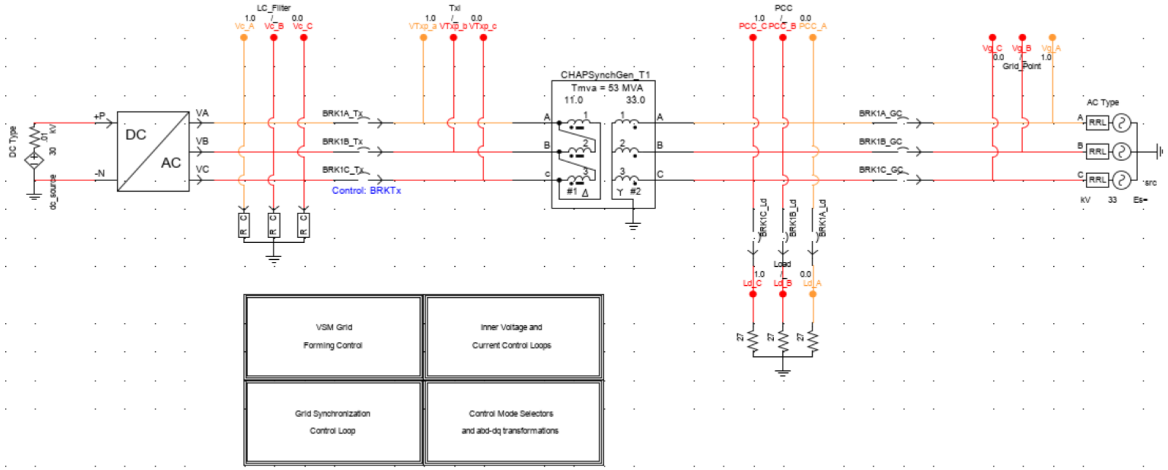
Experimental Validation

❑ Limitation of Pure Simulation

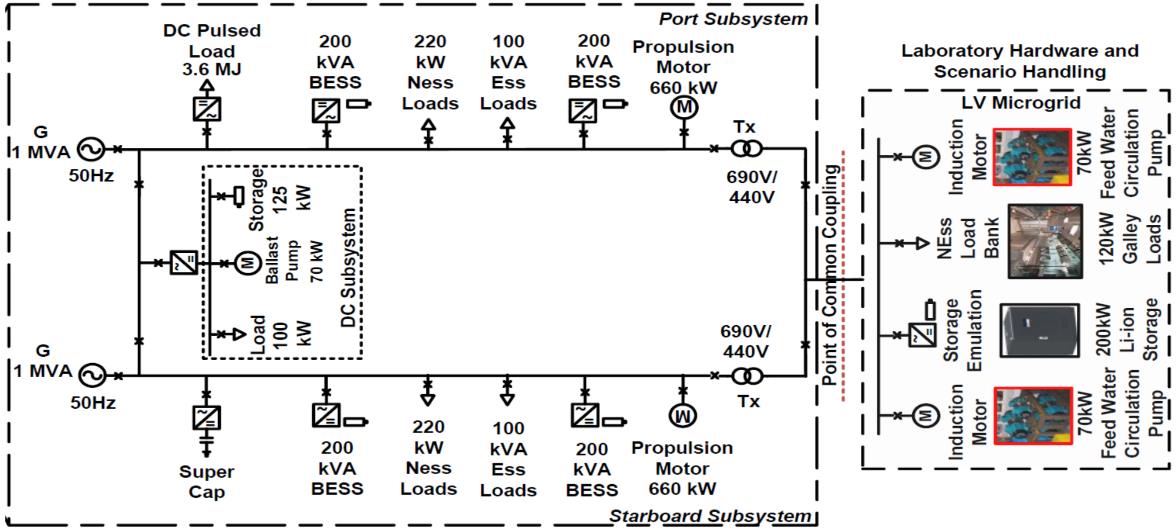
- Limited computation capability for In-depth and comprehensive testing of GFM
- Lack of real physical dynamics of GFM



Pure software based simulation and validation

❑ Limitation of Hardware Experiment

- Risky pure hardware experiment with high cost
- Impractical and inefficient hardware experiment in MW scale in laboratory



Pure hardware based experimental validation

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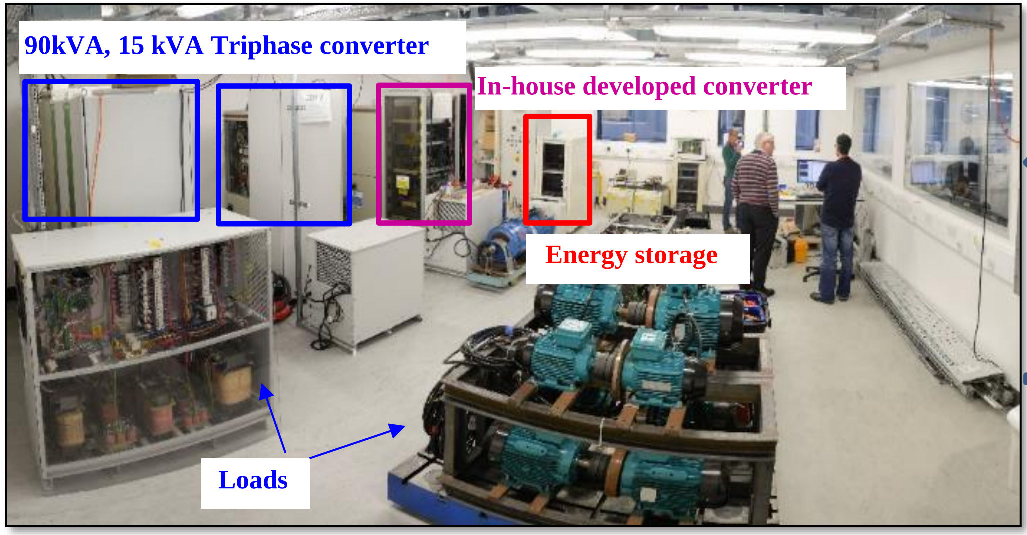
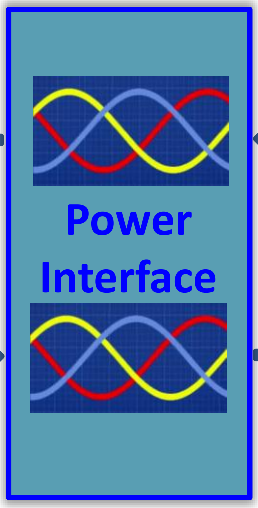
Experimental Validation

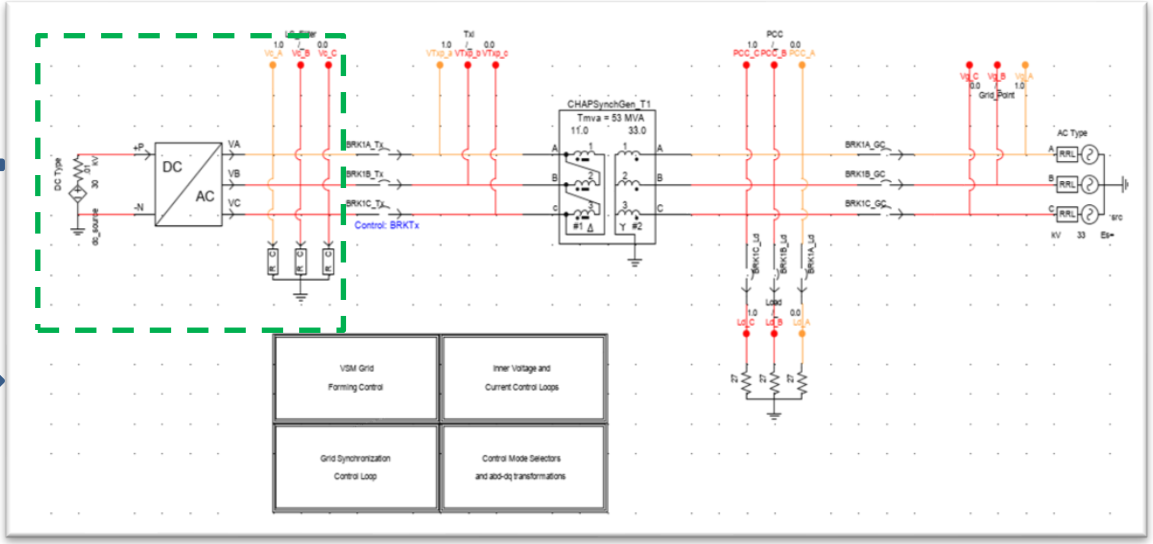
❑ Power Hardware-in-the-Loop Experimental Validation

- Narrow the gaps between pure simulation and hardware experiment
- Evaluate the potential of the network restoration capability of grid-forming converters in different networks and network configurations
- Grid-forming control validation in a controllable testing setup with massive testing scenarios



Hardware experimental setup of system under test





Pure simulation of system under test

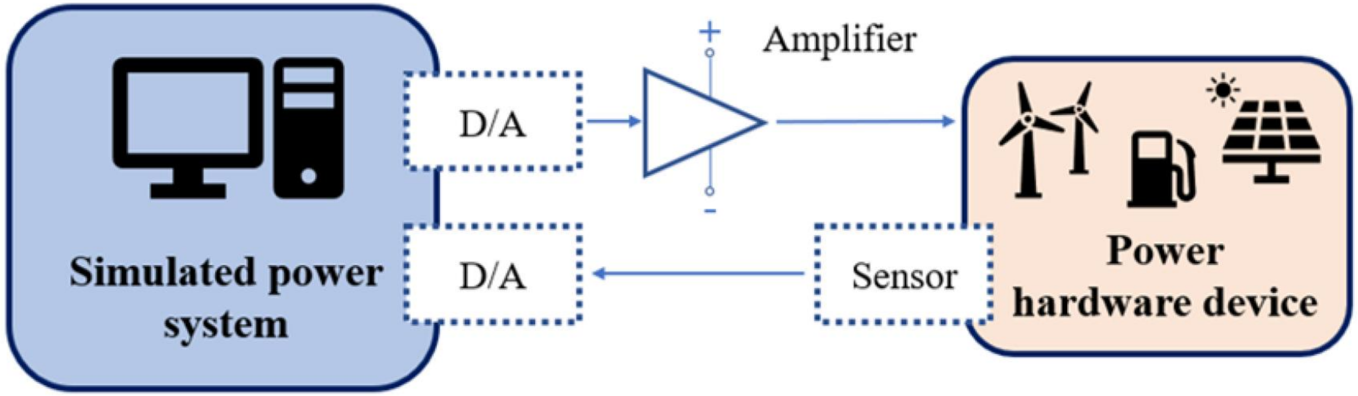
Experimental Validation

❑ Candidate PHIL Interfacing Methods

- **Ideal Transformer Model (ITM)**
- Transmission Line Model (TLM)
- **Partial Circuit Duplication (PCD)**
- Damping Impedance Method (DIM)
- Time-Variant First-Order Approximation (TFA)

❑ Assessment Criteria

- Feasibility
- Applicability
- Stability & Accuracy

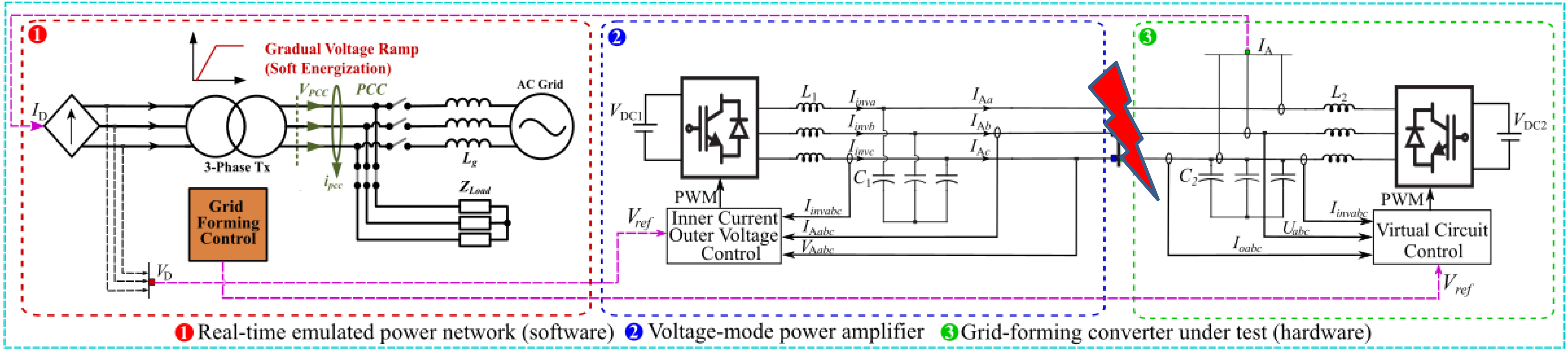


Equivalent PHIL diagram

Experimental Validation

❑ Interface Method I: Voltage-type ideal transformer model (ITM) interface

- Extensively applied for grid-following converter testing
- Simplified structure and ease of implementation
- Stability & Accuracy (?)



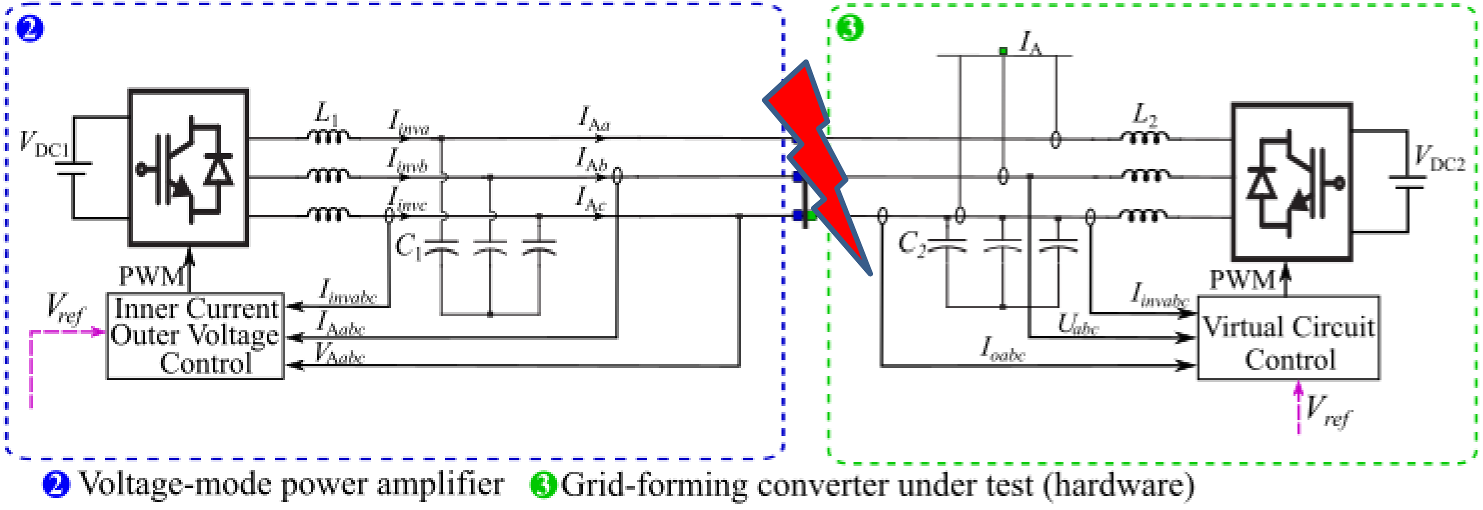
Equivalent circuit diagram of the PHIL with grid forming converter and voltage-type ITM interface

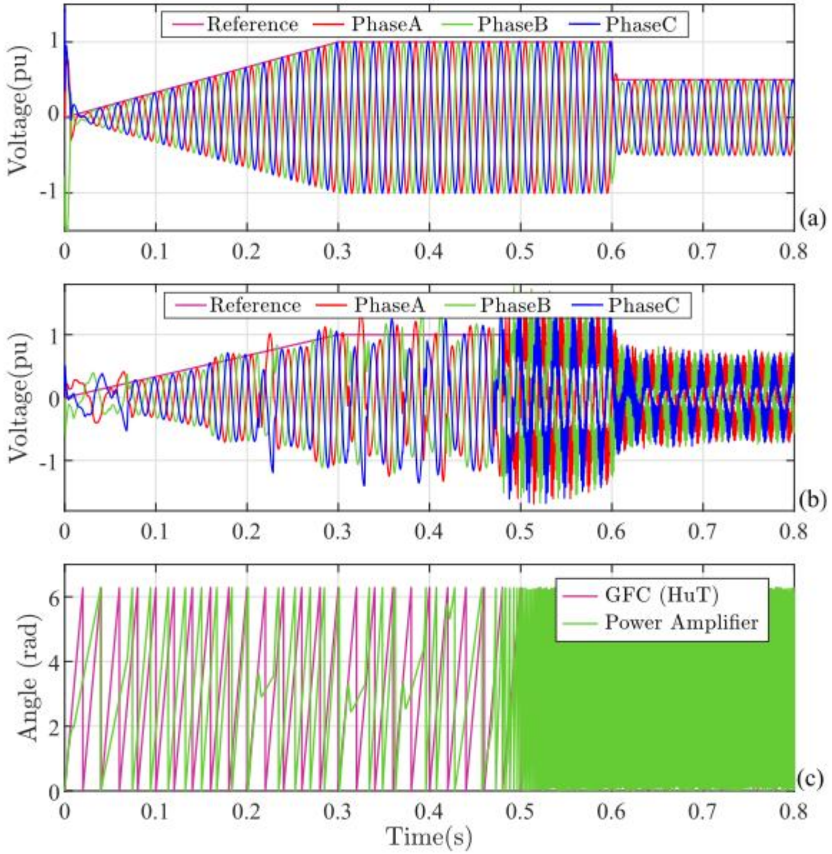
Z. Feng, A. Alassi, M. Syed, R. Pena-Alzola, K. Ahmed, G. Burt, *Current-type power hardware-in-the-loop interface for black-start testing of grid-forming converter*. in IECON 2022, The 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium, pp. 1-7, doi: 10.1109/IECON49645.2022.9968517

Experimental Validation

❑ Interface Method I: Voltage-type ITM interface

- Key Challenges: Lack of voltage angular synchronization at the coupling point between GFM and power amplifier
- Stability & Accuracy (x)
- Feasibility & Applicability (x)





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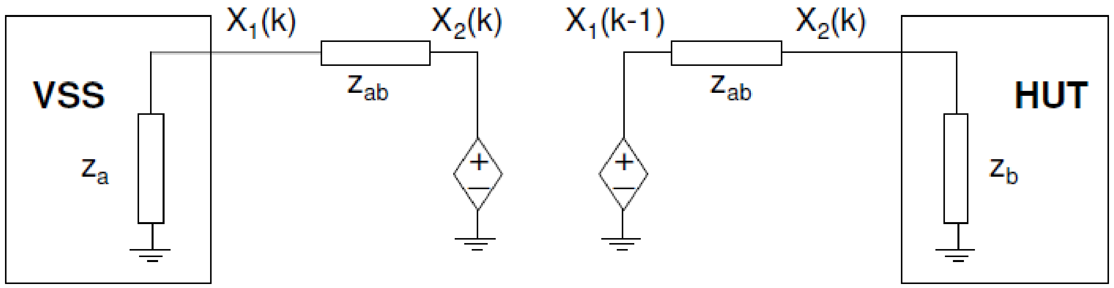
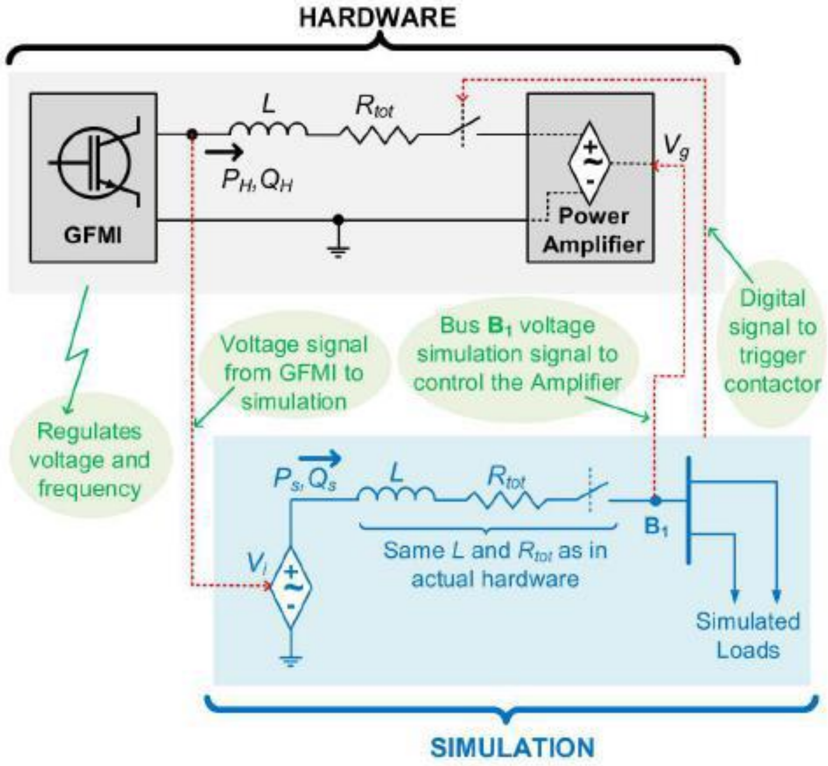
Experimental Validation

Interface Method II: Partial Circuit Duplication (PCD)

- Voltage synchronization issue was tackled by inserting a large physical linking impedance between GFM and power amplifier
- A physical linking impedance was implemented in simulation side to form a digital twin of the physical linking impedance
- Feasibility and Stability (✓)



Equivalent diagram of PCD interface



Equivalent diagram of PHIL setup with grid forming converter and PCD interface

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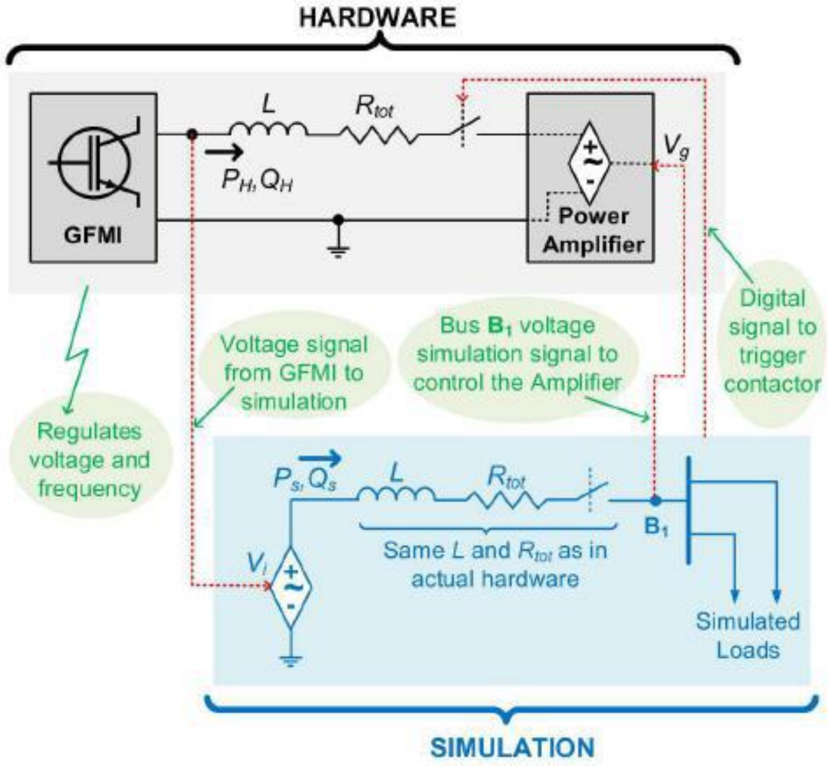
Experimental Validation

❑ Interface Method II: Partial Circuit Duplication (PCD)

- Feasibility and Stability (✓)
- Applicability (?):
- Limited by the availability of physical linking impedance in the lab
- Accuracy (x):
  - (i) The accuracy is highly dependent on the consistency between the physically inserted linking impedance and its digital twin in simulation
  - (ii) The implementation of the simulated linking impedance in the simulated network introduces additional dynamics to GFM
  - (iii) Detrimental impact on the power signal synchronization between hardware and simulated GFM

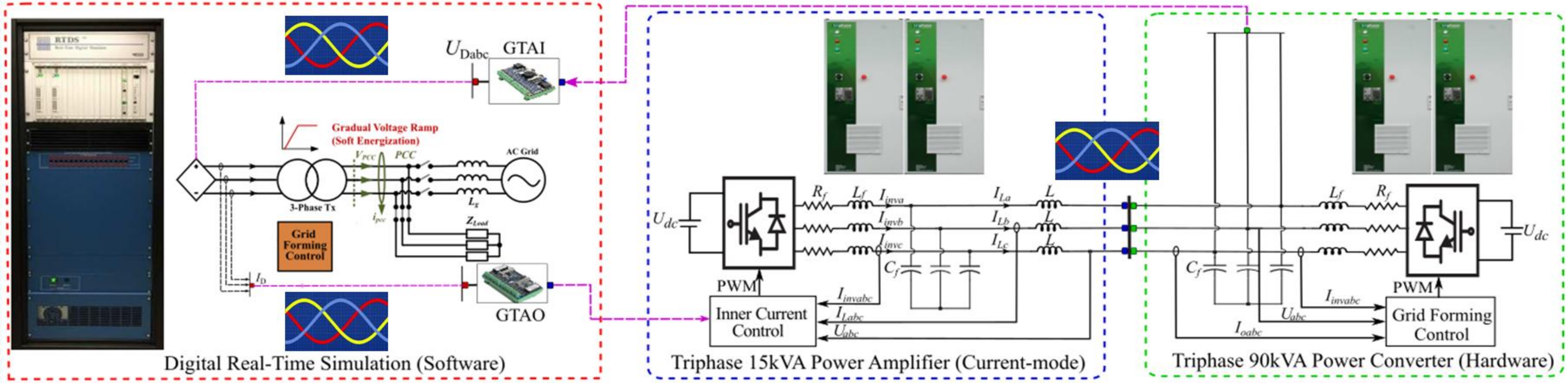


Equivalent diagram of PHIL setup with grid forming converter and PCD interface

Experimental Validation

❑ Interface Method III: Current-type ITM interface

- Current-mode power amplifier for interfacing GFM and simulated network
- GFM output voltage measured and injected to simulated network
- Dynamic replication of simulated network to GFM by Power amplifier
- Feasibility (✓)

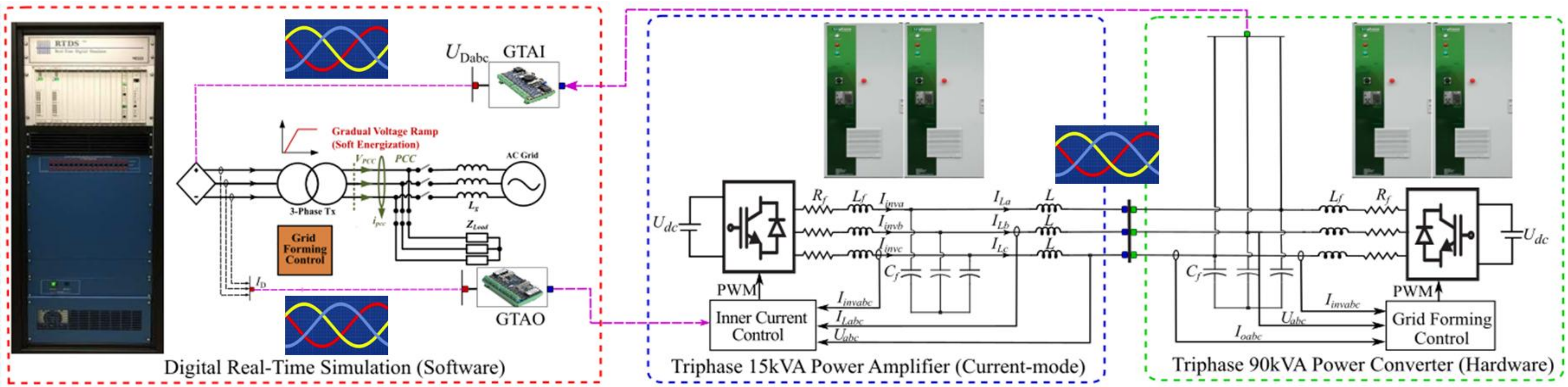


Equivalent circuit diagram of the PHIL with grid forming converter and current-type ITM interface

Experimental Validation

❑ Interface Method III: Current-type ITM interface

- Accuracy (?): Accuracy issue arising from the time delay within the PHIL setup
  - (i) Inaccurate voltage and current signal replications at both hardware and software
  - (ii) Inaccurate power measurement at the hardware and software, and leads to abnormal operation of grid synchronization control



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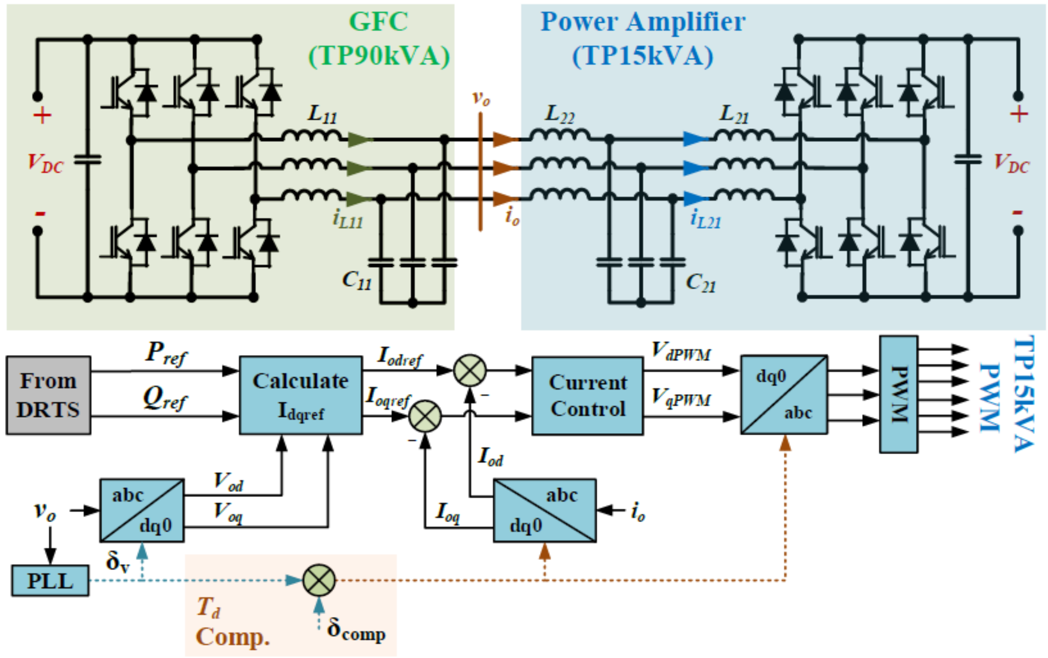
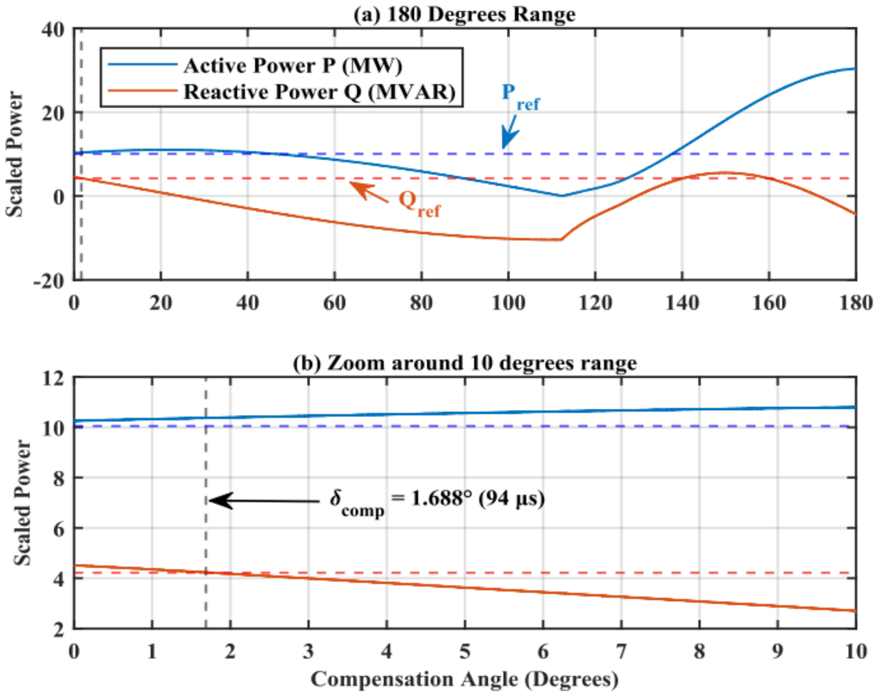
Experimental Validation

❑ Interface Method III: Current-type ITM interface

- Accuracy (✓): Accuracy issue arising from the time delay within the PHIL setup
  → Delay compensation by adding additional phase to the modulating signal



Time delay compensation for current-mode power amplifier



Time delay compensation impact illustration

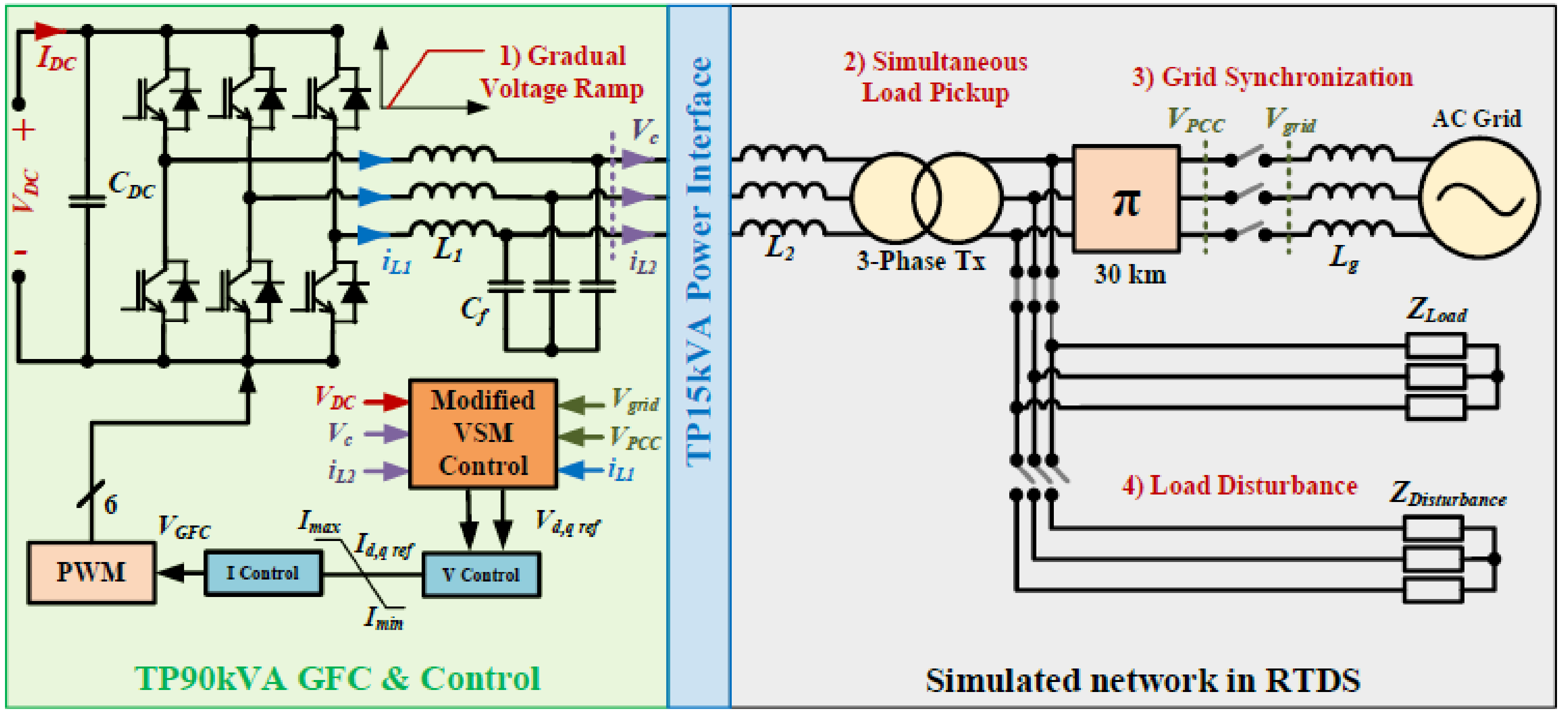
A. Alassi, Z. Feng, K. Ahmed, M. Syed, A. Egea-Alvarez, C. Foote, *Grid-forming VSM control for black-start applications with experimental PHiL validation,* International Journal of Electrical Power and Energy Systems, volume 151, 2023, 109119, Doi: 10.1016/j.ijepes.2023.109119.

Experimental Validation

❑ Interface Method III: Current-type ITM interface

Black Start Testing Scenarios

- GFM Voltage Ramp
- Critical Load Pick-up
- Grid Synchronisation
- Active Power Reference Change and Load Disturbance



The network diagram employed for PHIL black start experiment

Experimental Validation

❑ Interface Method III: Current-type ITM interface

Black-Start Testing Scenarios

- GFM Voltage Ramp
- Critical Load Pick-up
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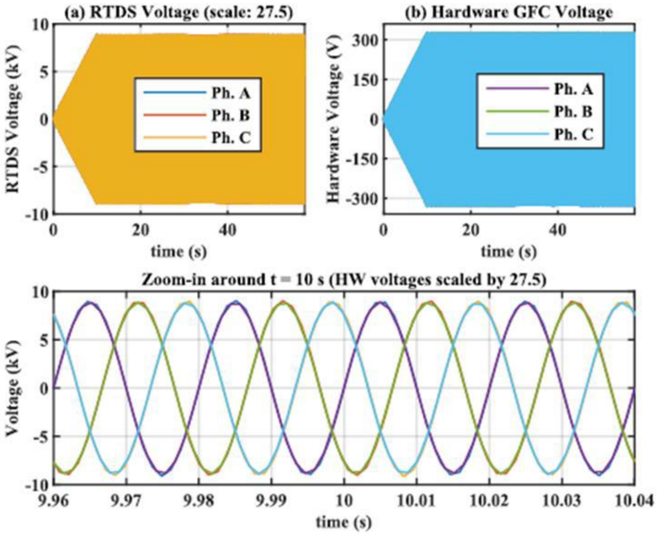

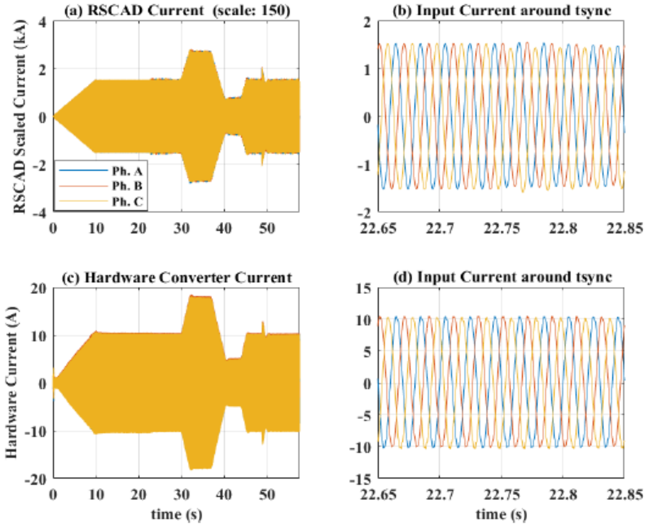

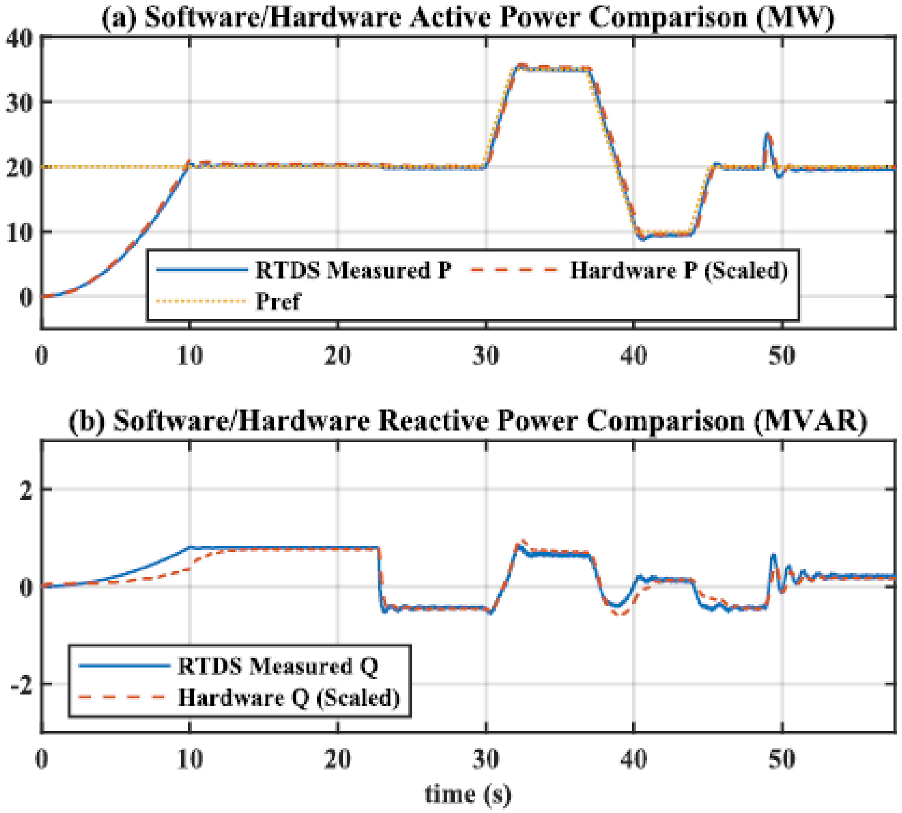

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- **Takeaway Messages**

Takeaway Messages

- Critical role of IBRs in the future of ancillary services
- Network restoration through IBRs is becoming more critical as their penetration increases
- GFMs can effectively play an anchor role in restoring power networks
- Classical GFM structures may require adjustments to adapt to application requirements (e.g., inrush mitigation)
- A restoration scenario is presented and validated with a modified VSM control and validated through PHiL experiments
- Electrolysers (coupled with energy buffers) can similarly play a role in networks restoration

Thank you!

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