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ERIGrid 2.0 Connecting European Smart Grid Infrastructures

University of Strathclyde

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Current-type Power Hardware-in-the-Loop Interface for Black Start Testing of Grid Forming Converter

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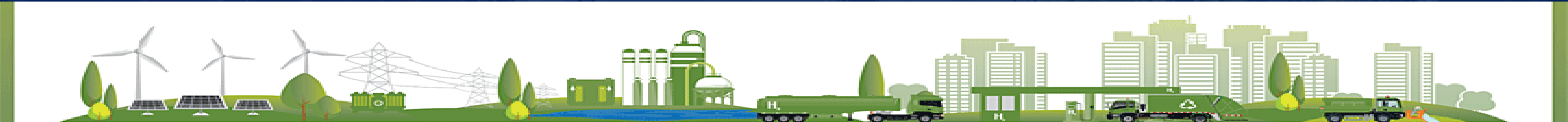
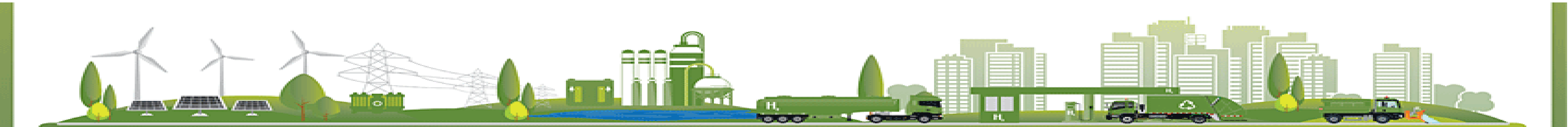


Outline of the presentation

- **Background**
- **Challenges and Motivation**
- **Novelty and Key Methodologies**
    - Selection of Proper Interface
    - Limited Power Rating, Stability and Accuracy Issue
    - Scaling and Compensation Techniques
    - Experimental Setup and Results
- **Conclusions**



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Transformation of power system

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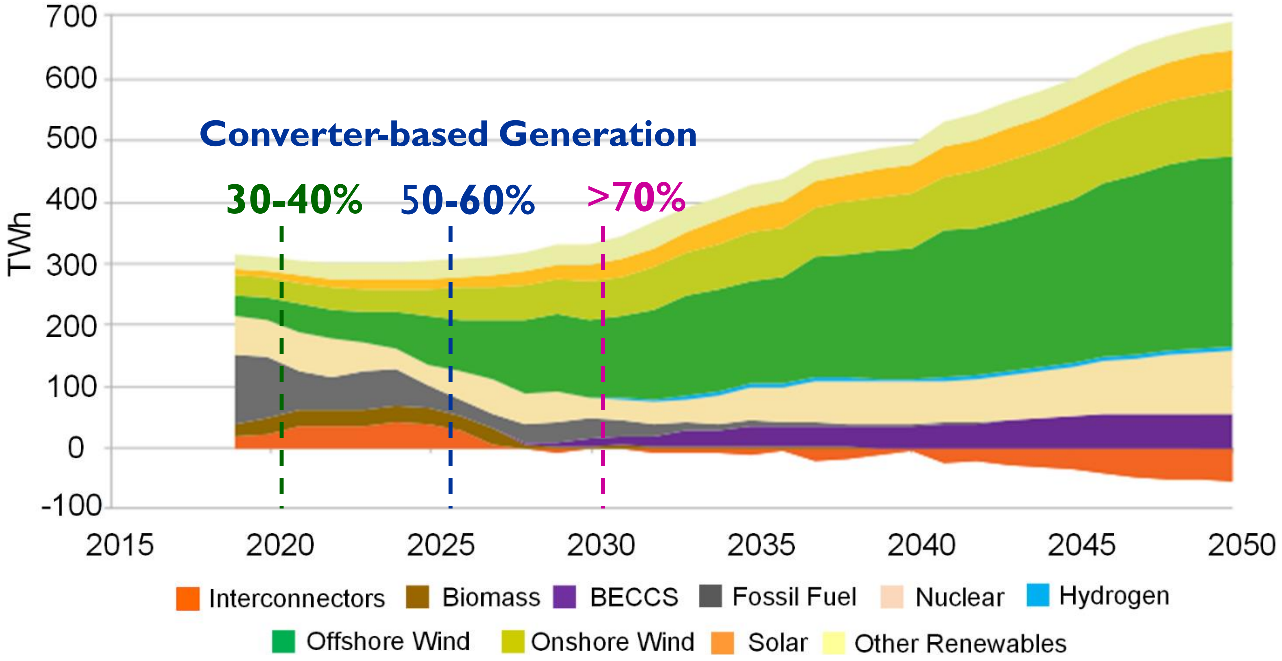
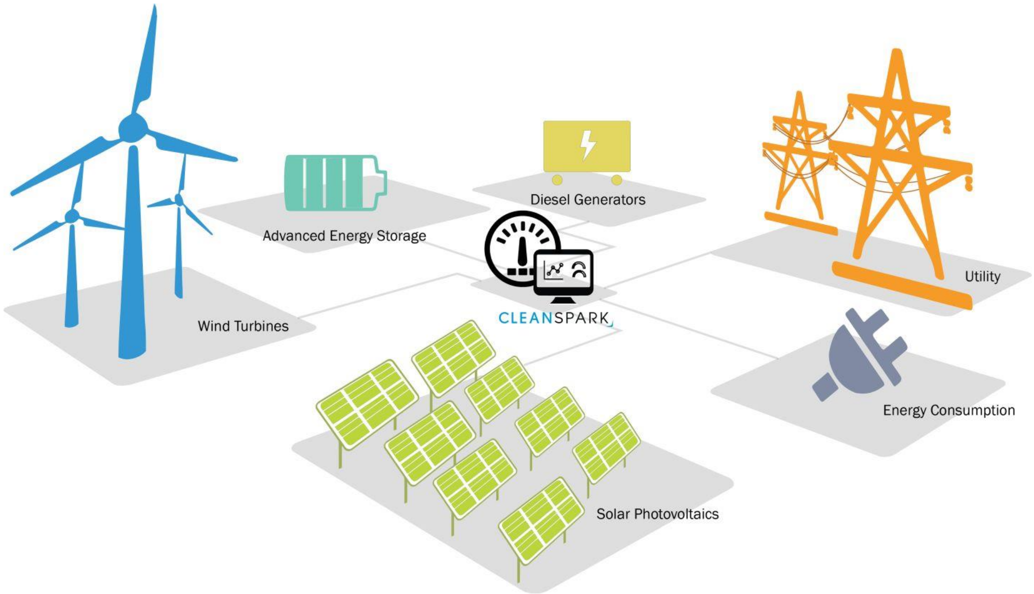
- GB system set to operate with net-zero by 2050
- Massive integration of wind and solar



Source: [1]

Transformation of power system

- Significant decentralised renewable generation
- Advancement of novel power electronics
- Wide array of ancillary gird service provision capability

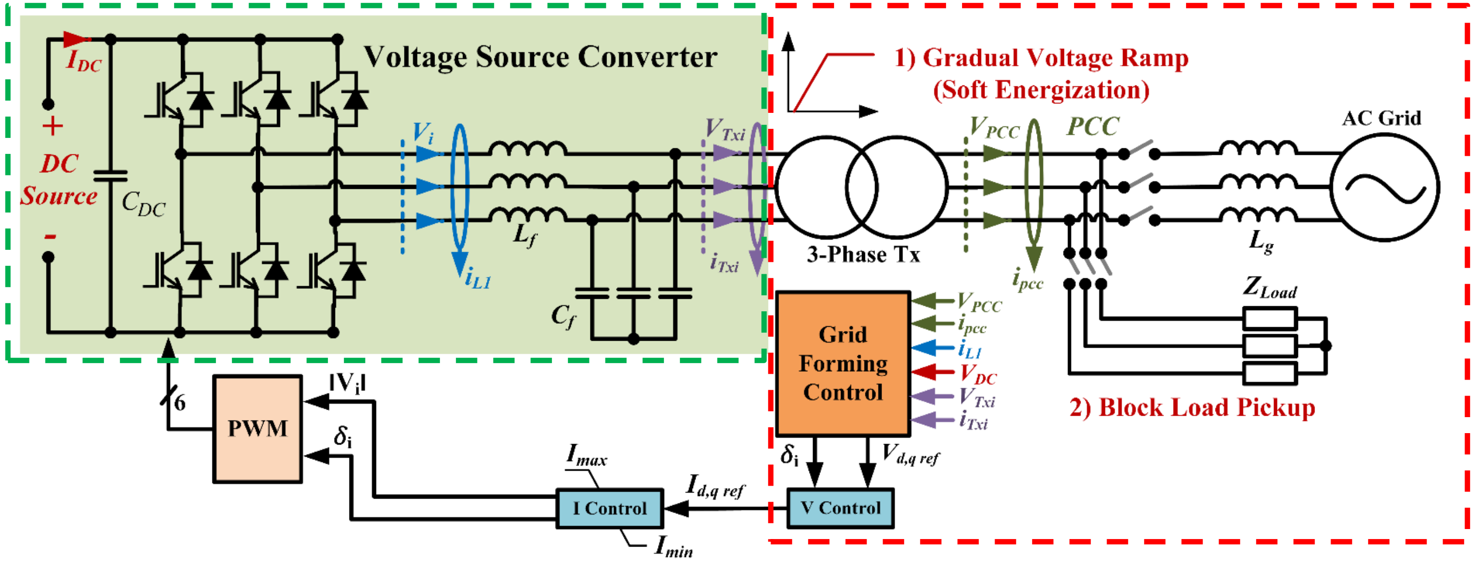


Source: [2]

- Frequency and inertia support
- Synchronized regulation
- Contingence reserve
- Black-start regulation

Grid Forming Converter for Black Start

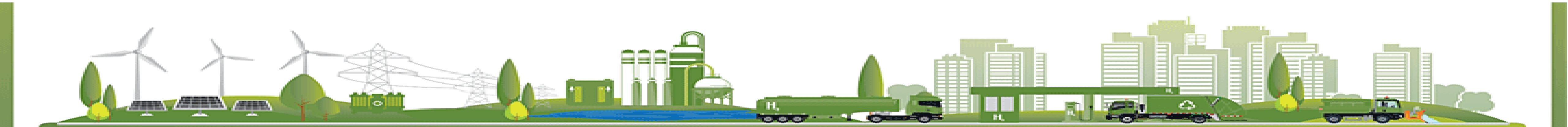
- Grid-forming converter (GFC)
  - Self-angular synchronization
  - Well-established controllable output voltage
- Black start support



Source: [3]

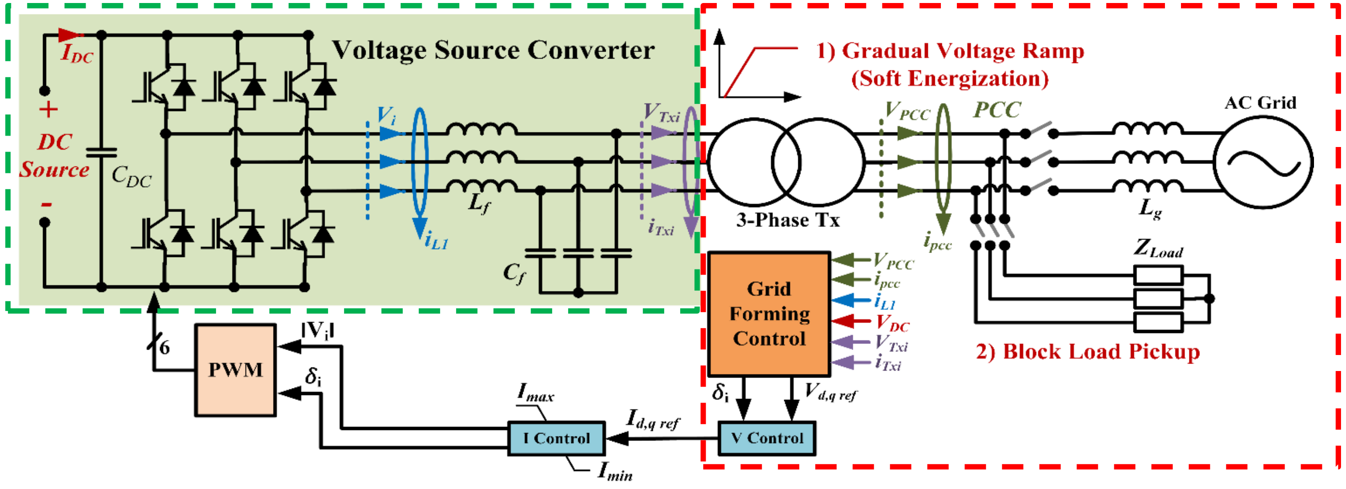
Distributed ReStart

"Distributed ReStart is a world-first initiative. The project explores 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

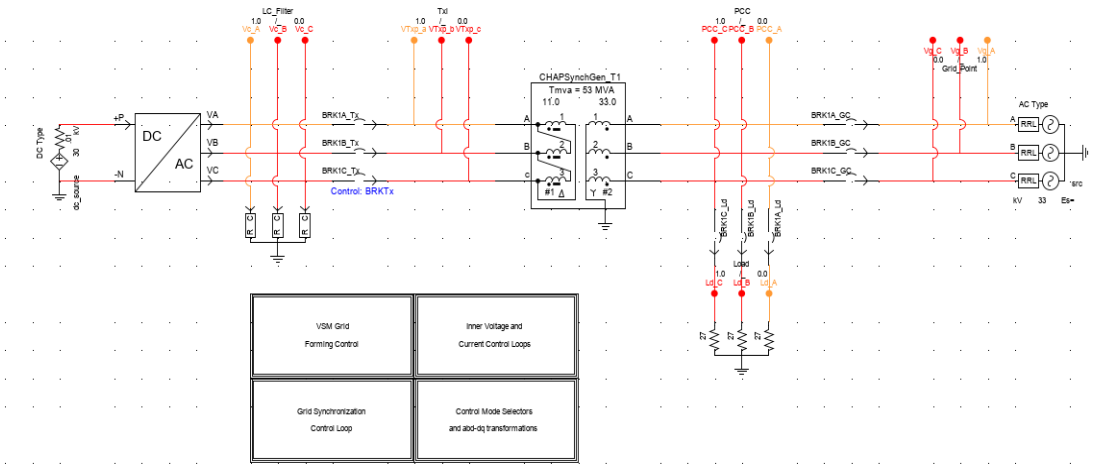


Challenges & Limitation

- In-depth and comprehensive testing of GFC
- Limited computation capability of pure software
- Lack of real physical dynamics of GFC



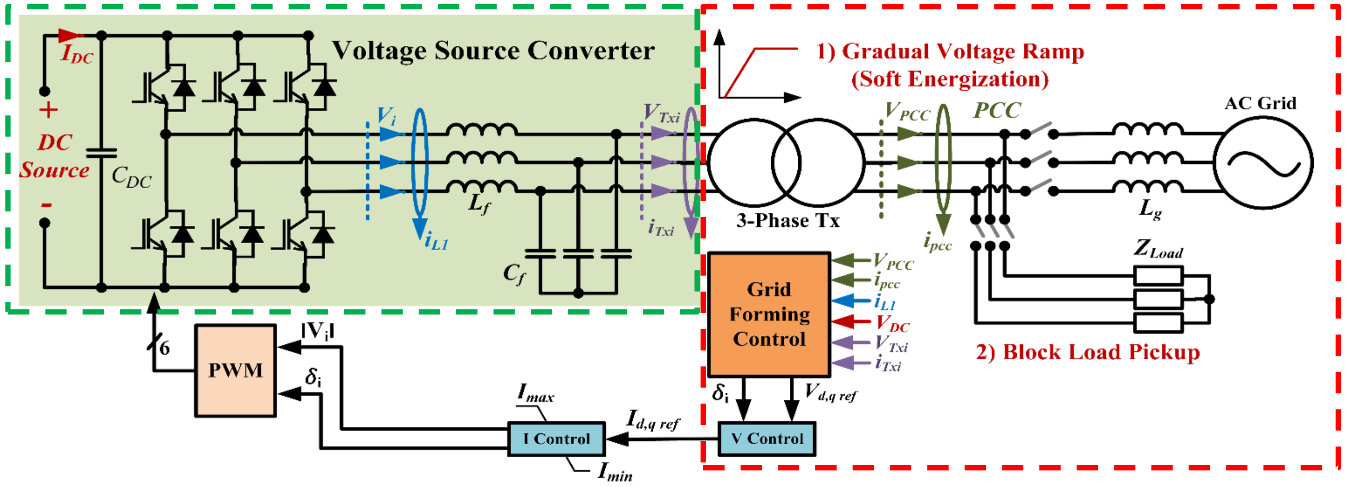
System under test with grid forming converter for black start



Pure simulation of system under test

Challenges & Limitation

- In-depth and comprehensive testing of GFC
- Risky pure hardware experimental with high cost
- Impractical and inefficient hardware experiment in MW scale



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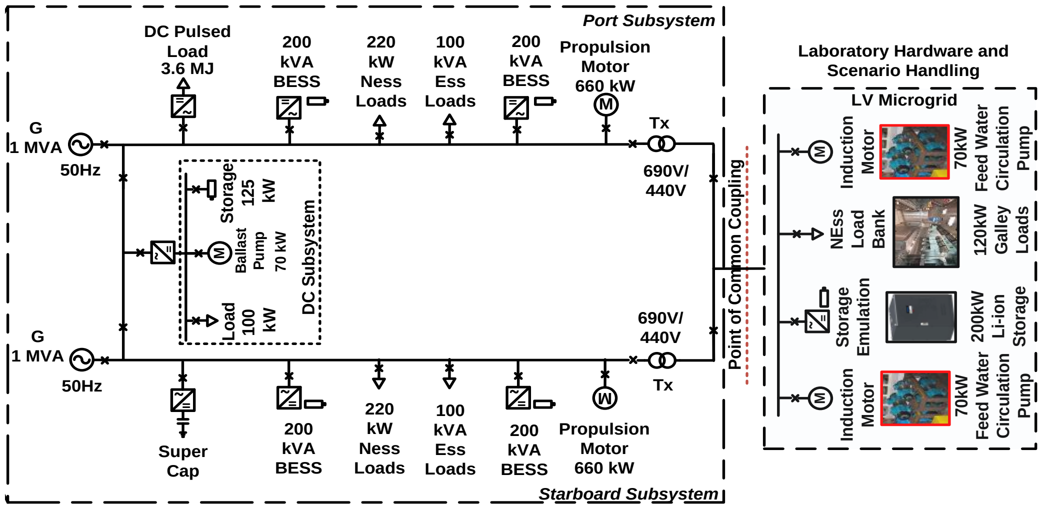
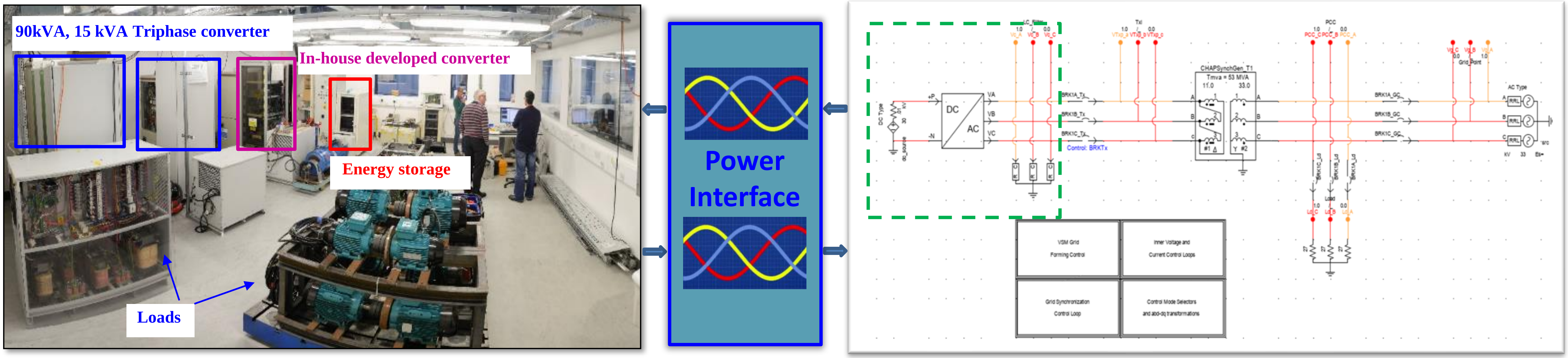


Hardware experimental setup of system under test

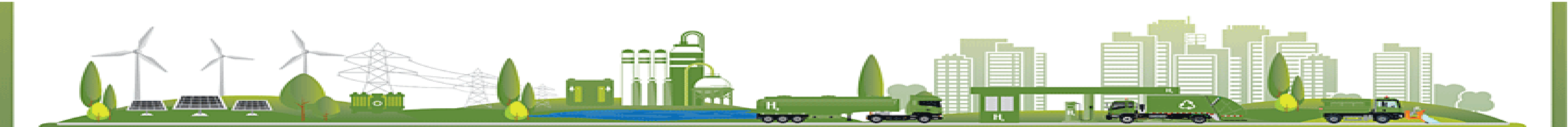
Motivation

- Applying Power Hardware-in-the-Loop Simulation
- Narrow the gaps between pure simulation and hardware experiment
- Develop novel interface for incorporating physical GFC with real-time simulation



Hardware experimental setup of system under test

Pure simulation of system under test



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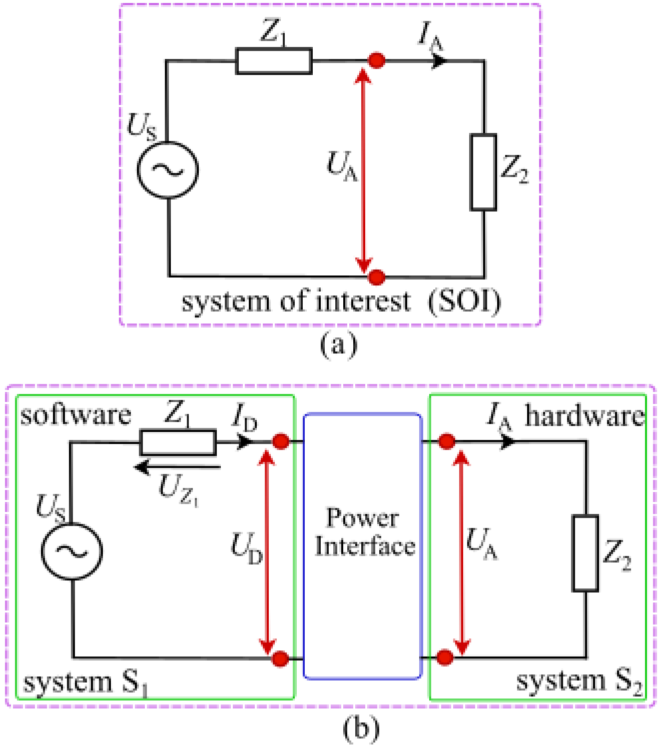
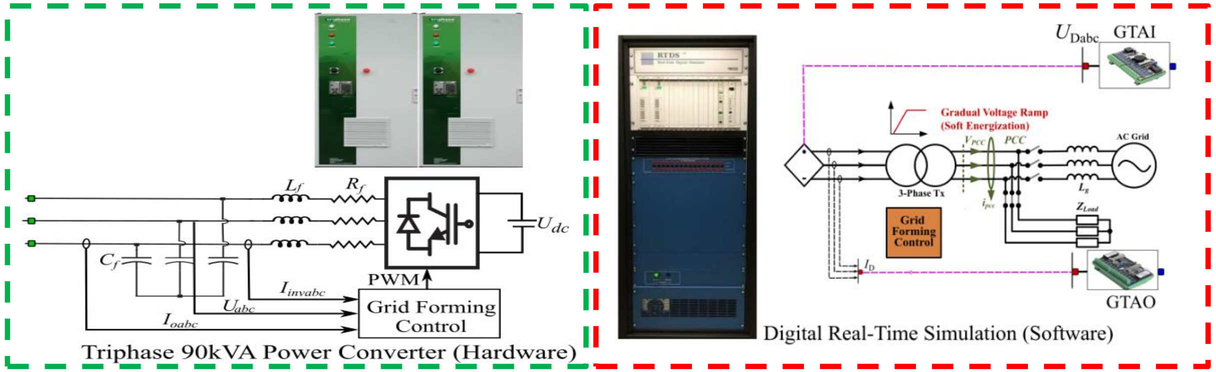
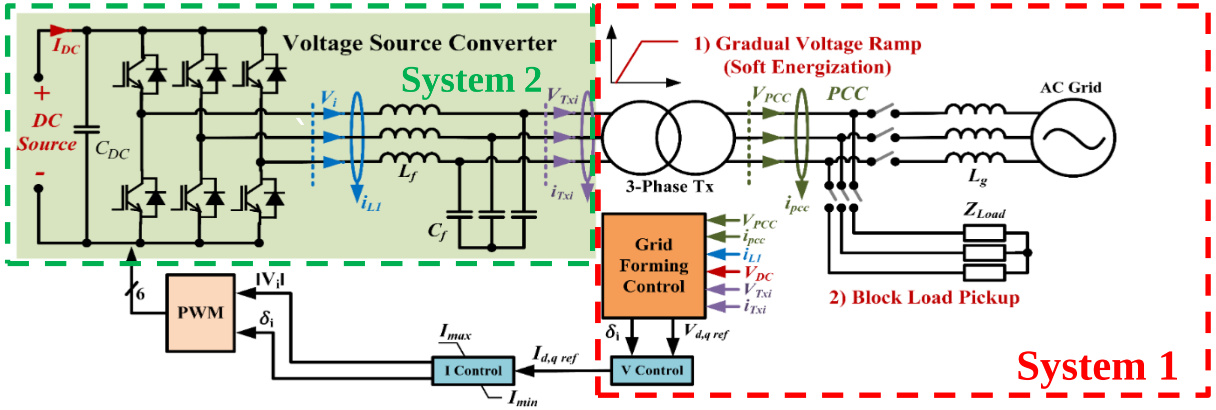
- Power Hardware-in-the-Loop Simulation



Principle topology of (a) the system of interest (SOI) and (b) the PHIL simulation system

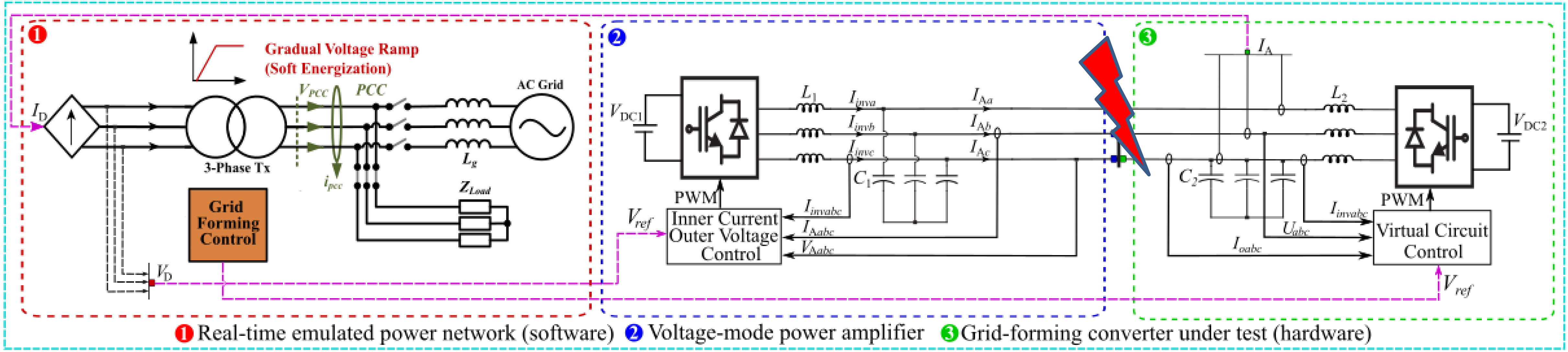




System under test with grid forming converter

Limitation of Conventional Interface

- Power Hardware-in-the-Loop Simulation
- Voltage-type ideal transformer model (ITM) interface
- Lack of voltage angular synchronization at the coupling point between GFC and power amplifier (PA)



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

Limitation of Conventional Interface

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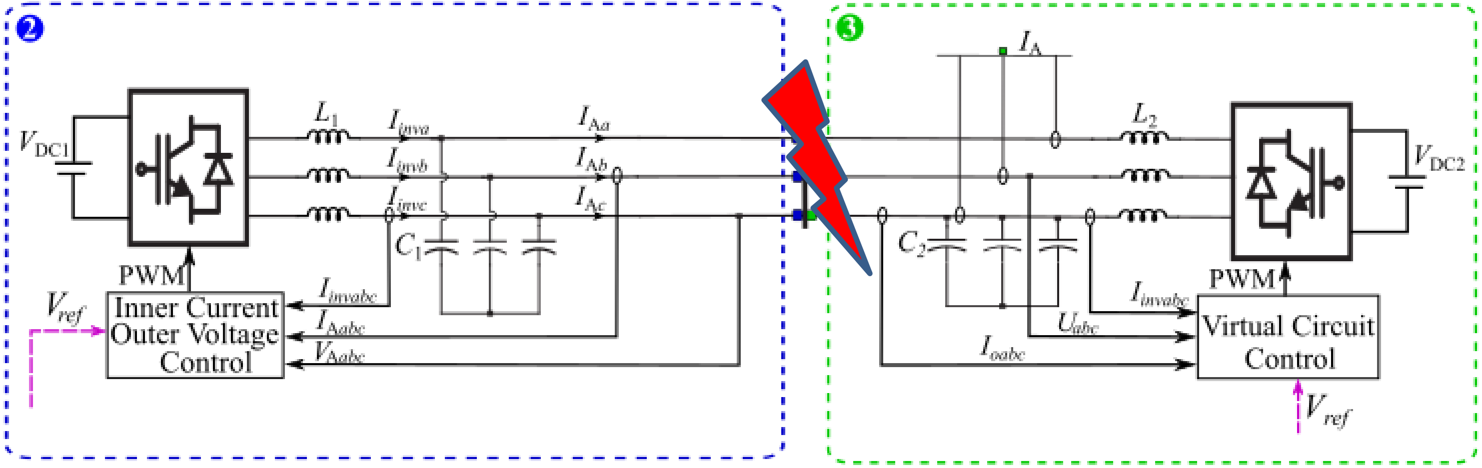
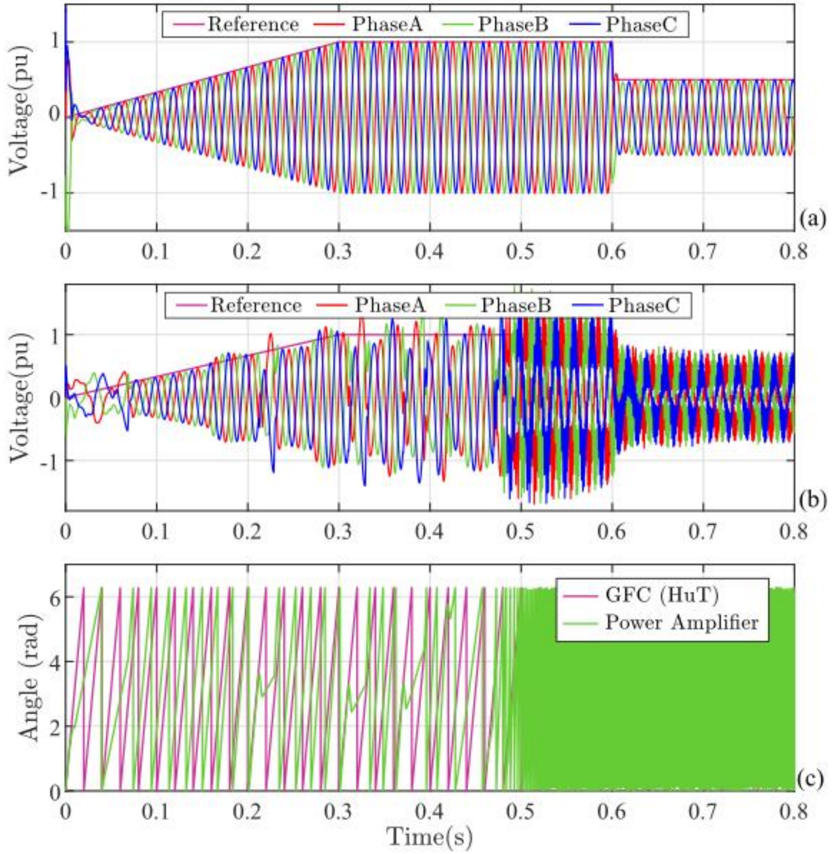
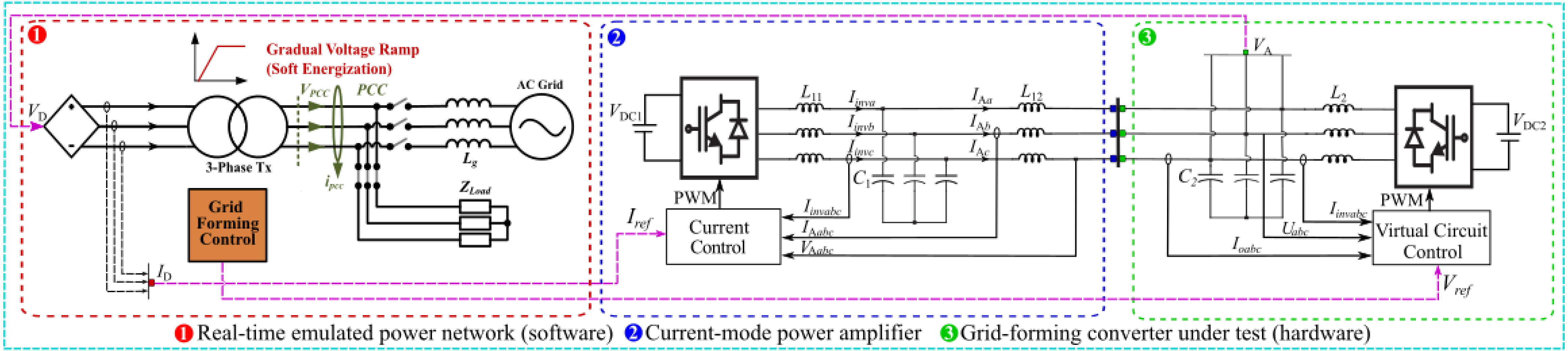


❷ Voltage-mode power amplifier ❸ Grid-forming converter under test (hardware)



Novelty and Methodologies

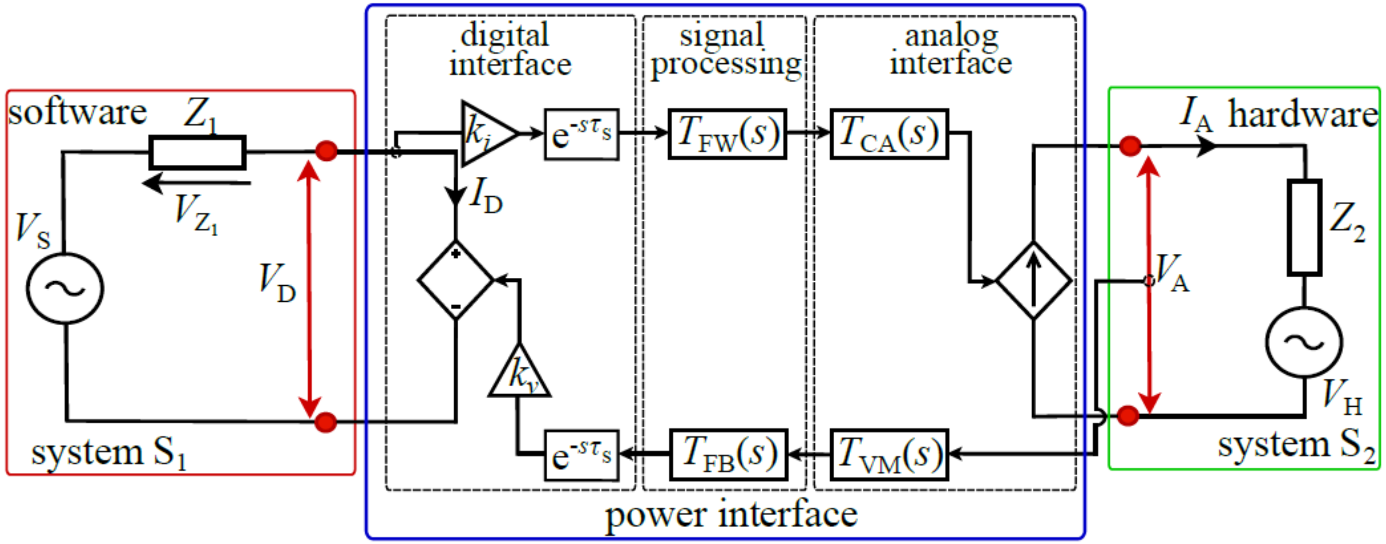
- Current-type ideal transformer model (ITM) interface
- Current-mode power amplifier for interfacing GFC and simulated network
- GFC output voltage measured and injected to simulated network
- Dynamic replication of simulated network to GFC by PA



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

Methodology: Scaling Ratio

- Limited power rating of the power converter
- Higher power level for black-start
- Limited current rating of current power amplifier
- Scaling ratio is employed
- Dynamic replication of simulated network to GFC by PA



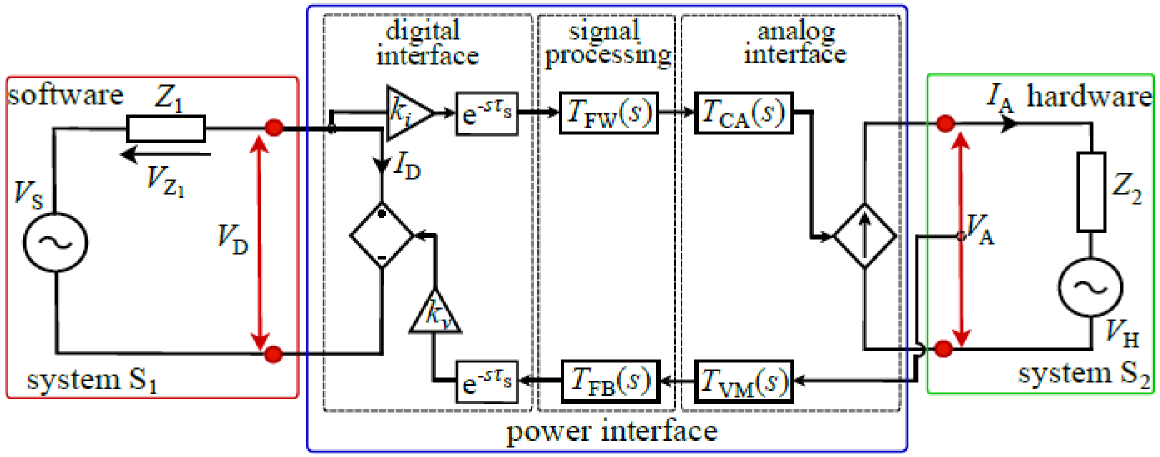
Voltage Scaling: $k_v = \frac{V_{Dnom}}{V_{Anom}}$

Current Scaling: $k_i = \frac{I_{Anom}}{I_{Dnom}}$

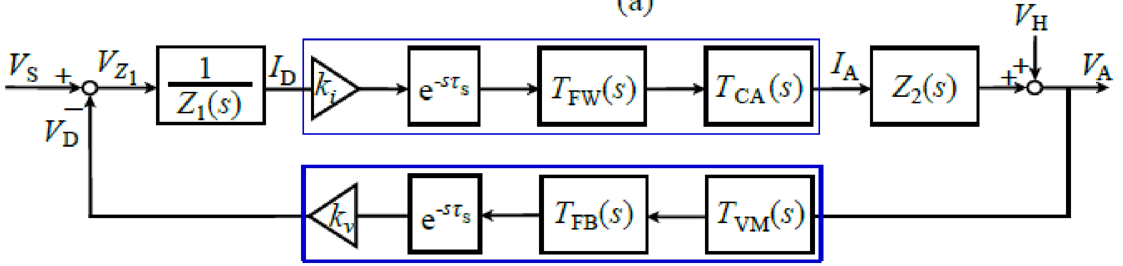
where V_A and V_D are the nominal voltage of the physical GFC and the emulated GFC at the simulation side, respectively. I_A and I_D are the nominal current of the power amplifier and the rated current of the emulated power network, respectively.

Methodology: Stability Assessment

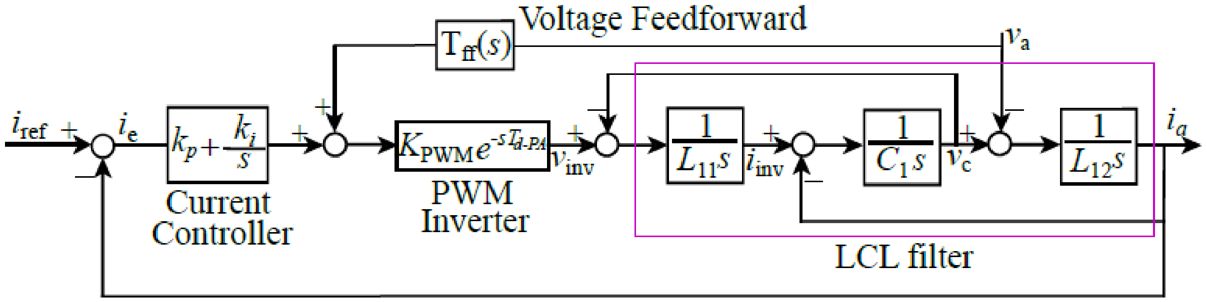
- System modelling (SISO) for stability study
- Closed-loop stability assessment



(a)

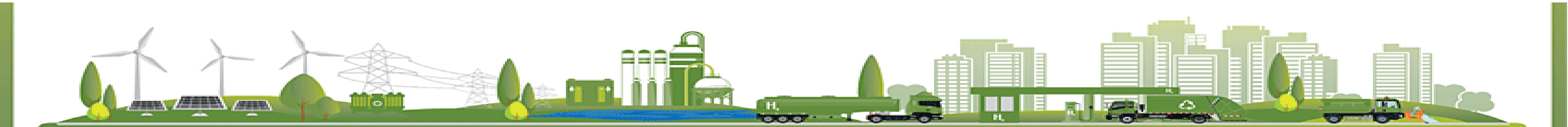


(b)



System modelling (SISO) open-loop transfer function

$$T_O(s) = k_v k_i T_{FW}(s) T_{CA}(s) T_{FB}(s) \frac{Z_2(s)}{Z_1(s)} e^{-s(2\tau_s)}$$



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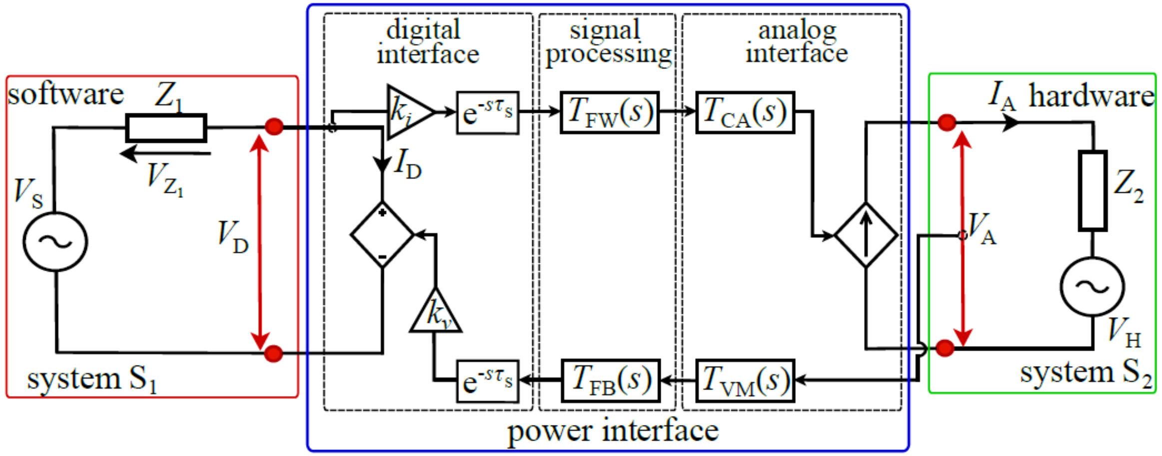

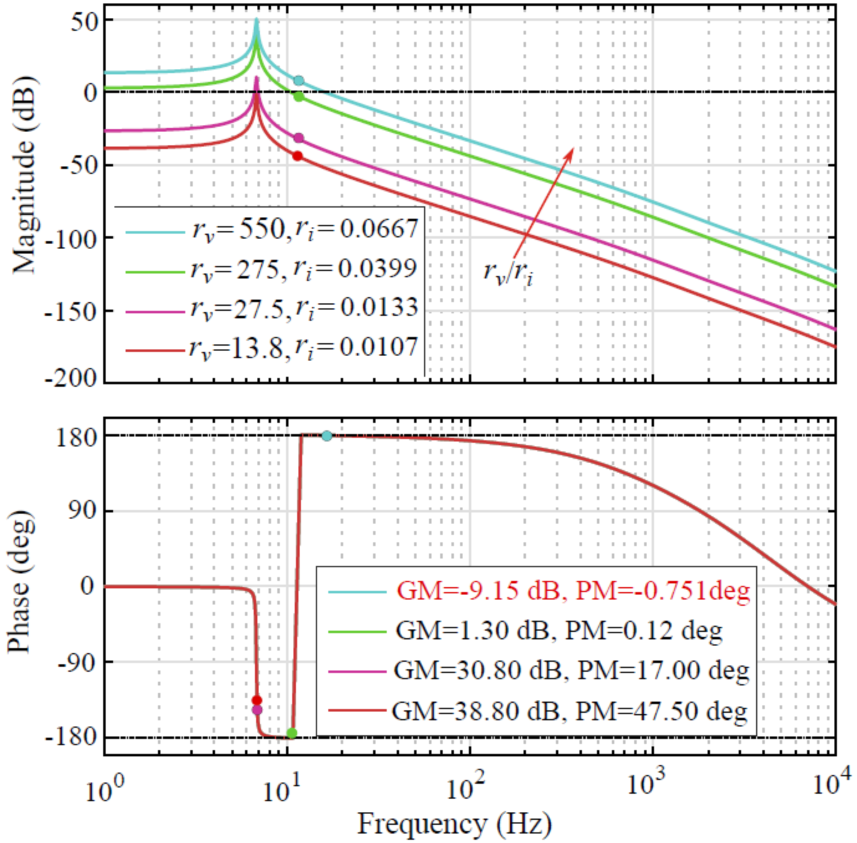

System modelling (SISO) open-loop transfer function

$$T_O(s) = k_v k_i T_{FW}(s) T_{CA}(s) T_{FB}(s) \frac{Z_2(s)}{Z_1(s)} e^{-s(2\tau_s)}$$

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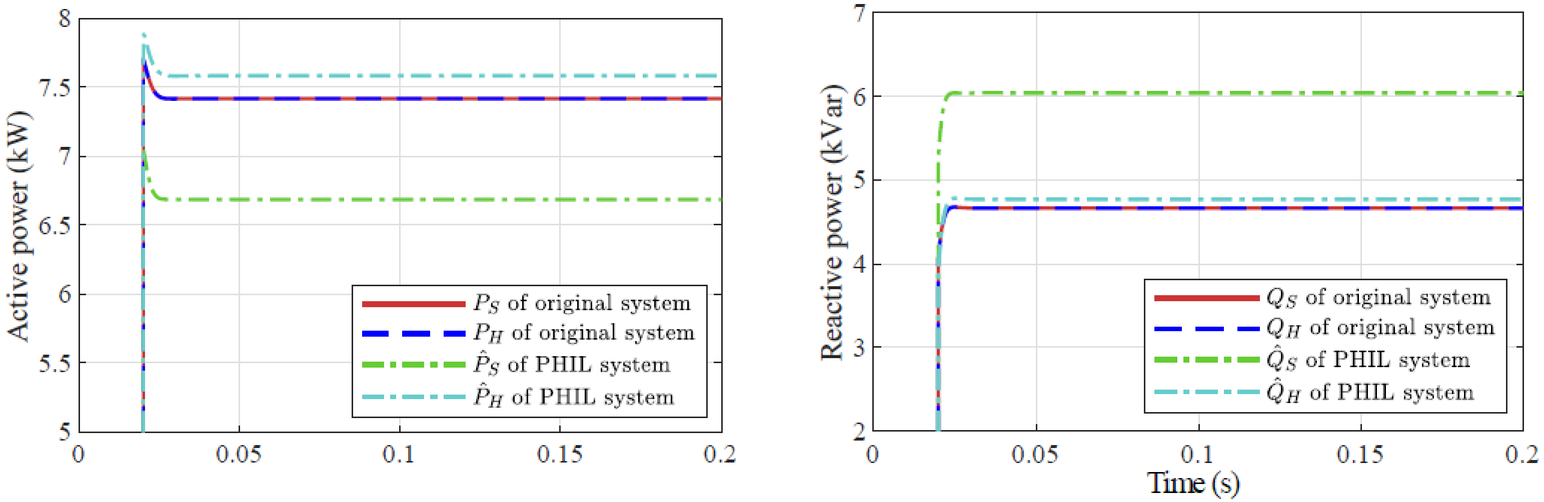
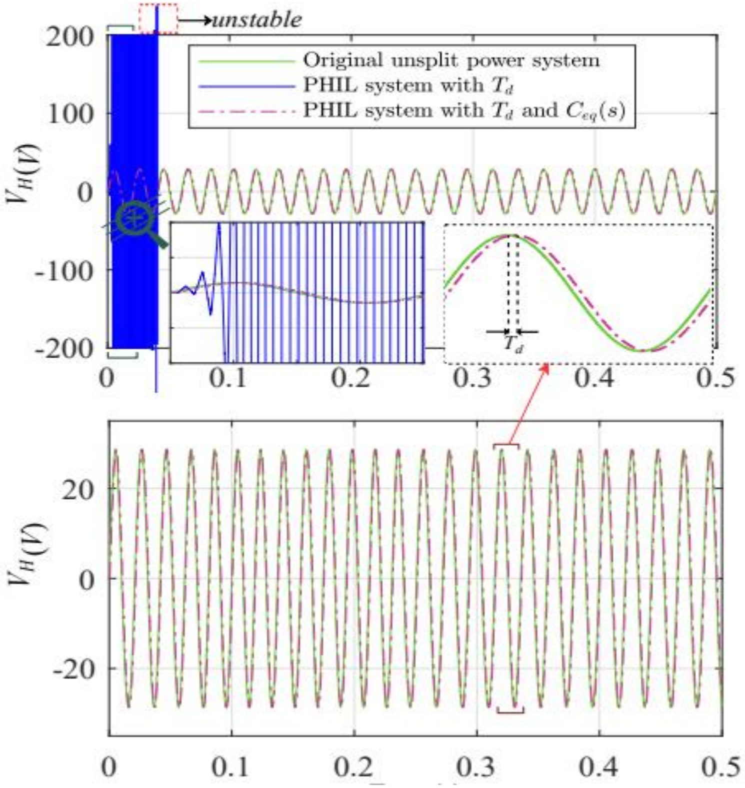
Methodology: Delay Compensation

- Accuracy issue arising from the time delay within the interface
- Incorrect power signal synchronization
- Degraded power transfer transparency

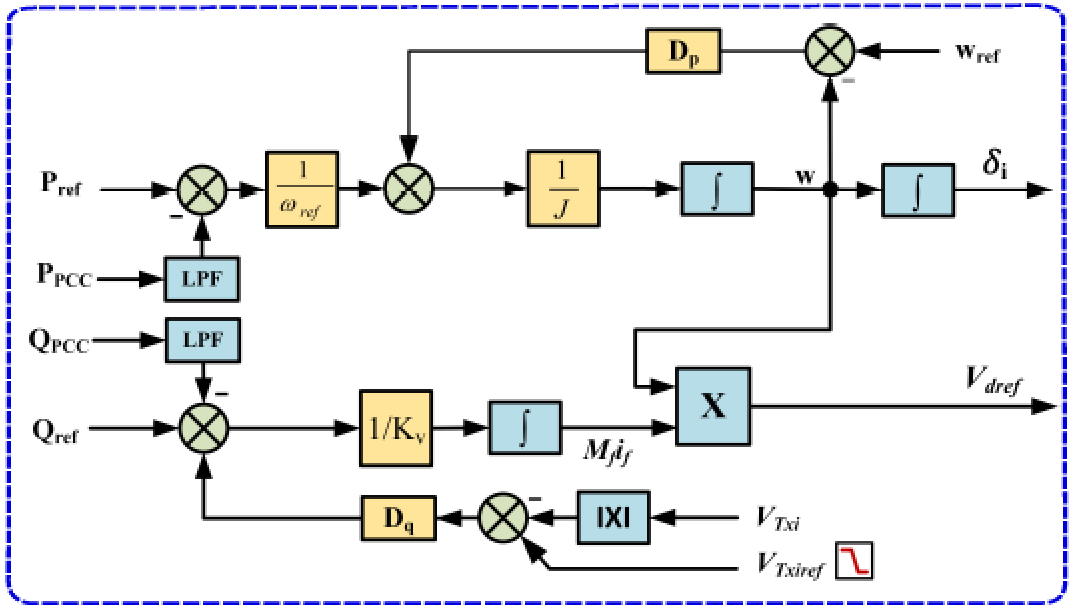




Active and reactive power of PHIL setup [4] and its voltage behaviour [5]

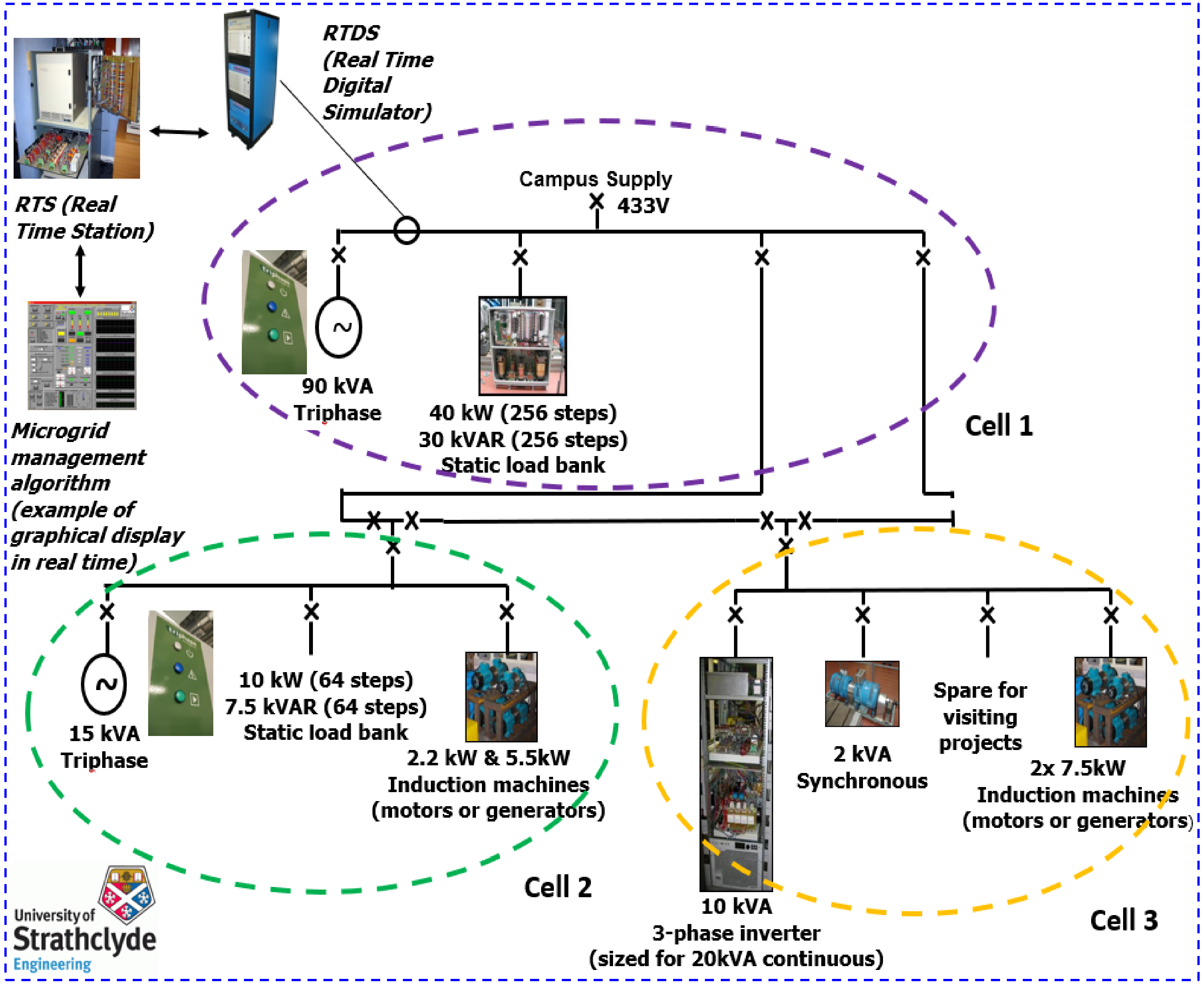
Methodology: Delay Compensation

- Accuracy issue arising from the time delay within the interface
- GFC control based on accurate power measurement
- Time delay compensation methods



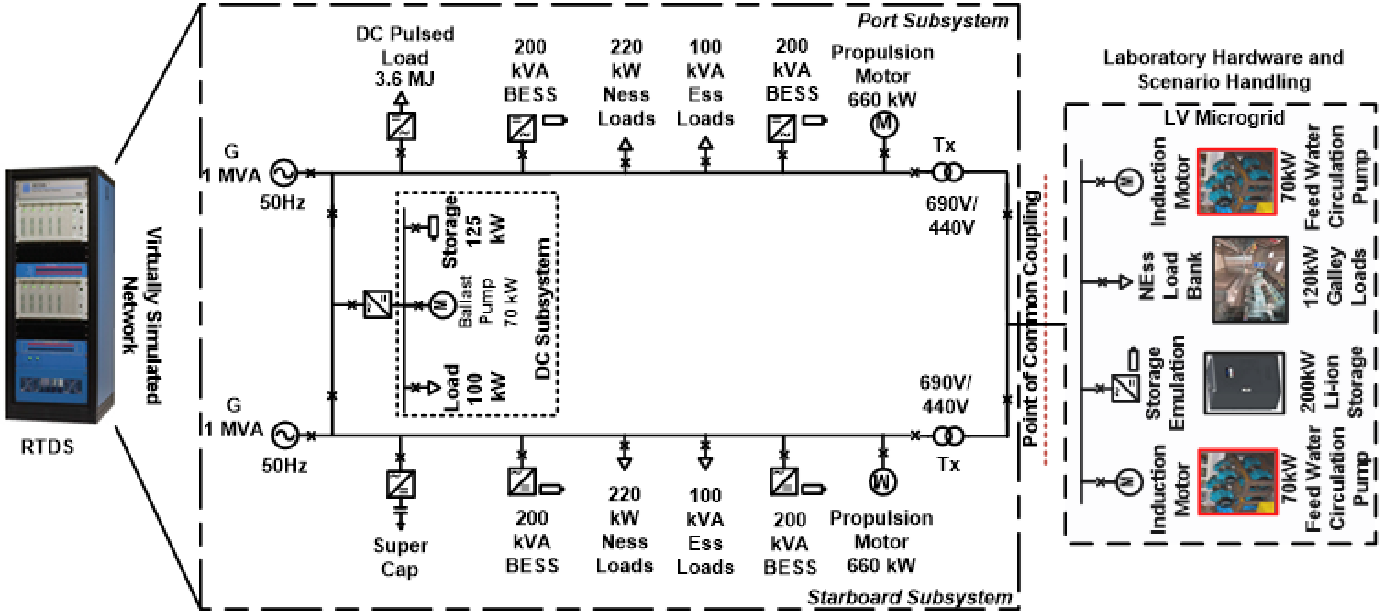
- Sliding DFT based abc frame signal manipulation and phase shift addition [4,5,9]
- Additional phase shift in dq frame for angular reference generation for current-type power amplifier [8]

Dynamic Power System Laboratory (DPSL)

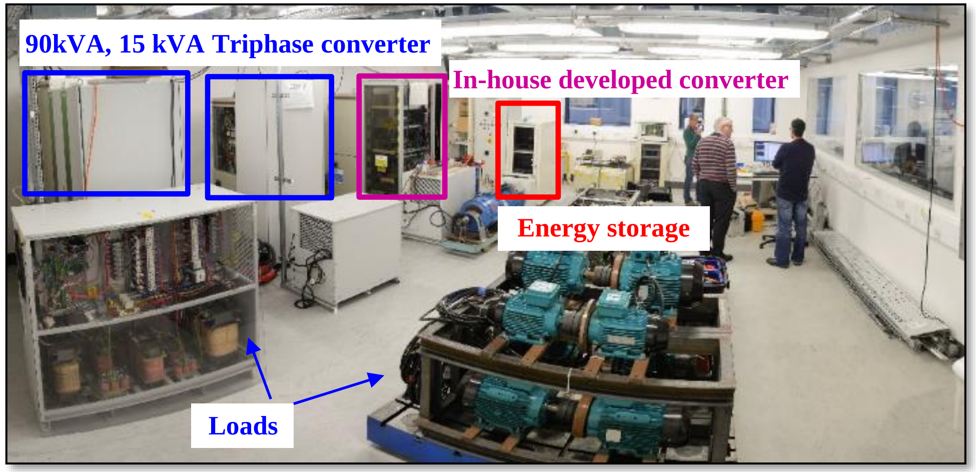


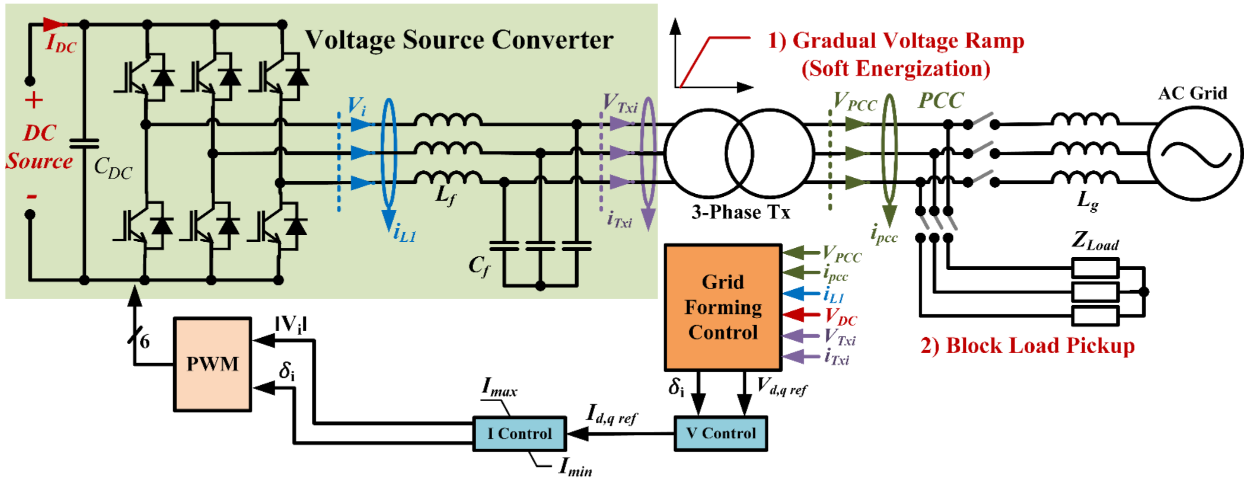
- Real-time digital simulation platform
- Real-time dynamic monitoring platform
- Triphase 90kVA (or 15kVA) power converter
- Static load banks
- Electrical machines
- Energy storage

Advanced Power System Testing Capabilities

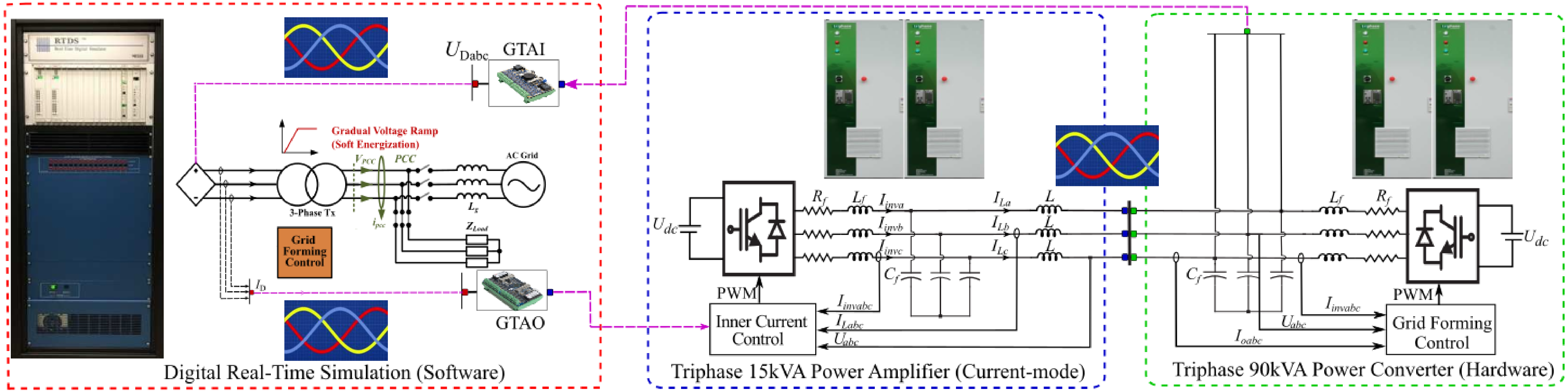


- Real-time emulation of large-scale power system
- Rapid prototyping and proof of concept validation
- Controller or Power hardware-in-the-loop testing
- Geographically distributed real-time co-simulation
- Dynamic modelling of renewable energy and its validation





System under test with grid forming converter for black start



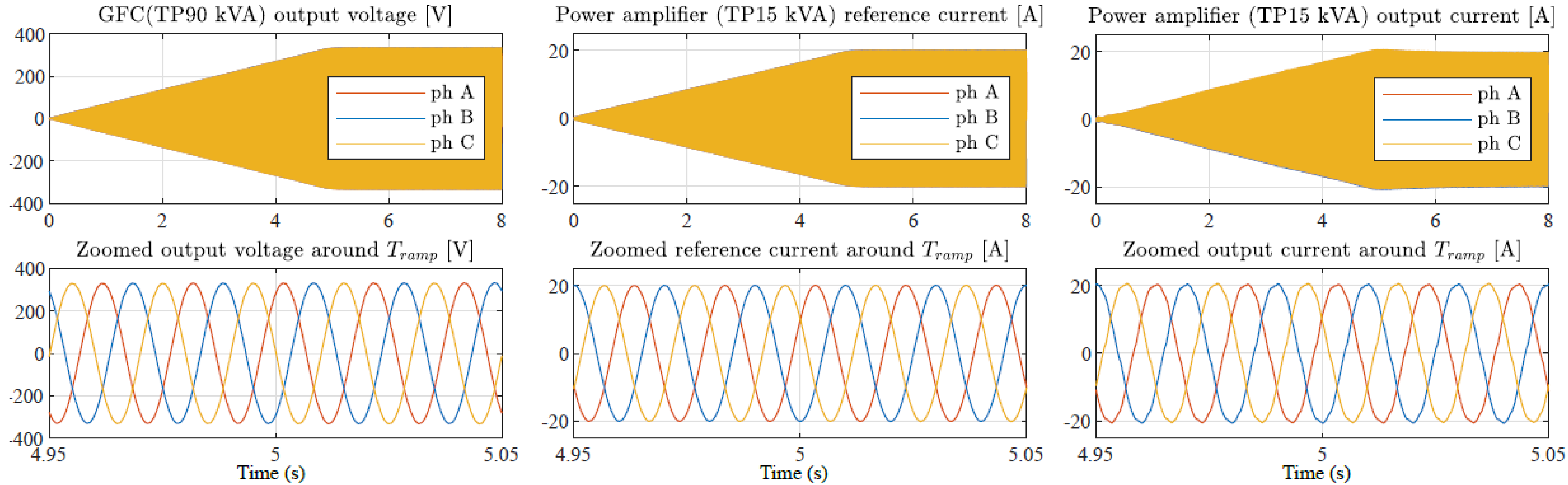
System under test with grid forming converter

Feng, Z., Alassi, A., Syed, M. H., Pena Alzola, R., Ahmed, K., & Burt, G. (Accepted/In press). *Current-type power hardware-in-the-loop interface for black-start testing of grid-forming converter*. Paper presented at 48th Annual Conference of the Industrial Electronics Society, IECON 2022, Brussels, Belgium.

Experimental results

PHIL black start testing scenarios:

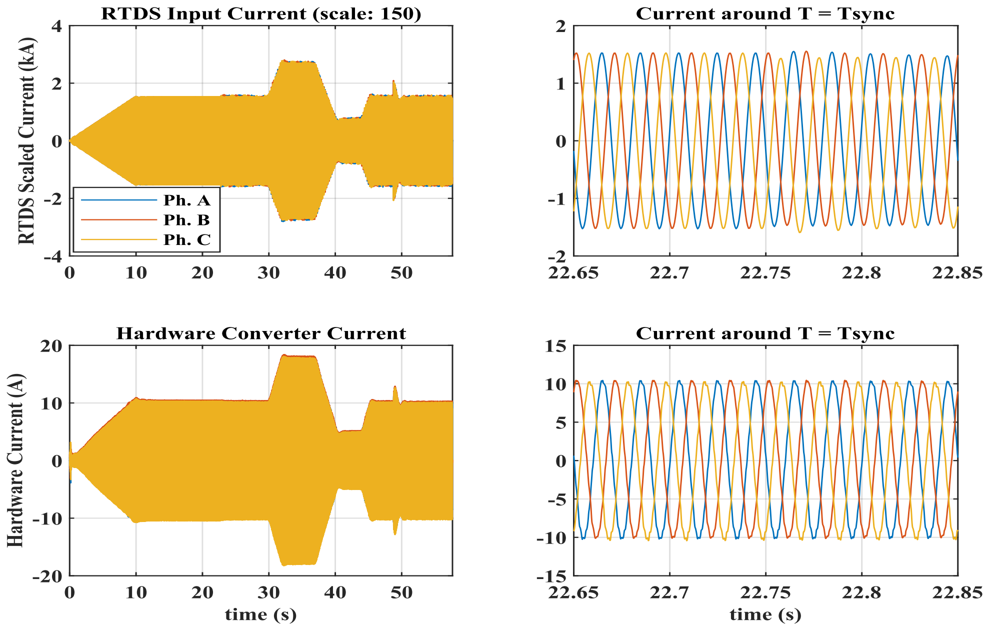
- GFC voltage ramp-up

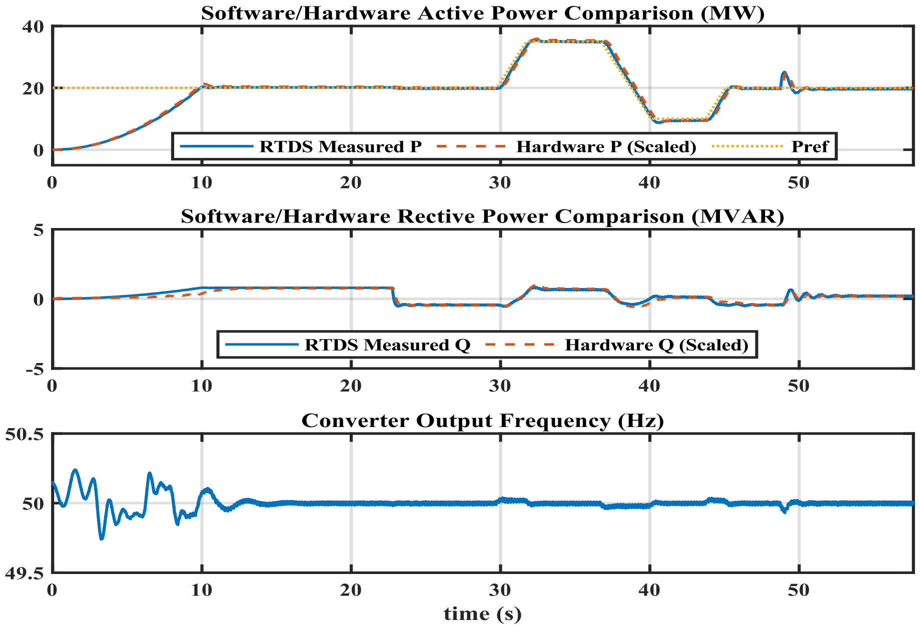


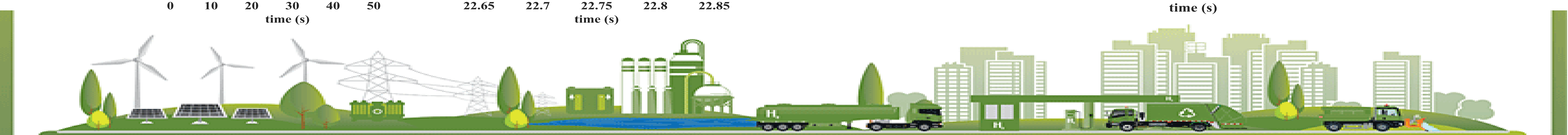
Experimental results

PHIL black start testing scenarios:

- GFC voltage ramp-up
- Critical load pick-up
- Load disturbance connection
- Grid synchronization







Conclusion

- Comprehensive evaluation of voltage-type and current-type PHIL interface (Suitability and applicability)
- Interface optimization (scaling ratio and delay compensation)
- System modelling, and stability assessment
- Triphase-based experimental validation

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[1] Manyu Solar Energy, https://www.szmysolar.com/

[2] 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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[4] Feng, Z., Pena Alzola, R., Seisopoulos, P., Syed, M. H., Guillo-Sansano, E., Norman, P., & Burt, G. (2021). Interface compensation for more accurate power transfer and signal synchronization within power hardware-in-the-loop simulation. In *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society* (IECON Proceedings (Industrial Electronics Conference); Vol. 2021-October). IEEE. https://doi.org/10.1109/IECON48115.2021.9589158

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[9] Feng, Z., Alassi, A., Syed, M. H., Pena Alzola, R., Ahmed, K., & Burt, G. (Accepted/In press). *Current-type power hardware-in-the-loop interface for black-start testing of grid-forming converter*. Paper presented at 48th Annual Conference of the Industrial Electronics Society, IECON 2022, Brussels, Belgium.

[10] Alassi, A., Feng, Z., Avras, A., Syed, M. H., Egea-Àlvarez, A., & Ahmed, K. (2021). *Distributed ReStart: Non-Conventional Black-Start Resources: RTDS Based Network Energization from Grid Forming Converters: Part 1., National Grid ESO, 2021*, https://pureportal.strath.ac.uk/en/publications/distributed-restart-non-conventional-black-start-resources-rtds-b

[11] Alassi, A., Feng, Z., Syed, M., Egea-Alvarez, A., Ahmed, K., & Burt, G. (2022). *Distributed ReStart: Nonconventional BlackStart Resources: RTDS Based Network Energization from Grid Forming Converters: Part 2*, *National Grid ESO, 2022,* https://pureportal.strath.ac.uk/en/publications/distributed-restart-nonconventional-blackstart-resources-rtds-bas

Thank you!

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