

# Active Hardware in Power Hardware-in-the-loop Testing: Introduction and Challenges

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- ▶ Karlsruher Institut für Technologie



# Karlsruher Institut für Technologie



# Energy Lab Facilities

## Large Testing Facility



1 MVA PHIL  
Testing Hall



45 kW & 2x 15kW  
PHIL Setups

## Energy Technologies



2x 60 kW  
Flywheel



500 kW  
Supercap



3x 50 kW  
AC/DC Test Houses



H<sub>2</sub>-in-loop



50 kW  
LH<sub>2</sub> Energy Plant



600 kW  
Battery

# Real Time Systems for Energy Technologies

## RTSET Group

Head: Prof. Dr.-Ing. Giovanni De Carne

### Advanced Grid Control

- Solid-state Transformers
- Hybrid AC/DC Systems
- DC Grids Protection
- Demand Response
- Low-inertia grids

### PHIL & Digital Twins

- PHIL Stability & Accuracy
- Digital Twins
- Fast Real-Time Models
- Superconductivity Grids and Devices

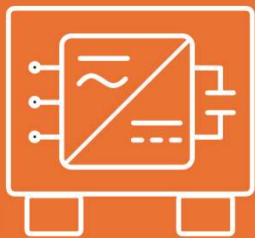
### Dynamic Energy Storage Systems

- Flywheels & Supercaps
- Batteries
- H2-Technologies
- Hybrid ESS Sizing and Control

### Sustainable Research Infrastructure

- RES & ESS Integration
- AI for Particle Accelerator Control
- LCA for Accelerators

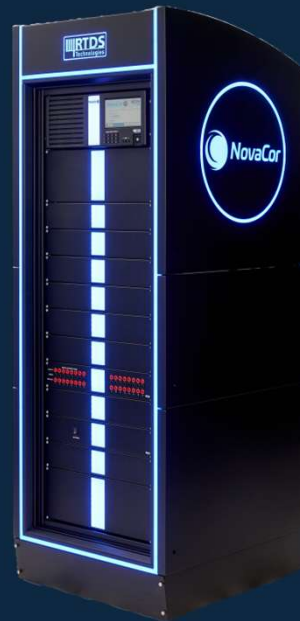
# Real-time Simulation



Power Electronics



Electrical Grids

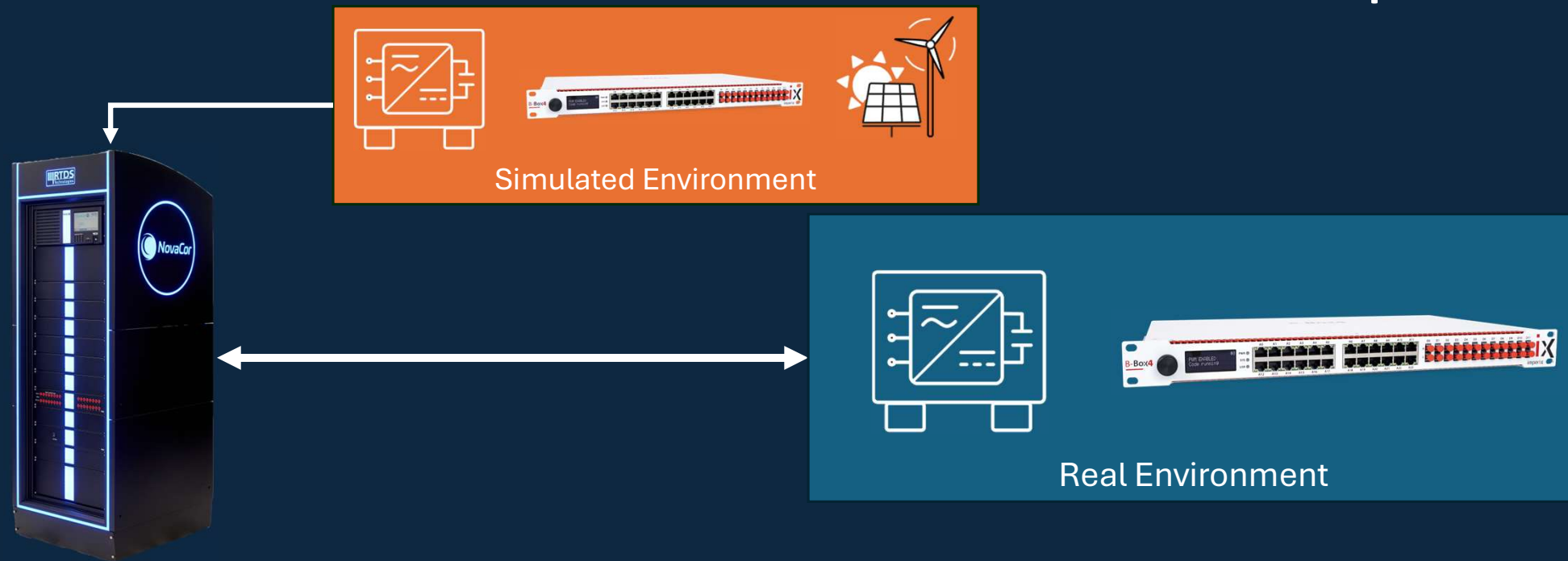


Transmission Lines

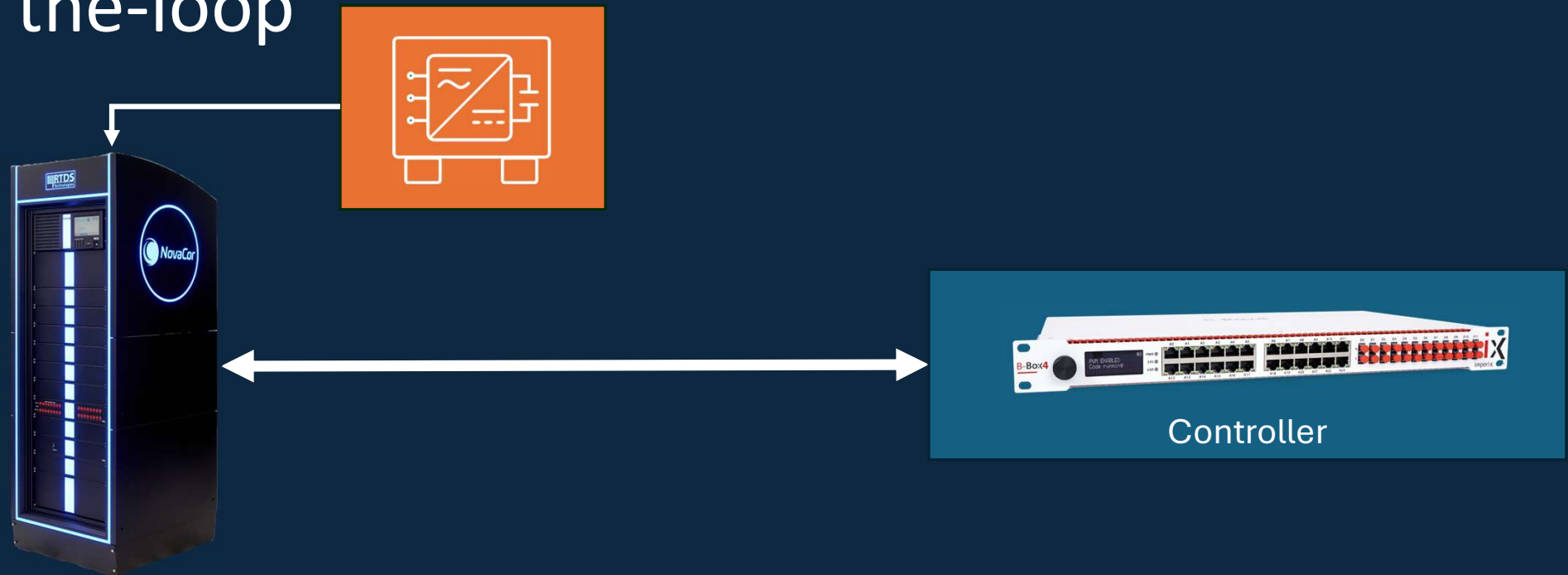


Power Plants

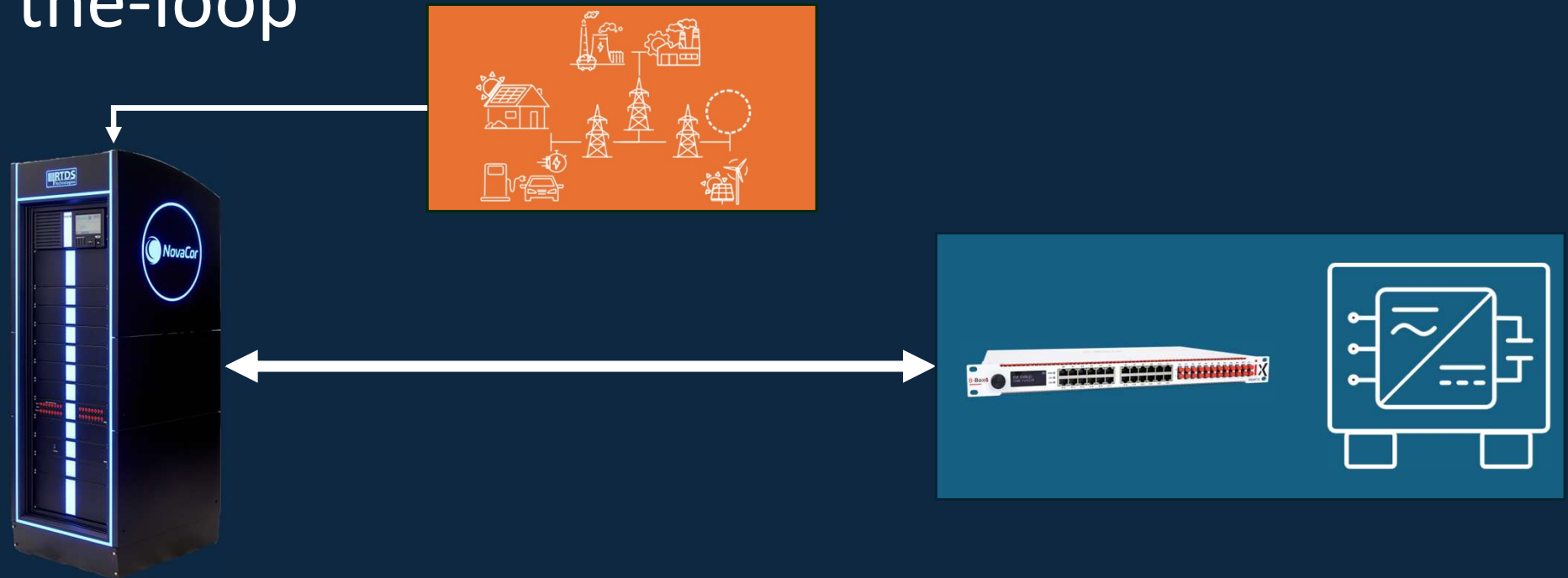
# Real-time Simulation: Hardware-in-the-loop



# Real-time Simulation: Control Hardware-in-the-loop

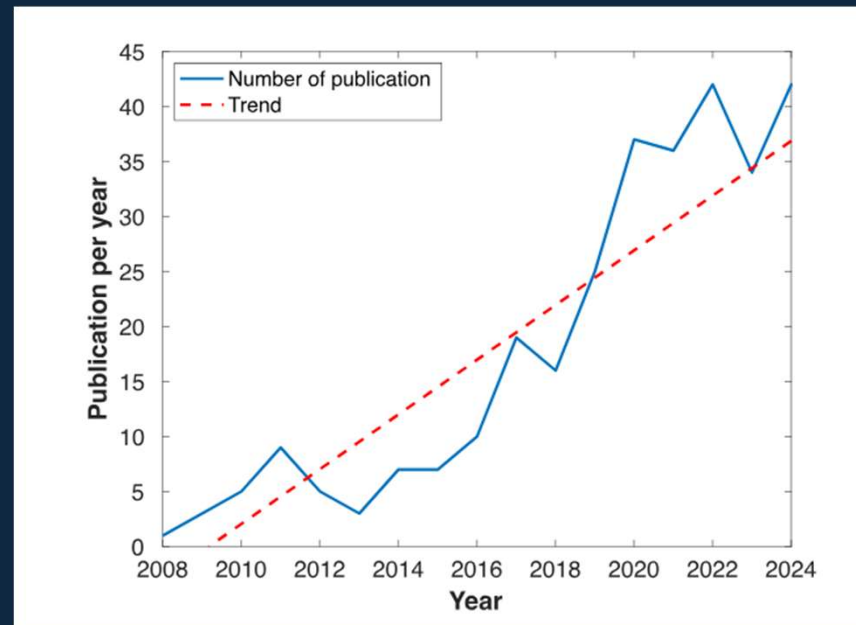


# Real-time Simulation: Power Hardware-in-the-loop



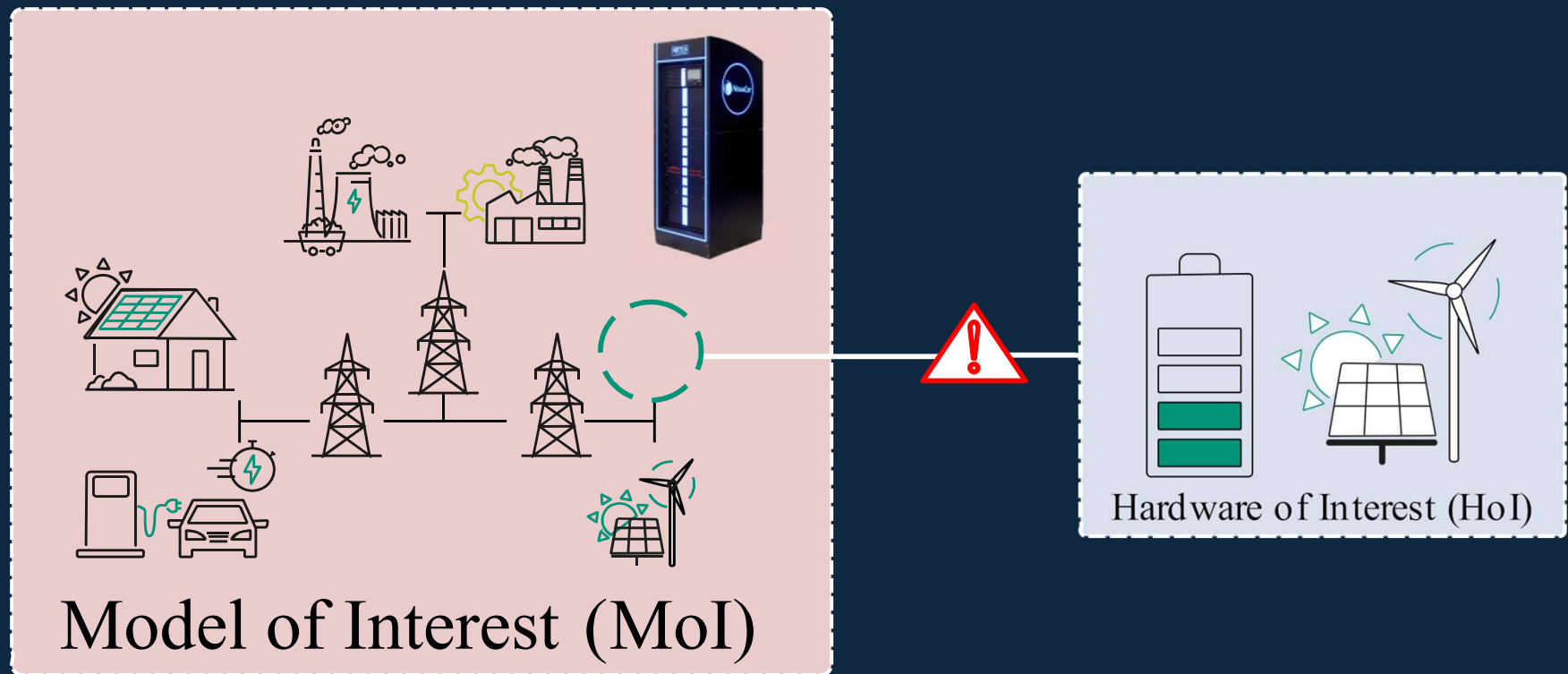
# Real-time Simulation: Power Hardware-in-the-loop

Query “Power hardware in the loop” OR “power-hardware-in-the-loop” in Web of Science

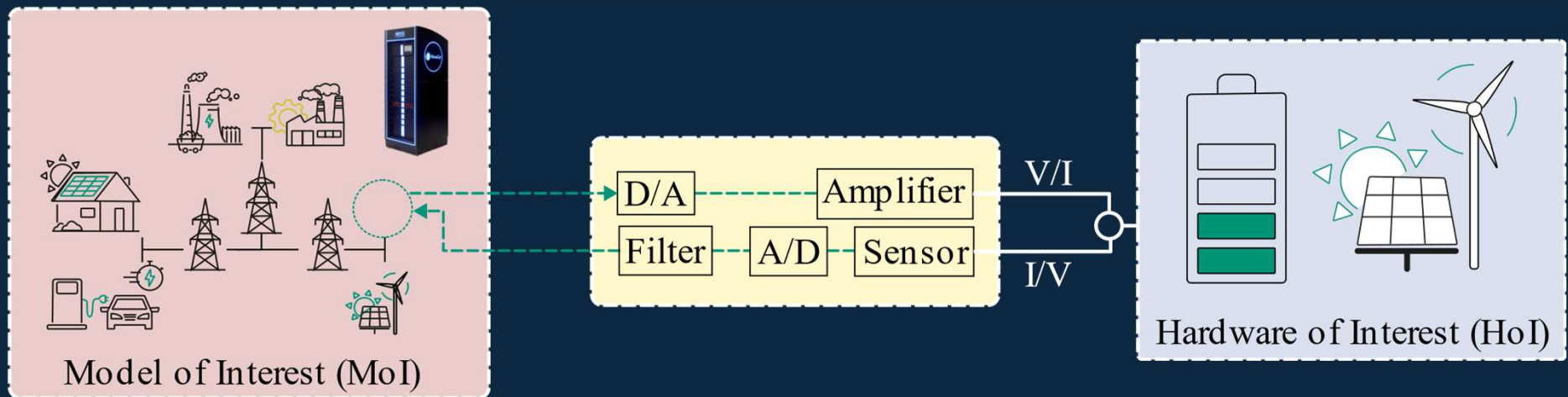


G. De Carne *et al.*, “Power Hardware-in-the-Loop for Electrical Systems: From Research Experience to Guidelines for Industrial Testing,” *IEEE Open Journal of Power Electronics*, vol. 7, pp. 822–842, 2026.

# Power Hardware-in-the-loop



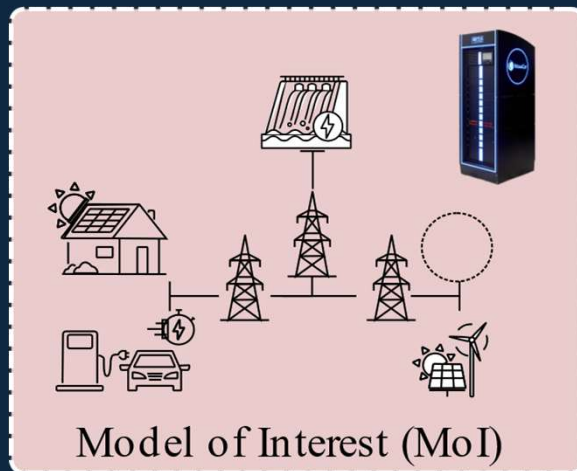
# Power Hardware-in-the-loop



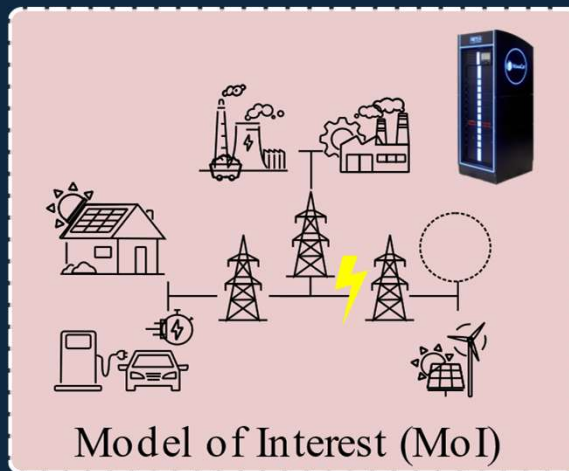
D/A: Digital-to-Analog Converter

A/D: Analog-to-Digital Converter

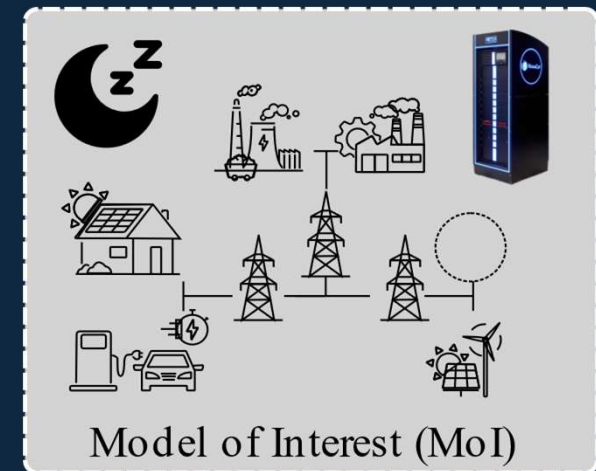
# Power Hardware-in-the-loop – Flexibility



Fully Renewable Grid

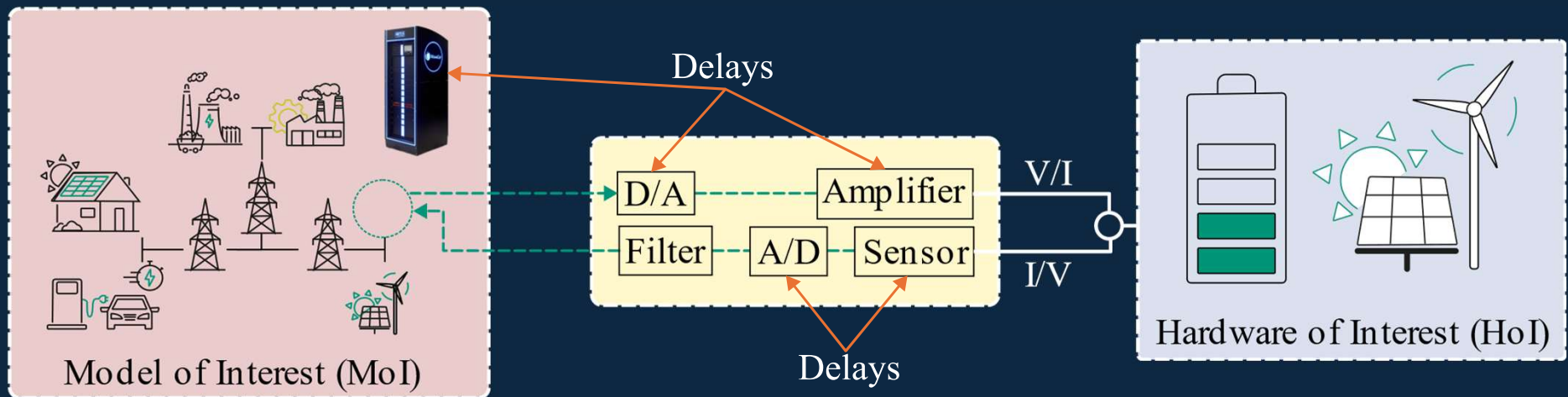


Fault Analysis



Flexible Scenarios

# Power Hardware-in-the-loop – Challenges



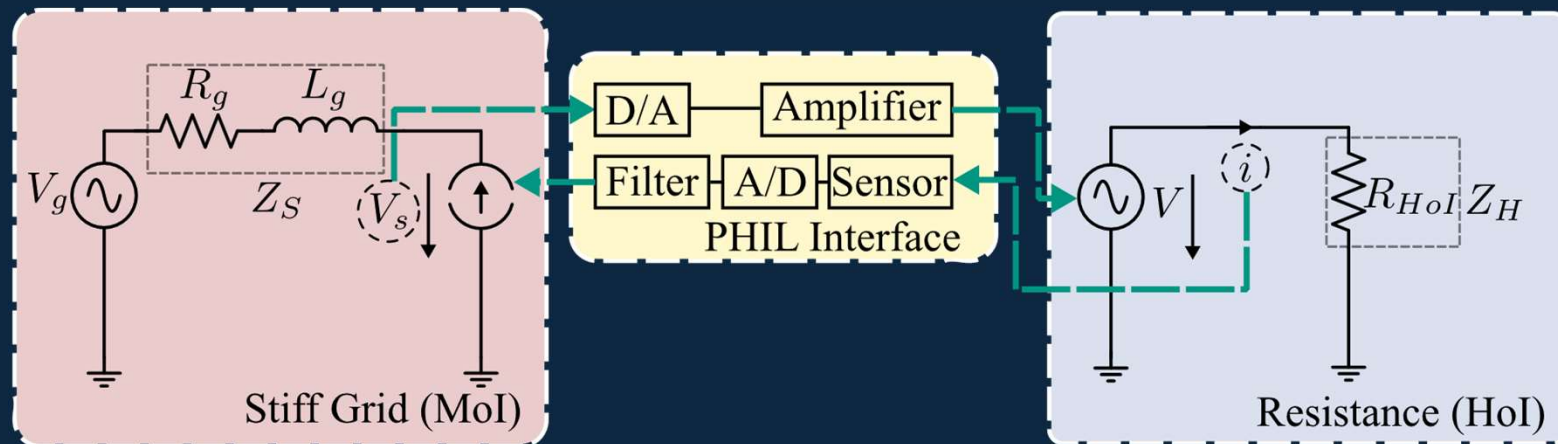
D/A: Digital-to-Analog Converter

A/D: Analog-to-Digital Converter

Impacts Stability and Accuracy

# Stability Analysis of PHIL

# Power Hardware-in-the-loop – Simple Setup



$$T_T = (2 \cdot T_{RT} + T_{Amplifier} + T_{D/A} + T_{sensor} + T_{D/A})$$

$$G_{OL}(s) = G_{Amp}(s) \cdot G_{LPF}(s) \cdot \frac{Z_S(s)}{Z_H(s)} \cdot e^{-s \cdot T_T}$$

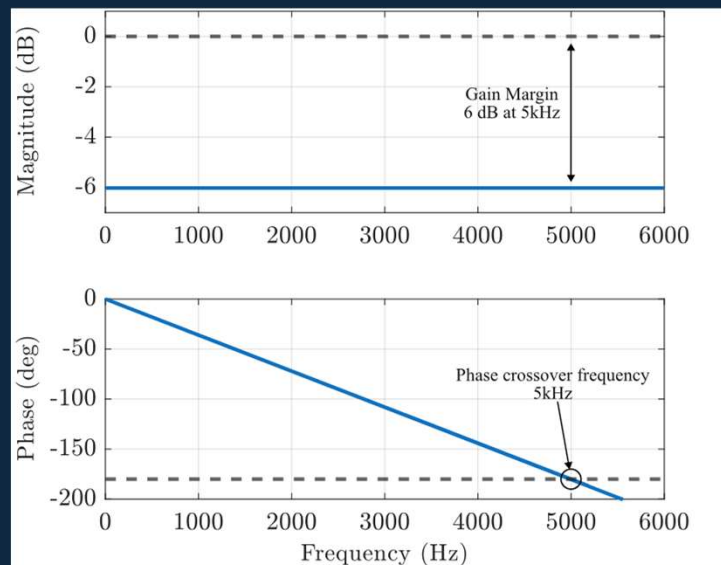
D/A: Digital-to-Analog Converter

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# Stability Analysis of a simple Setup

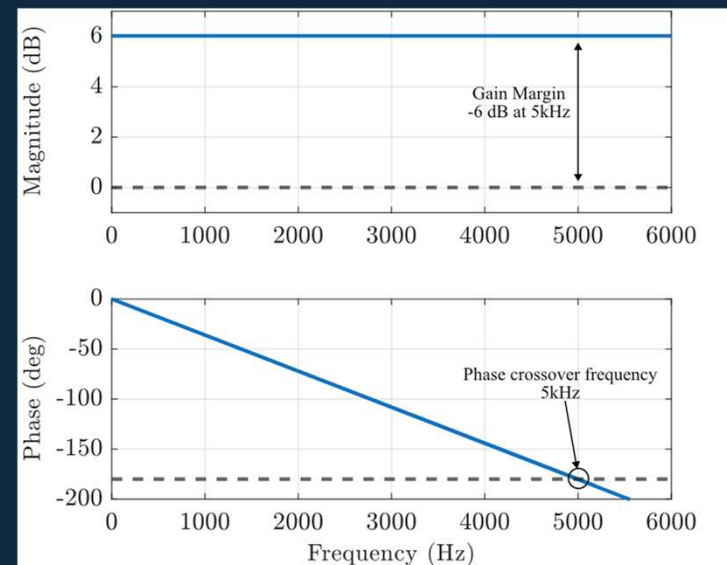
## Stable Case

$$\frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T} = 0.5 \cdot e^{-sT_T}$$

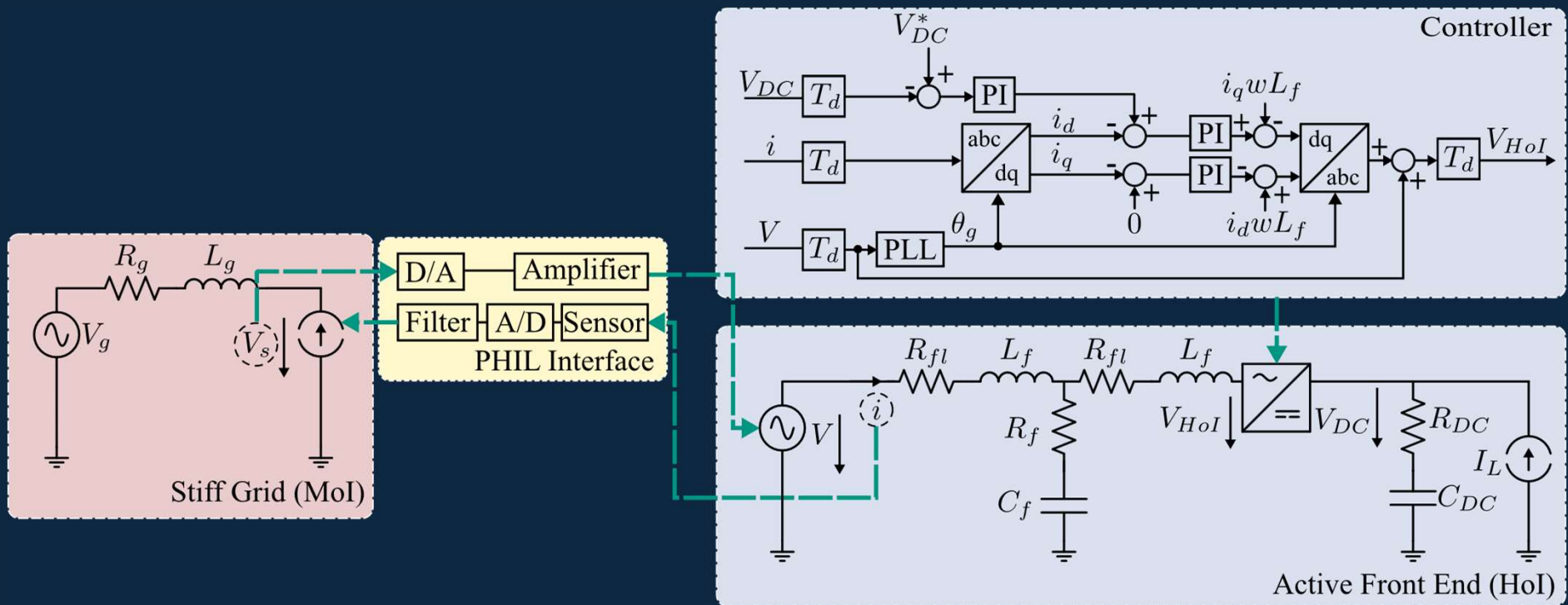


## Unstable Case

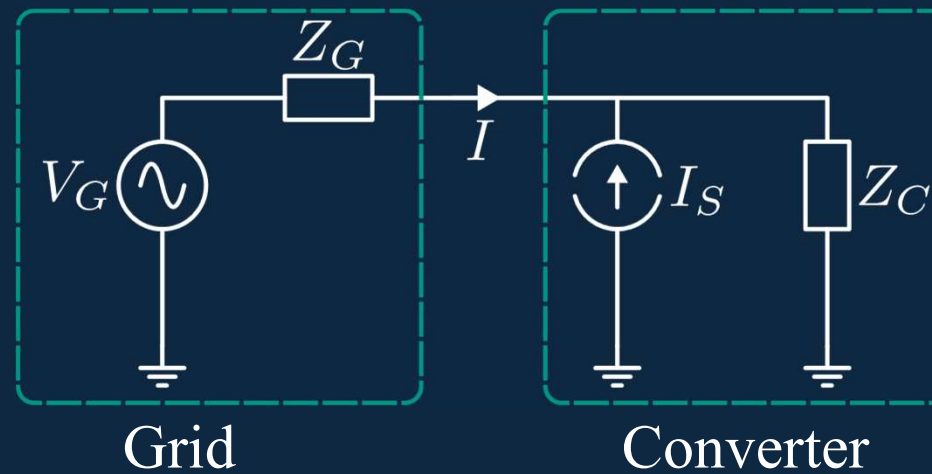
$$\frac{Z_S(s)}{Z_H(s)} \cdot e^{-sT_T} = 2 \cdot e^{-sT_T}$$



# Example Setup – AFE



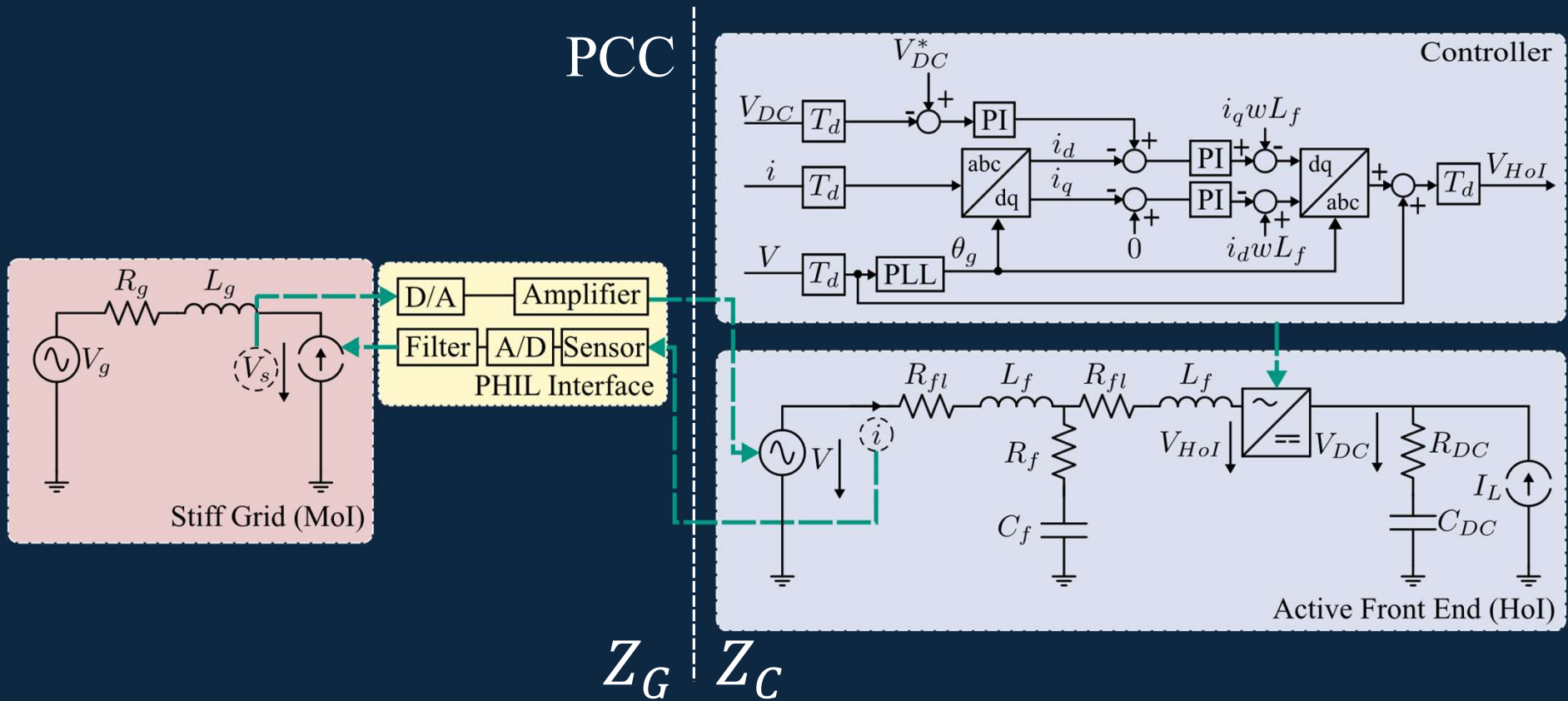
# Impedance-based Stability Analysis



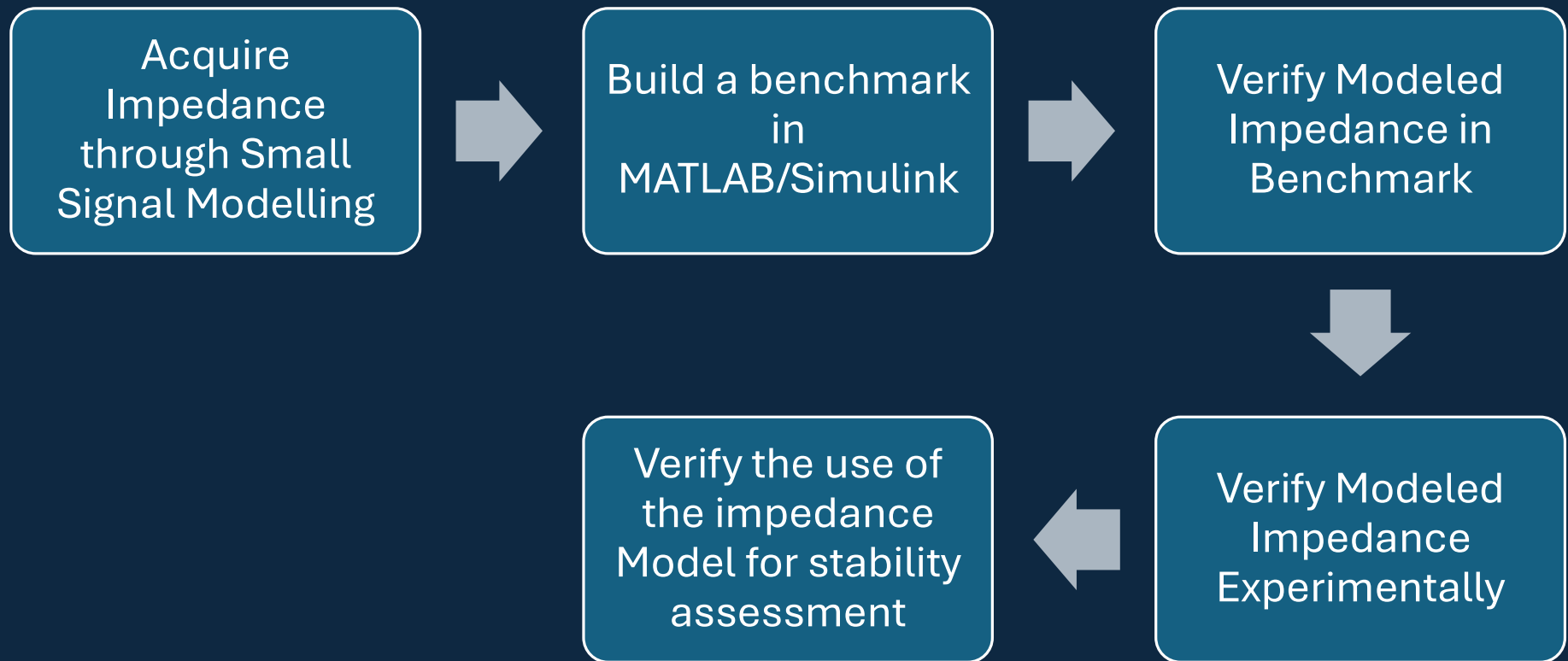
$$I(s) = \left[ I_S(s) - \frac{V_G(s)}{Z_C(s)} \right] \cdot \frac{1}{1 + \frac{Z_G(s)}{Z_C(s)}} \text{ Open Loop}$$

J. Sun, "Impedance-Based Stability Criterion for Grid-Connected Inverters," IEEE Transactions on Power Electronics, vol. 26, no. 11, pp. 3075–3078, Nov. 2011

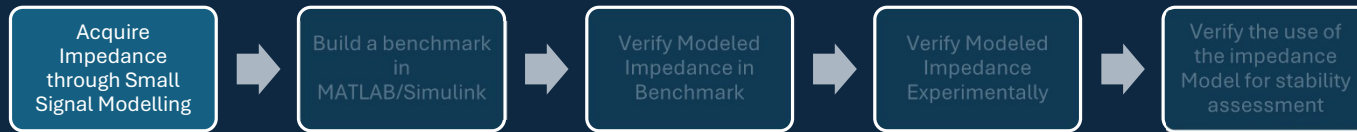
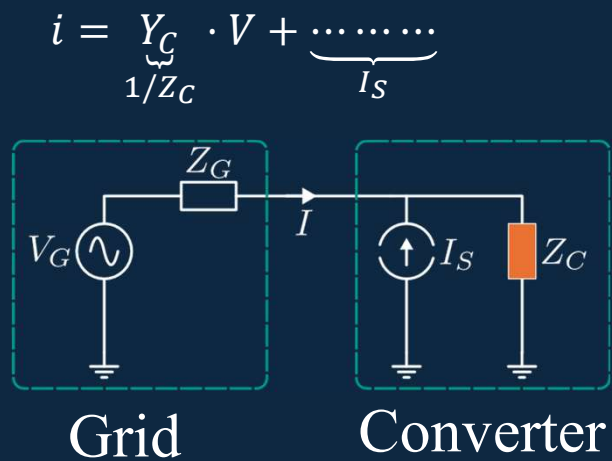
# Example Setup – AFE - Impedances



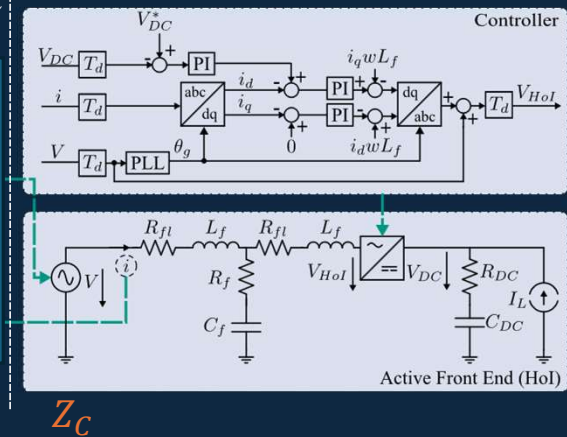
# Impedance-based Stability Analysis Process



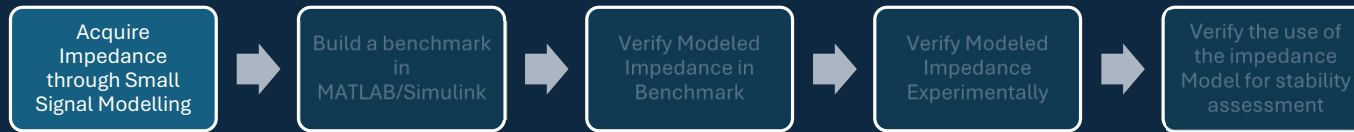
# Modelling Converter Impedance



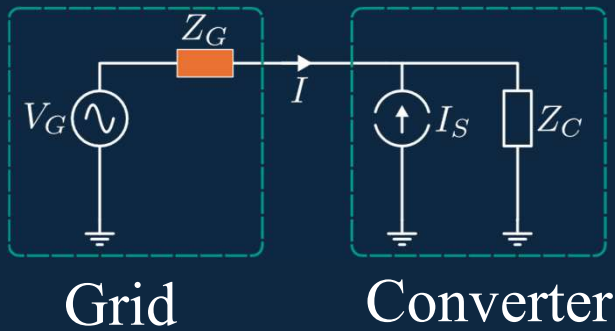
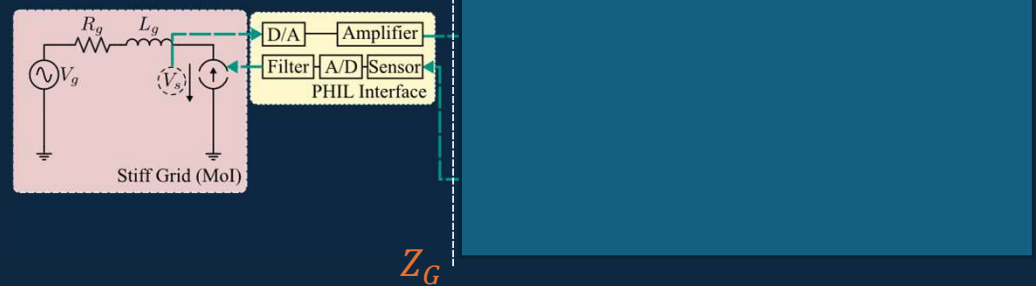
PCC



# Modelling Mol & Interface Impedance

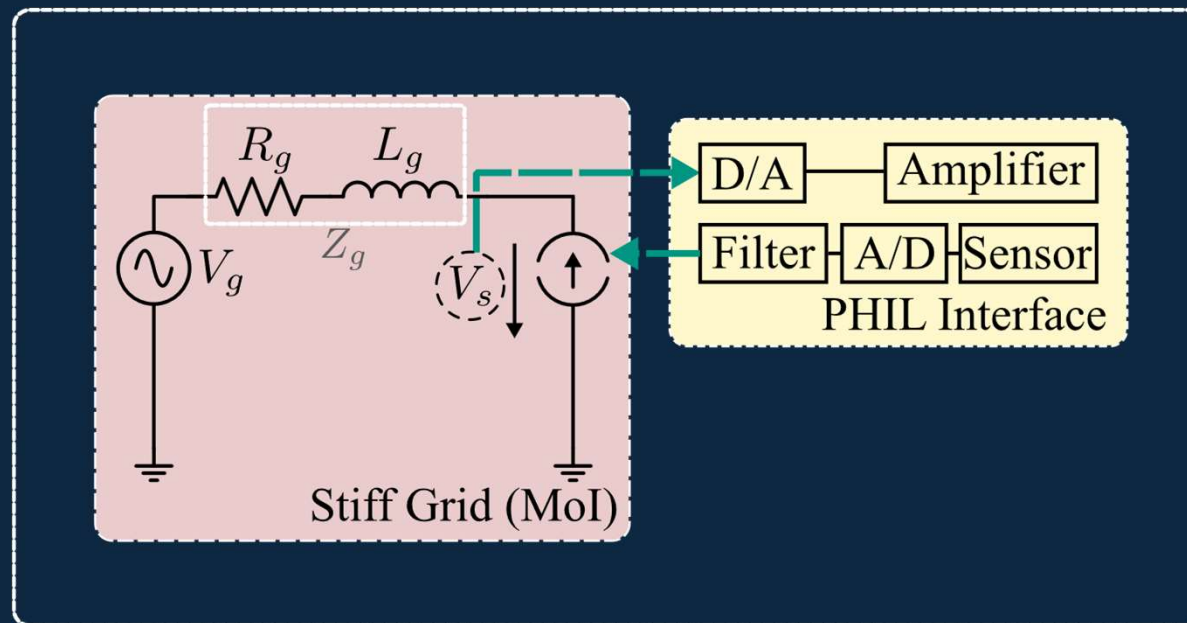


$$V = Z_G \cdot i + \underbrace{\dots\dots\dots}_{V_G}$$



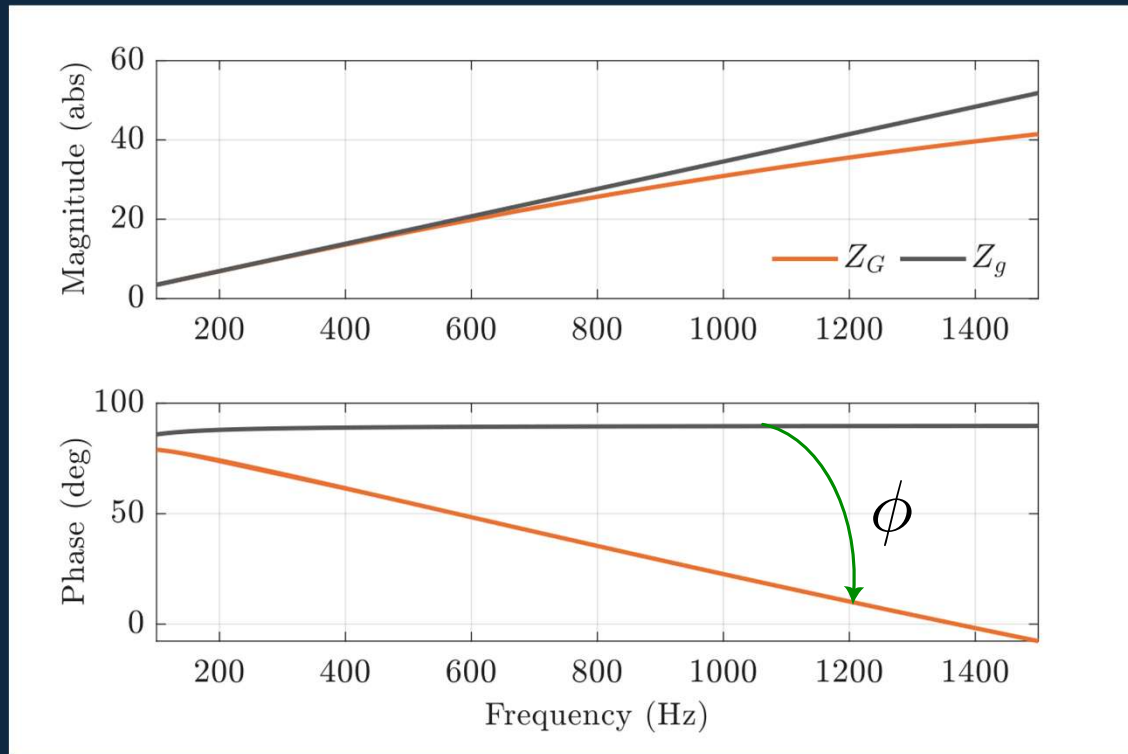
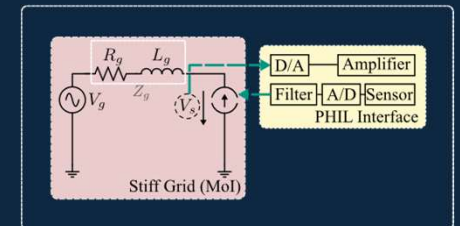
F. Ashrafiidehkordi, X. Liu, and G. D. Carne, "Impedance-based Stability Analysis of a Power Hardware-in-the-Loop for Grid-Following Inverter Testing," in *2023 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2023, p. 1116.

# Impact of PHIL interface on Grid Impedance



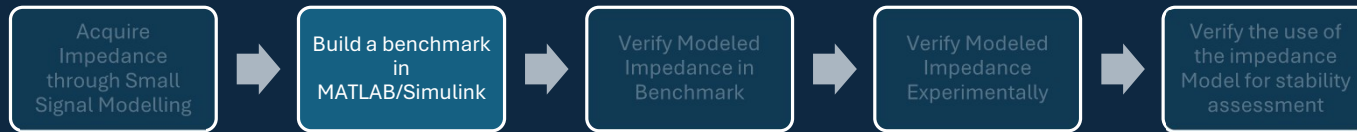
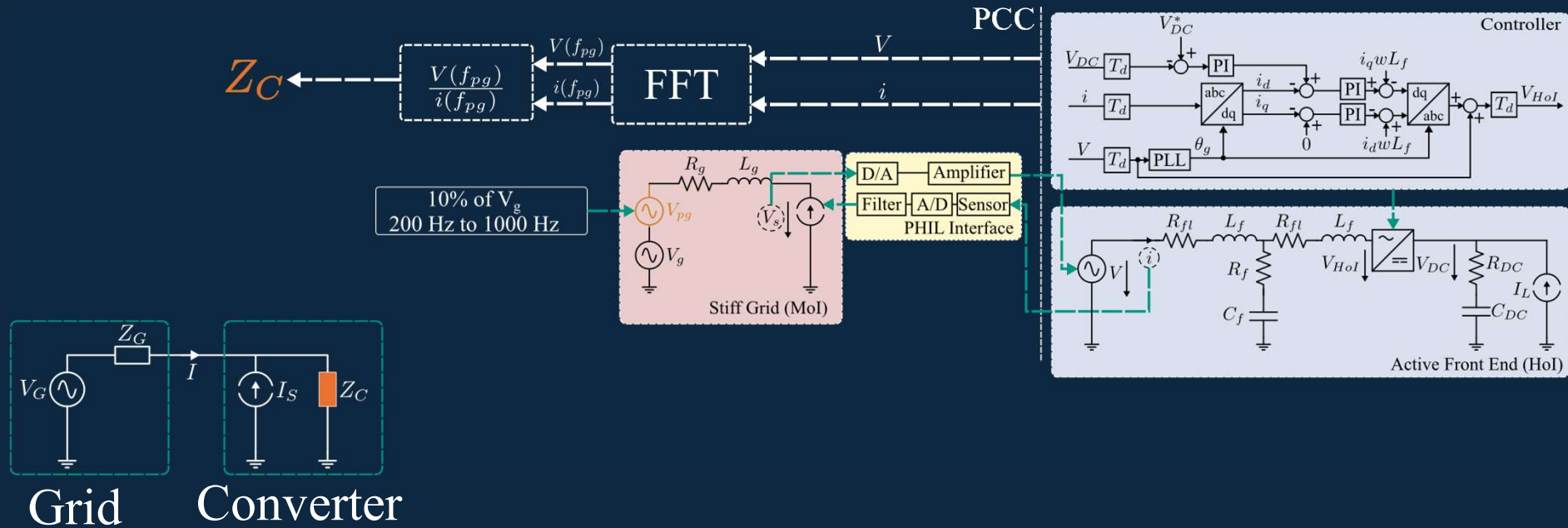
$Z_G$

# Impact of PHIL interface on Grid Impedance

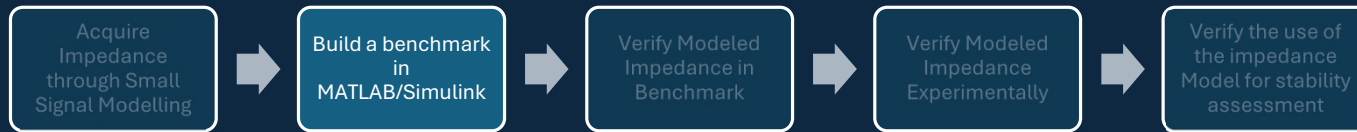
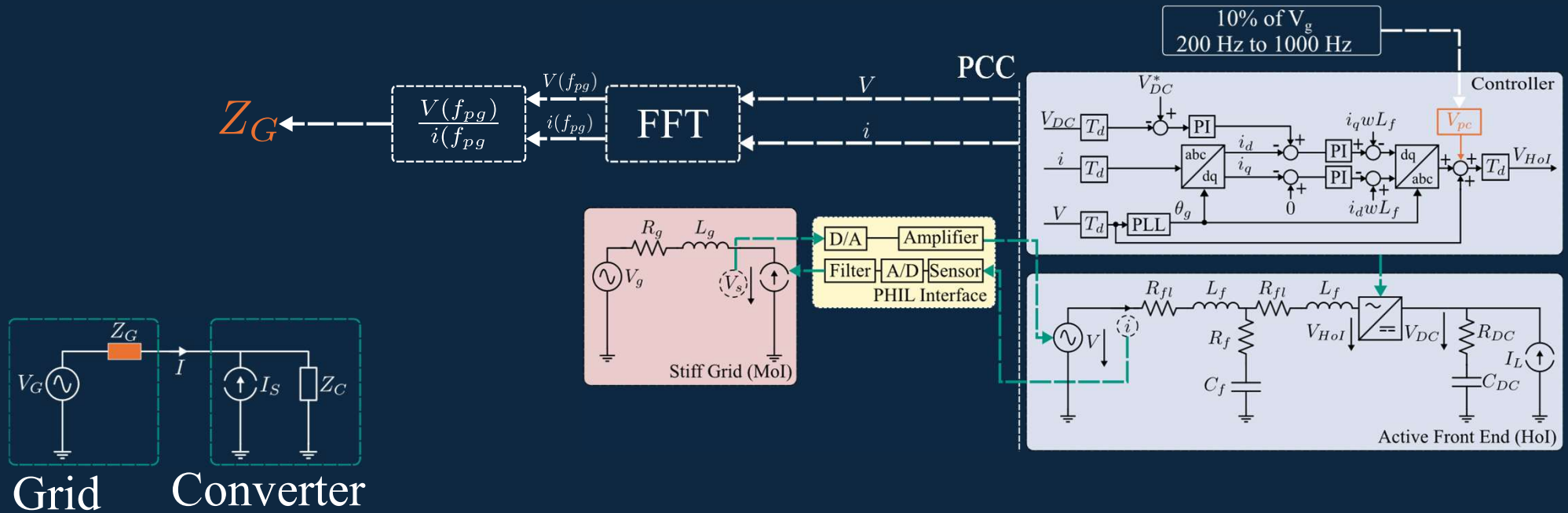


$Z_G$

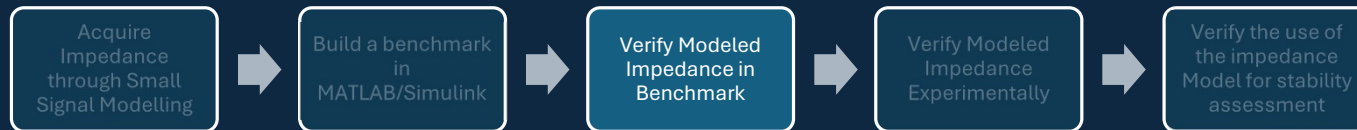
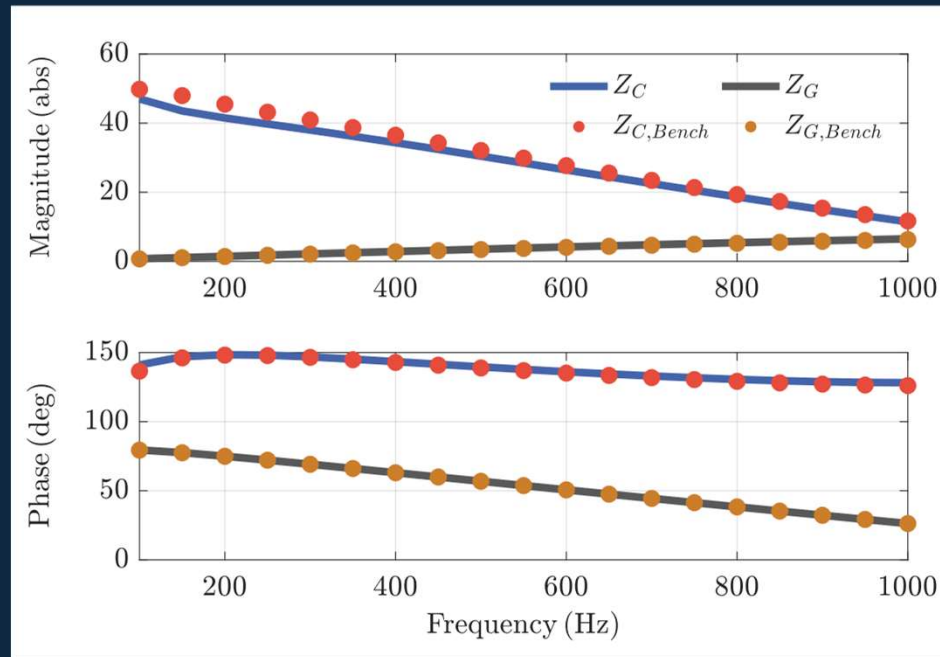
# Verifying Converter Impedance



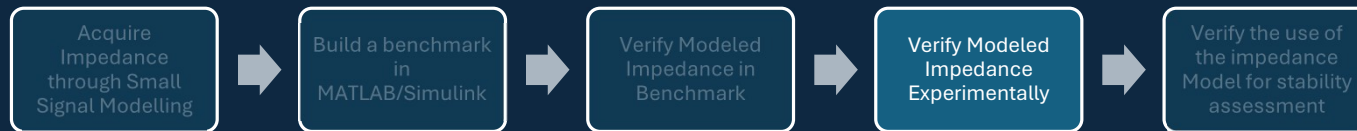
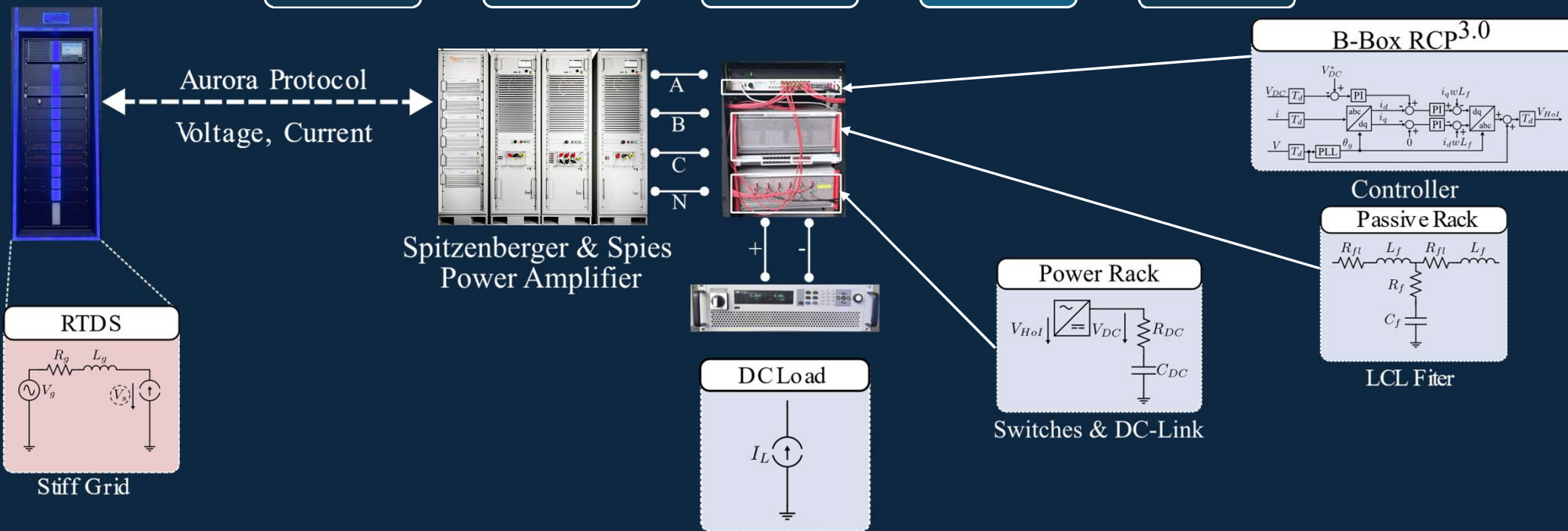
# Verifying Mol & Interface Impedance



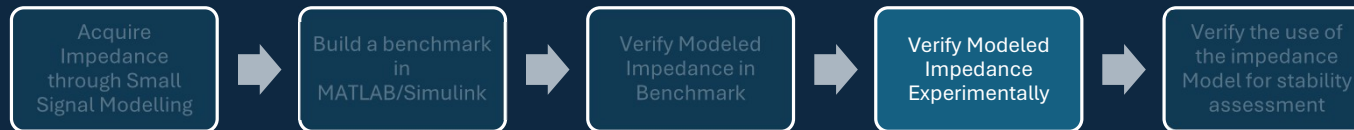
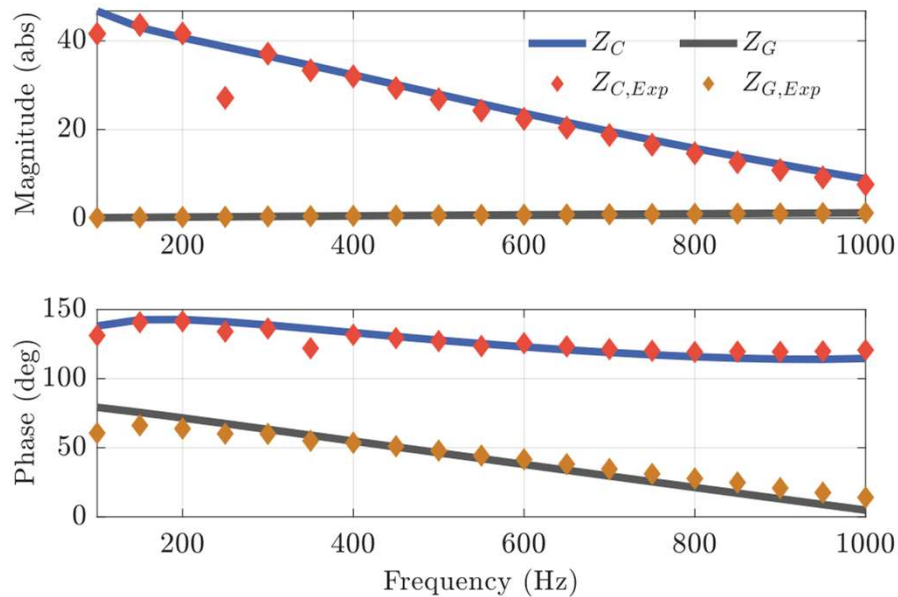
# Benchmark Impedance Verification Results



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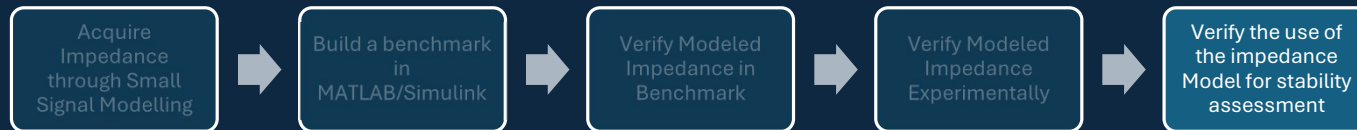


# Experiment Impedance Verification Results



| Impedance | NRMSE (Gain) | NRMSE Phase |
|-----------|--------------|-------------|
| $Z_C$     | 0.085        | 0.225       |
| $Z_G$     | 0.012        | 0.128       |

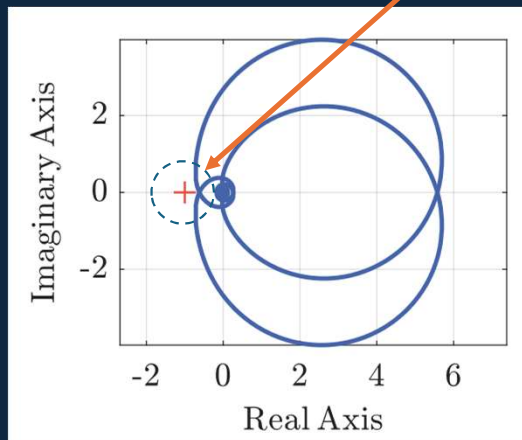
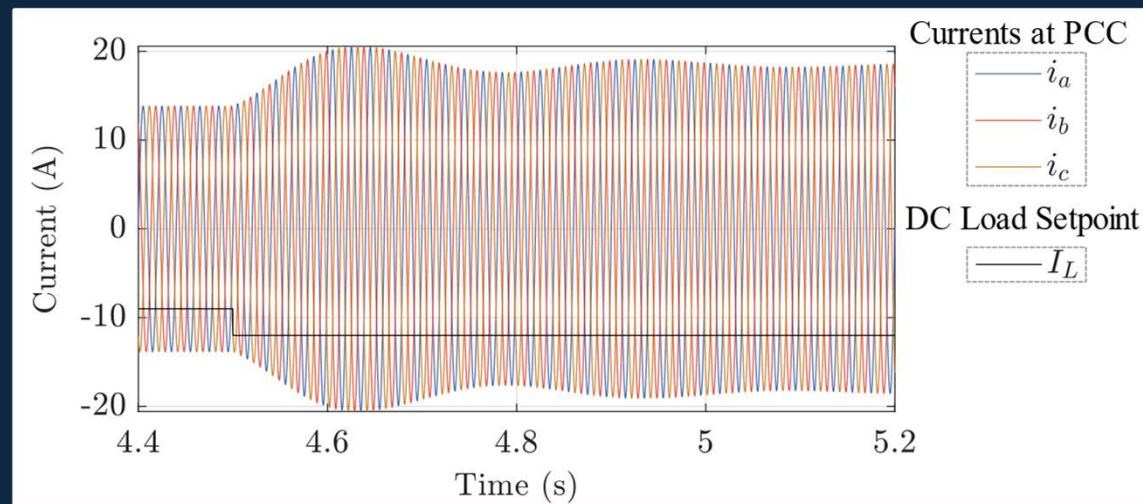
# Stability Verification



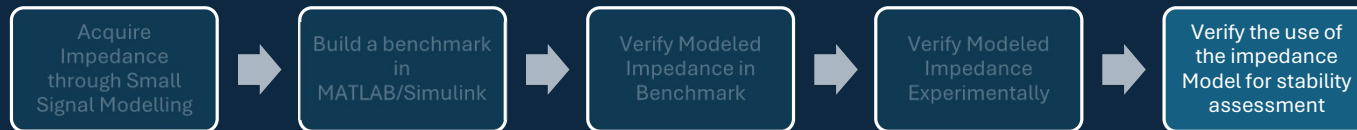
Nyquist Plot of  $\frac{Z_G}{Z_C}$   
 $R_g = 0.1 \Omega, L_g = 2.2 \text{ mH}$

No encirclement of critical point  
setup is predicted to be stable

Benchmark verifies Nyquist stability

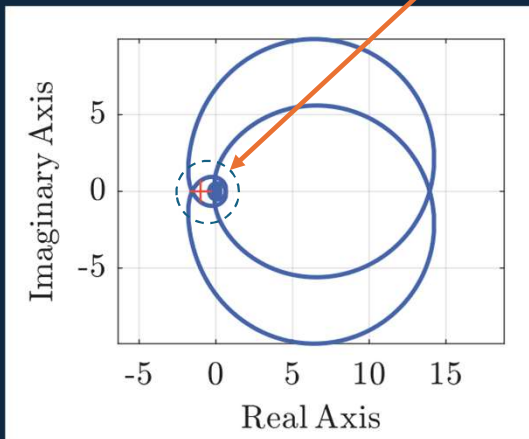


# Stability Verification



Nyquist Plot of  $\frac{Z_G}{Z_C}$

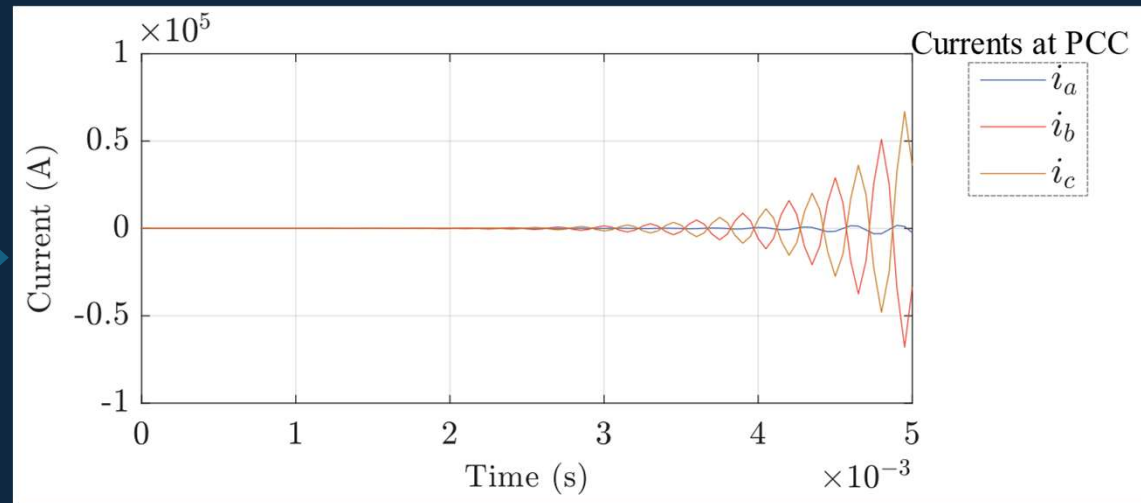
$R_g = 0.25 \Omega, L_g = 5.5 \text{ mH}$



Encirclement of critical point

Setup is predicted to be unstable

Benchmark verifies Nyquist instability



# Conclusion

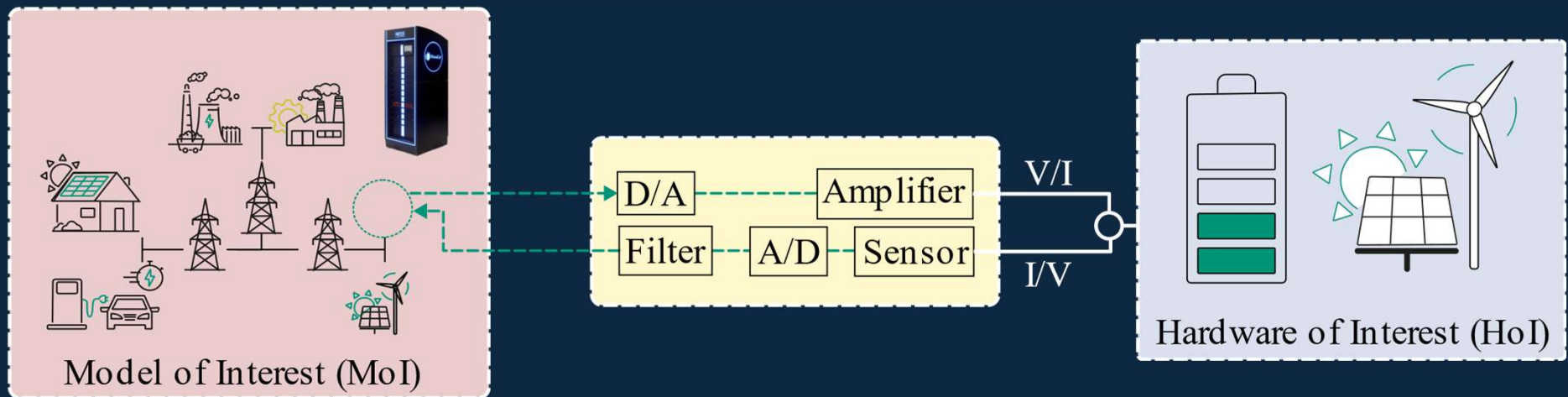


2026 MADRID USER'S GROUP MEETING

MADRID, SPAIN



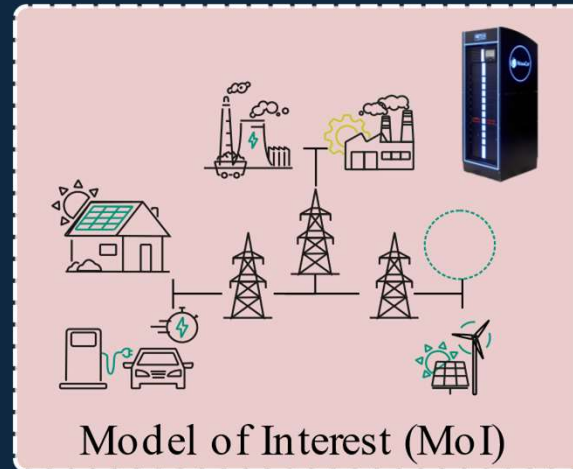
# Power Hardware-in-the-loop – Overview



D/A: Digital-to-Analog Converter

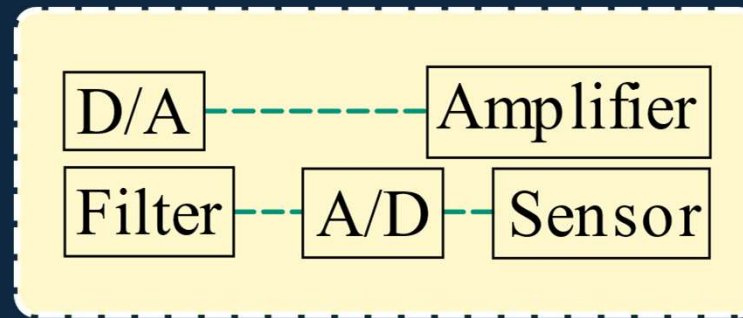
A/D: Analog-to-Digital Converter

# Power Hardware-in-the-loop – Overview



- Offers the Necessary Flexibility for testing
- Requires a real-time simulator

# Power Hardware-in-the-loop – Overview

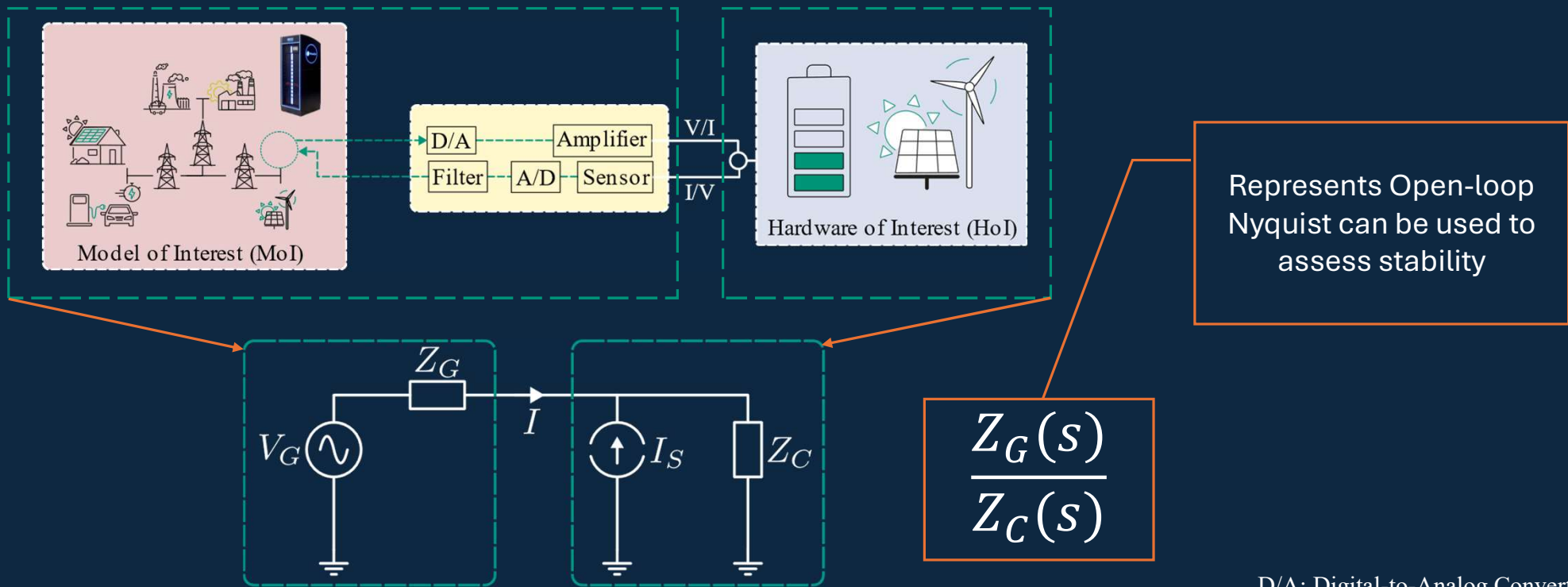


- Required to connect the Mol to the Hol
- Changes the shape of the grid impedance
- Leading to impacts on stability and Accuracy

D/A: Digital-to-Analog Converter

A/D: Analog-to-Digital Converter

# Power Hardware-in-the-loop – Stability



D/A: Digital-to-Analog Converter

A/D: Analog-to-Digital Converter