Energy-in-the-Loop: From Grid Simulation to High-power Testing at the Energy Lab

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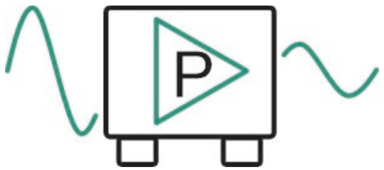
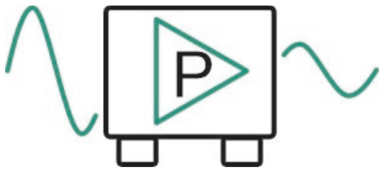
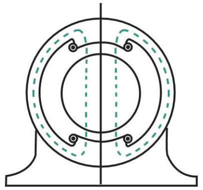
Energy Lab - Power Hardware-in-the-Loop



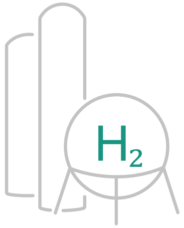
- **Egston Power Amplifier**
  up to 1MW
  Switch-mode



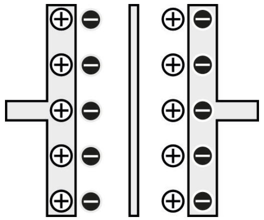
- **Spitzenberger Power Amplifier**
  up to 45kW
  Linear



- **Flywheel Energy Storage**
  120 kW
  7.2 kWh



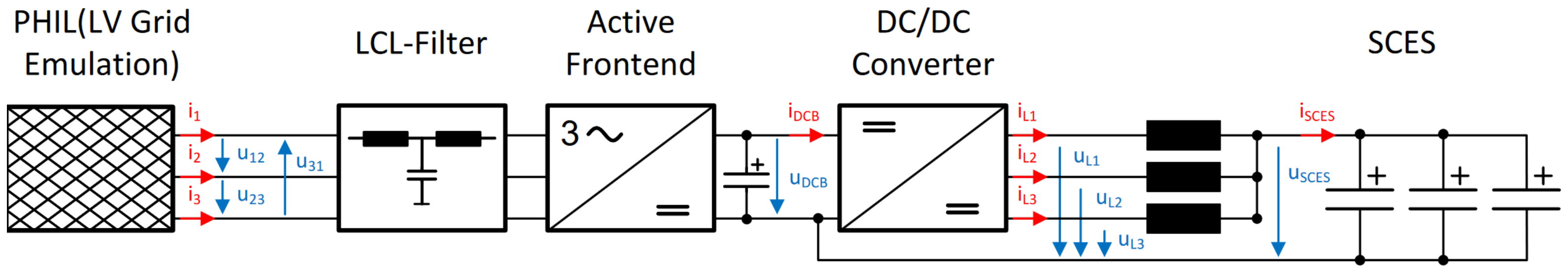
- **Hydrogen Energy Storage**
  10-50kW
  1000kWh



- **Supercapacitor**
  400 kW
  1 kWh

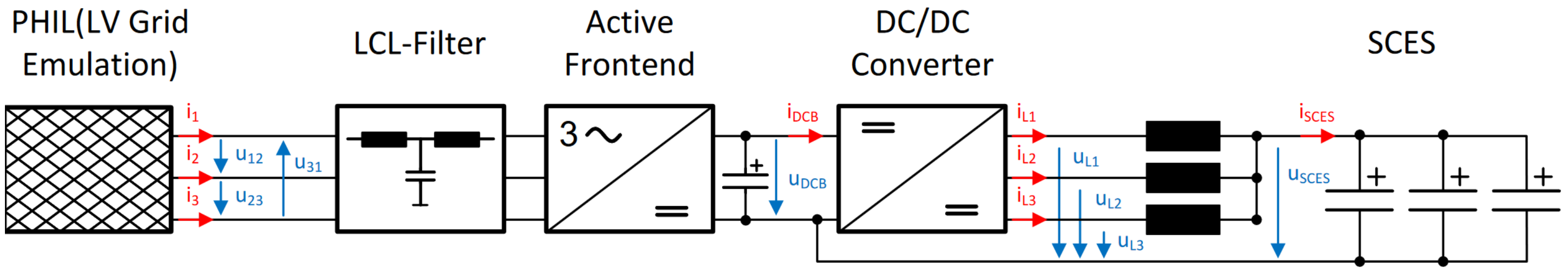
- **Battery Energy Storage**
  100 kW
  400 kWh

SCESS Testbench

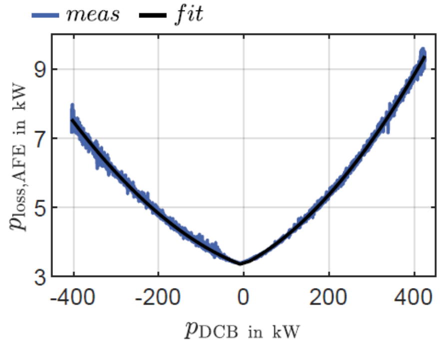


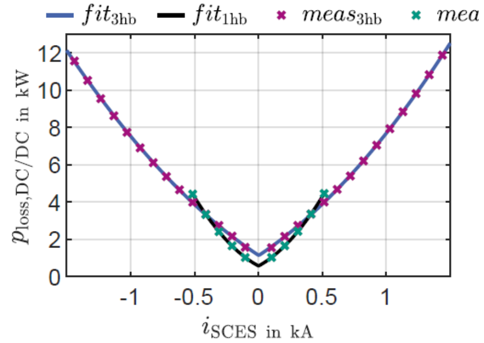
Test Stand	
$P_{N,SCES}$	400 kW
U_{SCES}	250..550 V
$I_{SCES,max}$	1400 A
$E_{SCES@400kW}$	~1kWh

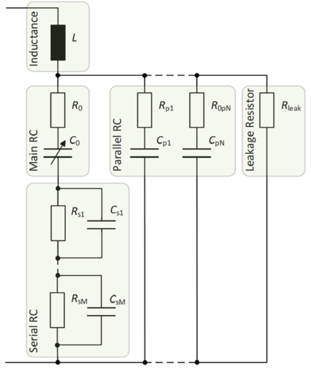
SCESS Testbench

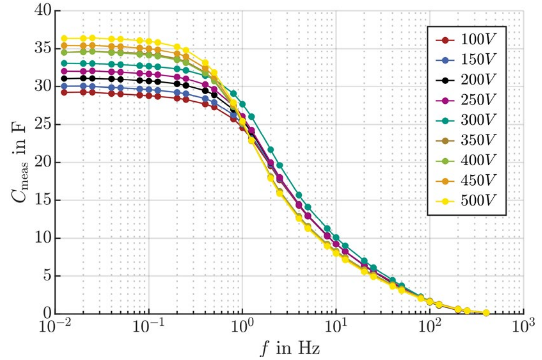


General Goal	• Investigate power system impact
System Modeling	• Inverter losses • Voltage and loss prediction of the SCES
Results	• Losses, SoC and voltage can be predicted for approx. 15 min. with <= 5% error
Current research topics	• Pulsed load peak shaving • Fast Frequency Response

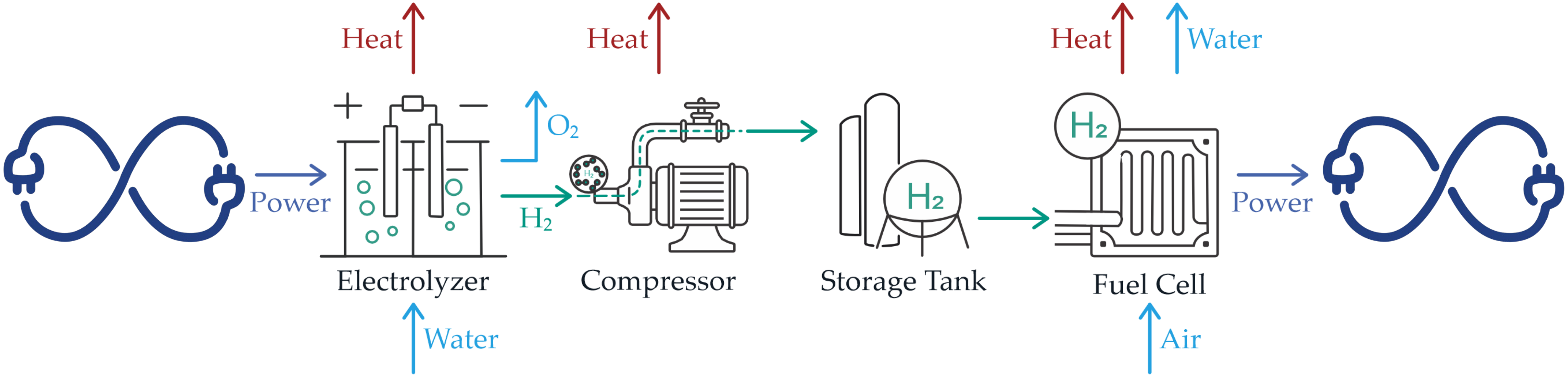






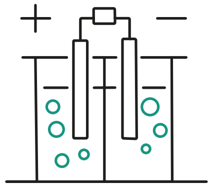


H_2-in-the-Loop Plant Overview

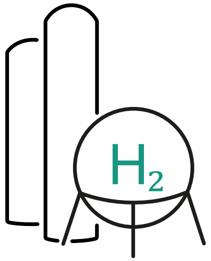


- Investigation of Electrolyzer systems as variable load
- Investigation of Fuel Cell systems as variable source
- Simulation of various grid support scenarios in PHIL

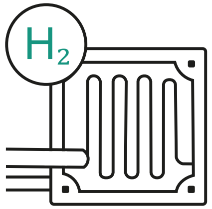
H_2-in-the-Loop Plant Technical Details



- **Alkaline Electrolysis Unit**
  Rated input power 50 kW
  Hydrogen output 8 Nm^3/h at 8 bar



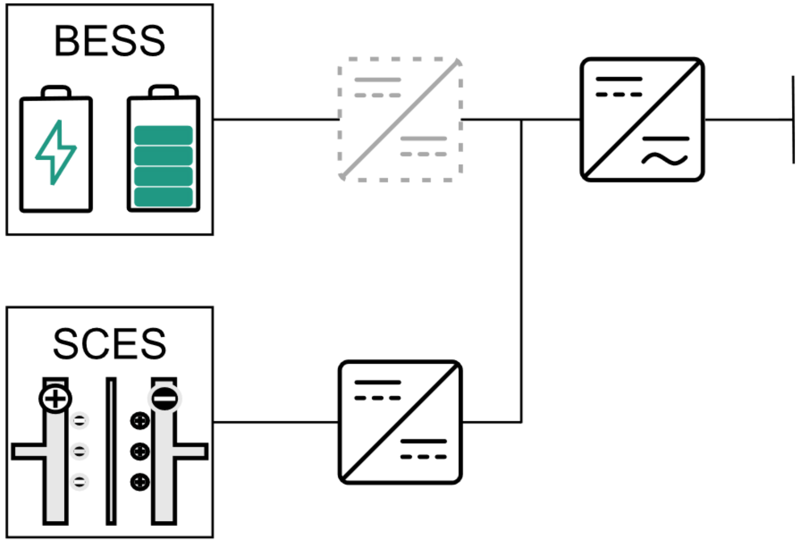
- **Hydrogen Storage**
  Compression to up to 450 bar
  Tank capacity 800 L / 32 kg / 1000 kWh



- **PEM Fuel Cell Unit**
  Rated output power 10 kW
  Battery buffered DC interface at 48V

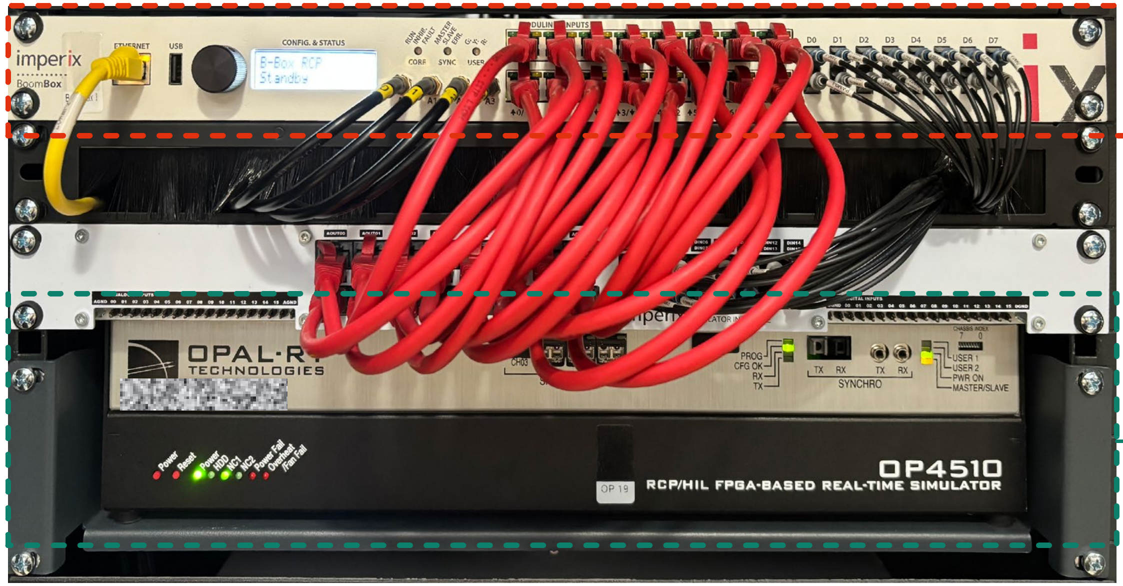
Outlook - Energy Storage Systems

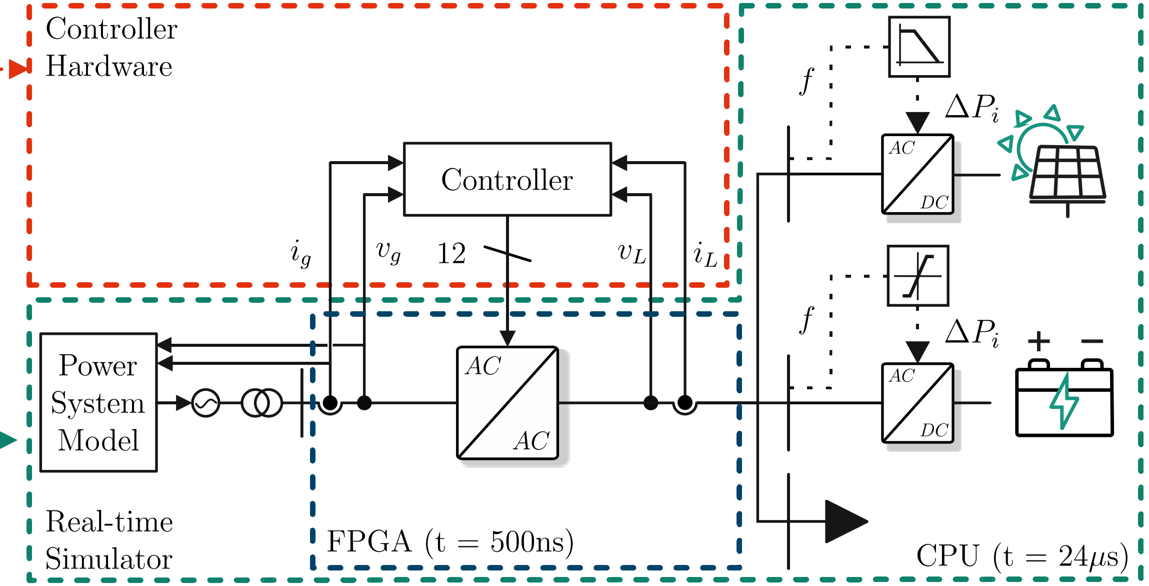
- Integrate new storage systems
  - Hydrogen
  - MMC Battery
- Testing combinations of Storage Systems
- Develop and Validate Hybrid Control Concepts



G. De Carne *et al.*, “The role of energy storage systems for a secure energy supply: A comprehensive review of system needs and technology solutions,” *Electric Power Systems Research*, vol. 236, p. 110963, Nov. 2024, doi: 10.1016/j.epsr.2024.110963.

Controller Hardware-in-the-Loop



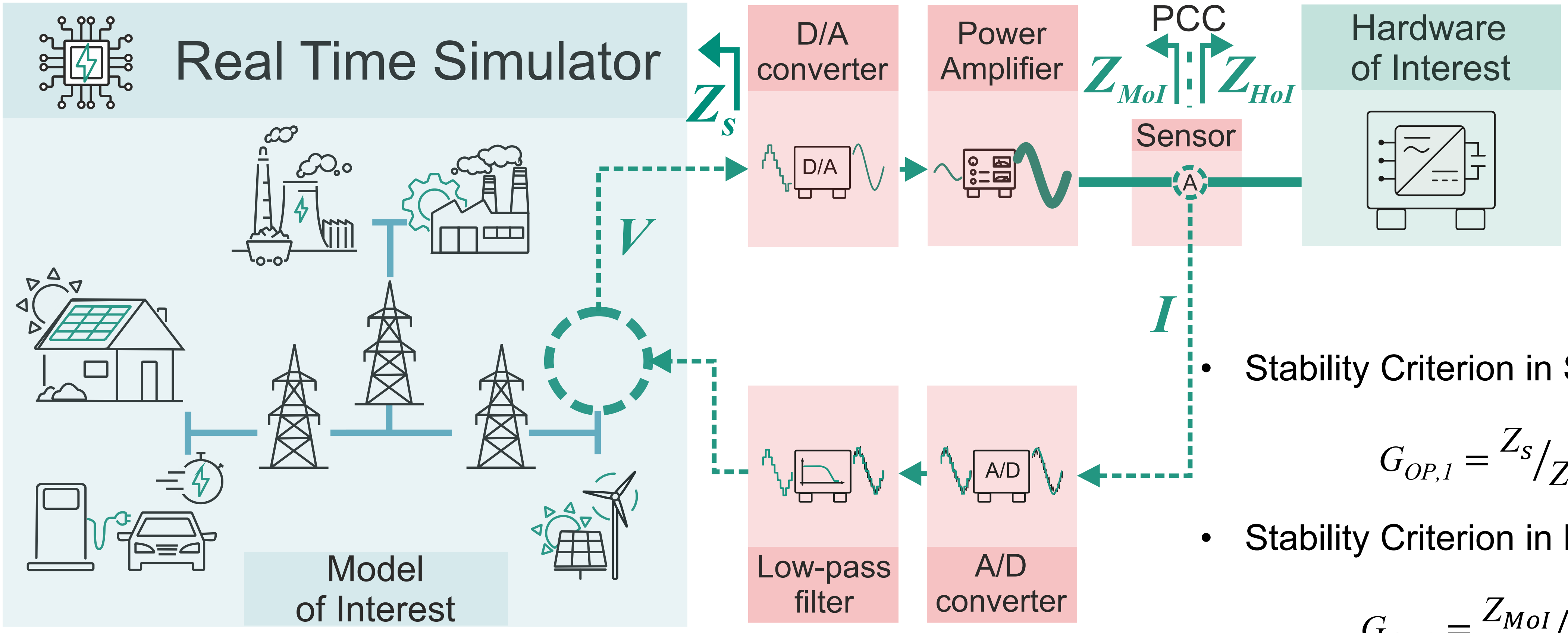


- **Model validation**: Sufficient for a lot of system level analysis – much faster
- **Teaching:** Easily accessible (also remote) – safe – fast results -> self-efficacy

New Course - Digital Real-Time Simulations for Energy Technologies

- Real-time Simulation Basics (Hands on Exercises)
- Modelling of Power Systems and Power Electronics (Hands on Exercises)
- Rapid Control Prototyping
- Controller Hardware-in-the-Loop (Hands on Exercises)
- Power Hardware-in-the-Loop (Lab Demo)

Impedance-based Stability Analysis of Power Hardware-in-the-Loop Setups



- Stability Criterion in Simulation:

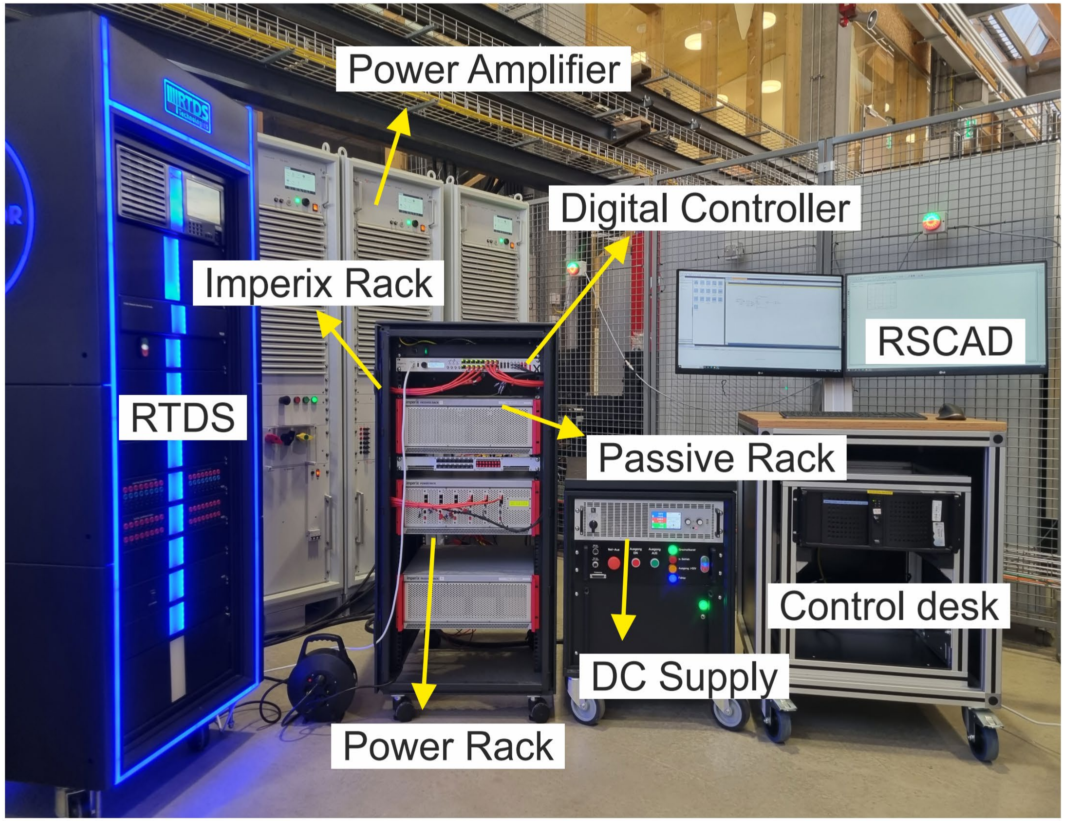
$$G_{OP,1} = {}^{Z_S}\!/_{Z_{HoI}}$$

- Stability Criterion in PHIL:

$$G_{OP,2} = {}^{Z_{MoI}}\!/_{Z_{HoI}}$$

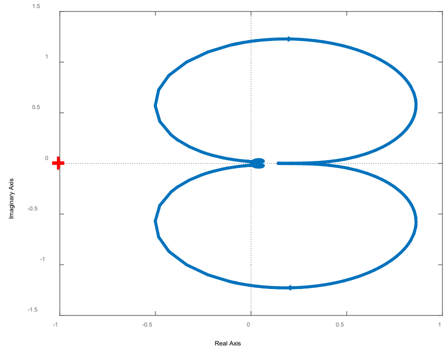
Impedance-based Stability Analysis of Power Hardware-in-the-Loop Setups – Grid-tied Converters

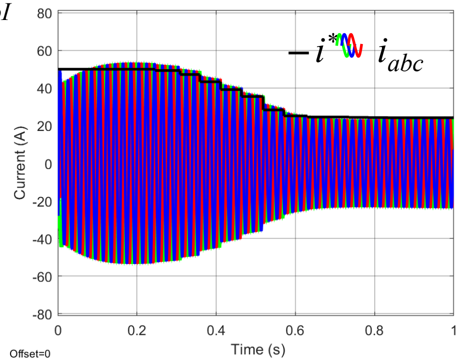
Impedance Verification



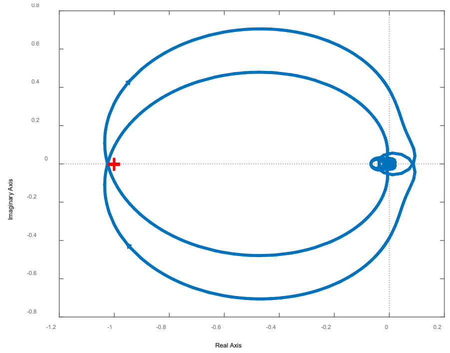
Stability Verification

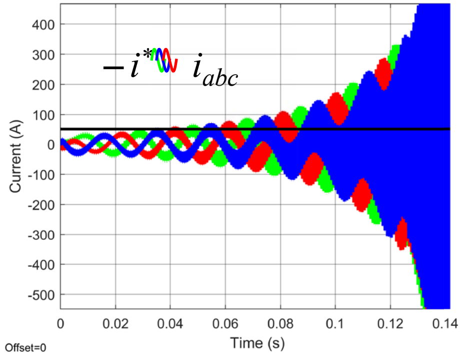
Simulation Scheme, $G_{OP,1} = Z_s / Z_{HoI}$:





PHIL Scheme, $G_{OP,2} = Z_{MoI} / Z_{HoI}$:



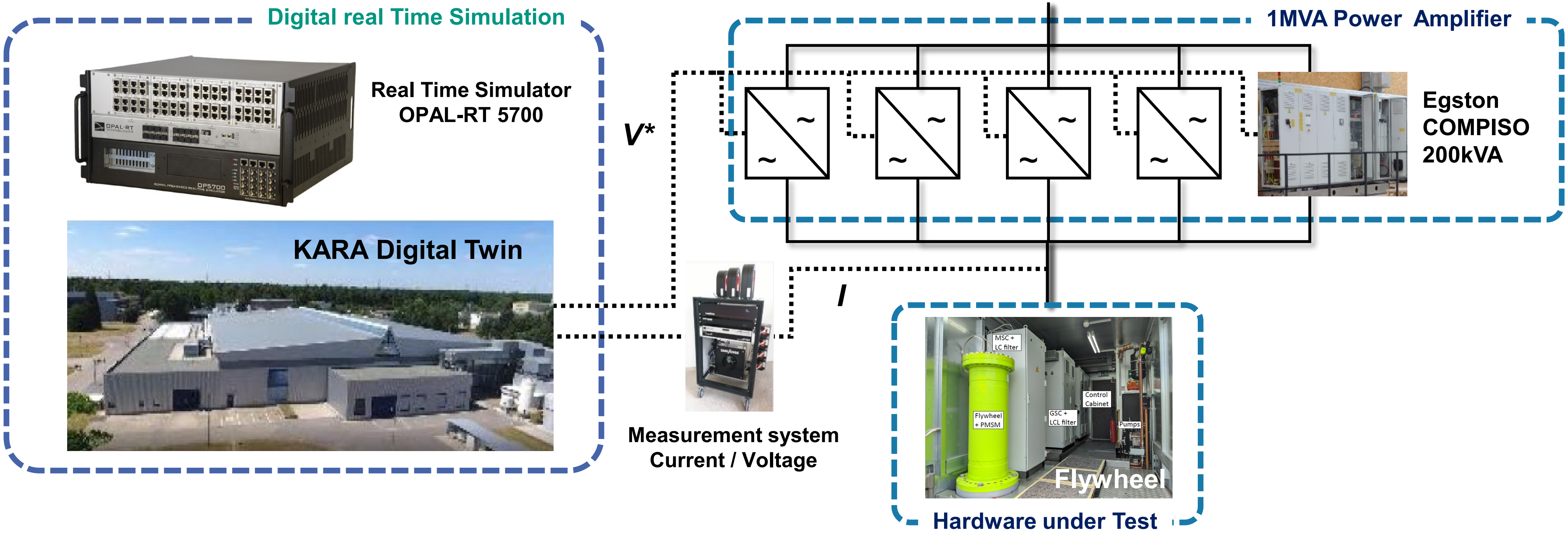


F. Ashrafidehkordi, X. Liu and G. De Carne, "Impedance-based Stability Analysis of a Power Hardware-in-the-Loop for Grid-Following Inverter Testing," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 1116-1121, doi: 10.1109/ECCE53617.2023.10362808.

Digital Twin-in-the-Loop

Karlsruhe Institute of Technology

- **Digital real time simulator**: simulate the KARA electrical grid
- **Power amplifier**: reproduce a point of the simulated grid in lab (e.g., measured voltage)



Thank You for Your Attention

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