IMPEDANCE-BASED STABILITY ANALYSIS OF A POWER HARDWARE IN-THE-LOOP FOR GRID-FOLLOWING INVERTER TESTING

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2023 EUROPEAN RTDS TECHNOLOGIES INC. USER'S GROUP MEETING 2023

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OUTLINE

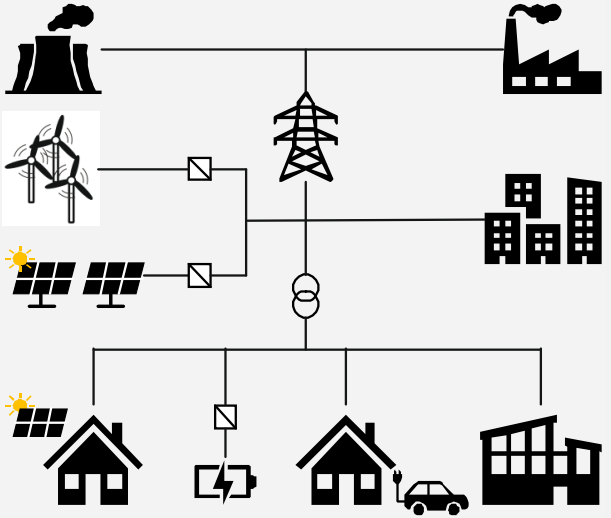
- Why Power Hardware-in-the-Loop (PHIL)?
- What are the challenges?
- Impedance-based stability analysis
- Simulation verifcation
- Experimental results
- Conclusion

WHY PHIL?

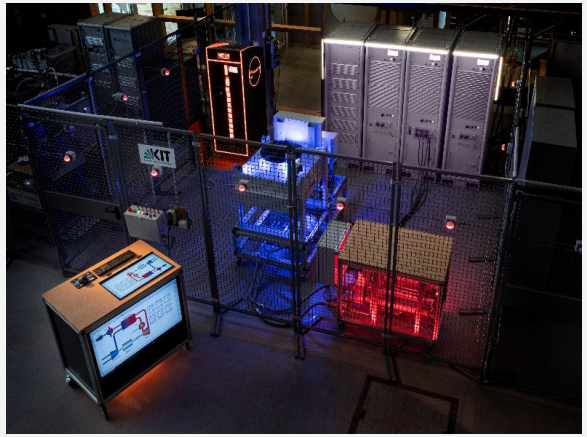
Power Hardware

PHIL

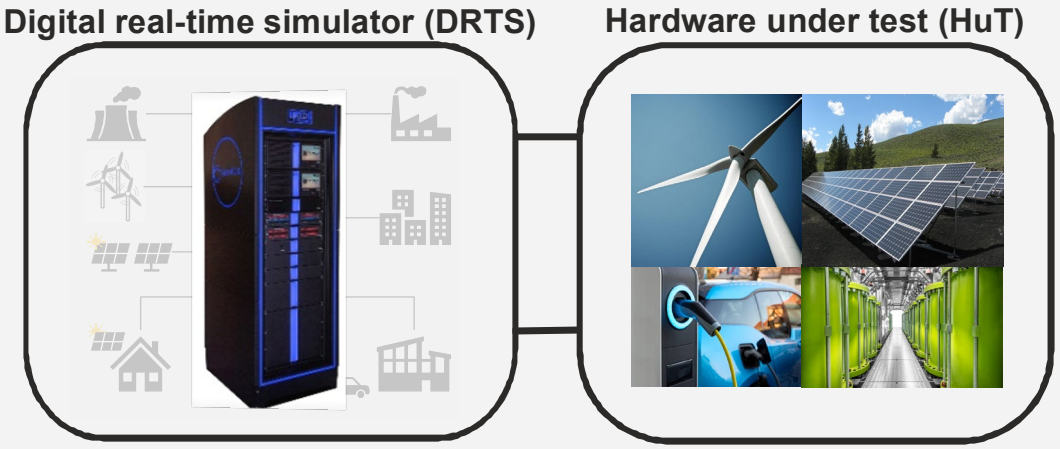
Power Grid



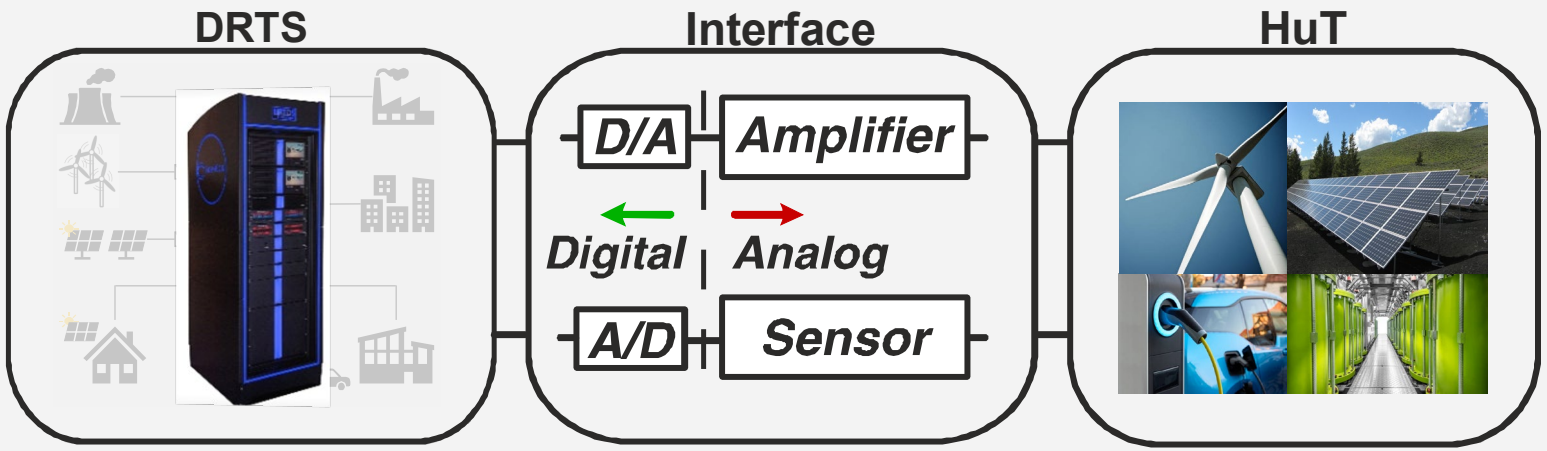
CHALLENGES OF PHIL



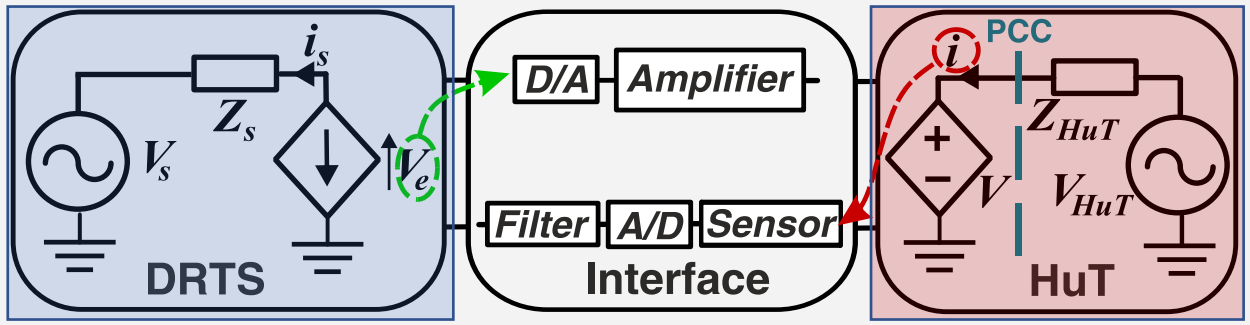
Ideal Scheme

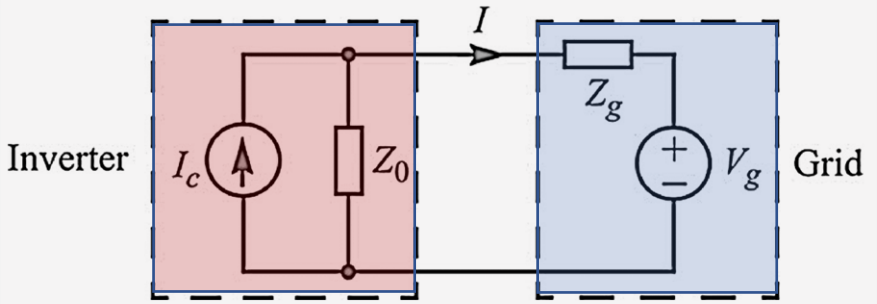


Existing Scheme



IMPEDANCE-BASED STABILITY ANALYSIS





Voltage-type Ideal Transformer Method (V-ITM)

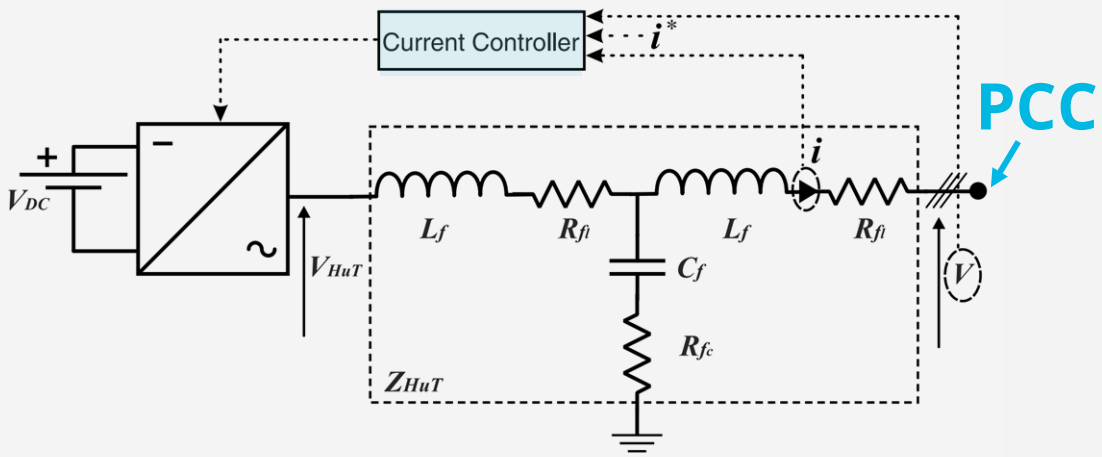
$$G_{OL} = ?$$

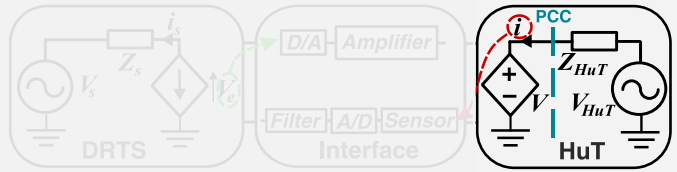
$$I(\mathrm{s}) = [I_c(\mathrm{s}) - \frac{V_g(\mathrm{s})}{Z_0(\mathrm{s})}]\frac{1}{1+Z_g(\mathrm{s})/Z_0(\mathrm{s})}$$

G_{OL}

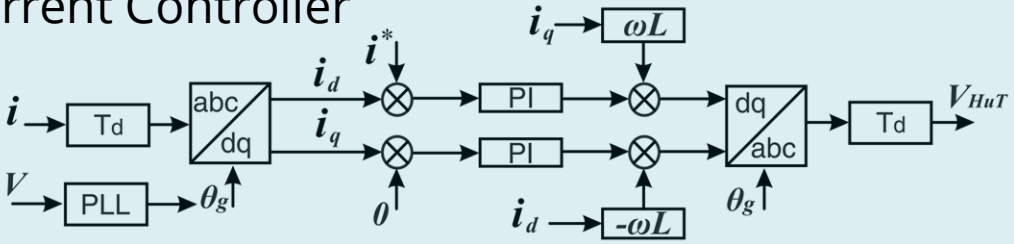
[1] J. Sun, "Impedance-Based Stability Criterion for Grid-Connected Inverters," in IEEE Transactions on Power Electronics, vol. 26, no. 11, pp. 3075-3078, Nov. 2011, doi: 10.1109/TPEL.2011.2136439

IMPEDANCE MODEL OF THE GRID-FOLLOWING INVERTER





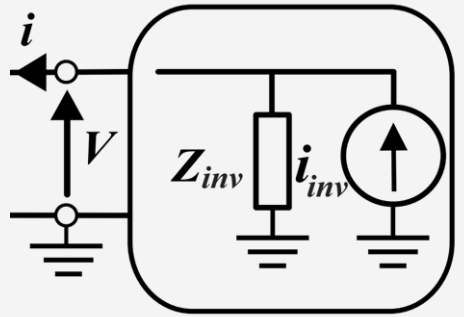
Current Controller



$$i = Y_{LCL,V_{HuT}}(s) \cdot V_{HuT} + Y_{LCL,V}(s) \cdot V$$

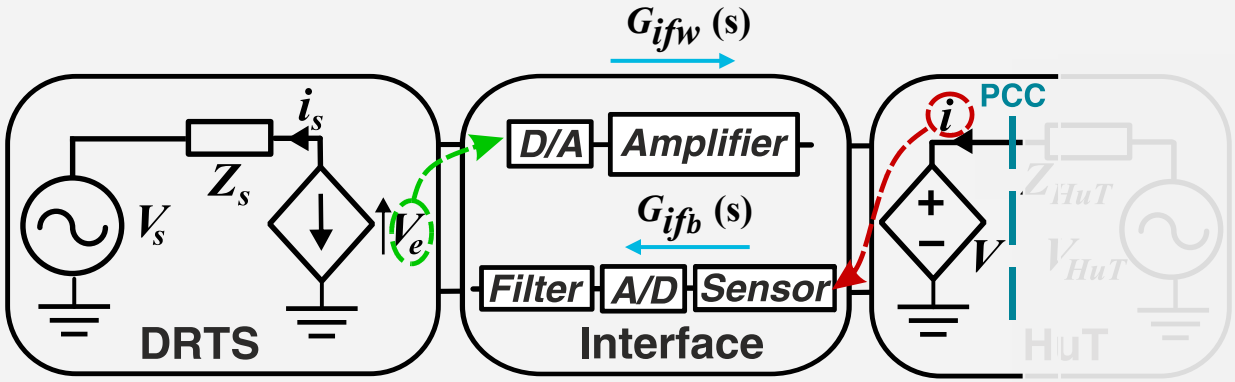
$$V_{HuT} = (i^* - T_d(s) \cdot i) \cdot G_{PI}(s) \cdot T_d(s)$$

$$i = \underbrace{\frac{G_{PI}(s) \cdot T_d(s) \cdot Y_{LCL,V_{HuT}}(s)}{1 + G_{PI}(s) \cdot T_d(s)^2 \cdot Y_{LCL,V_{HuT}}(s)}}_{H_{inv}(s)} i^* \underbrace{- \frac{Y_{LCL,V}(s)}{1 + G_{PI}(s) \cdot T_d(s)^2 \cdot Y_{LCL,V_{HuT}}(s)}}_{Y_{inv}(s)} V$$



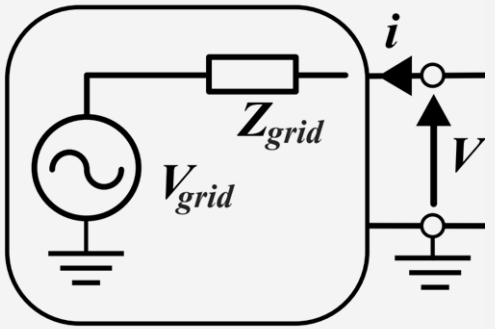
$$i_{inv} = H_{inv}(s) \cdot i^*$$

IMPEDANCE MODEL OF THE GRID



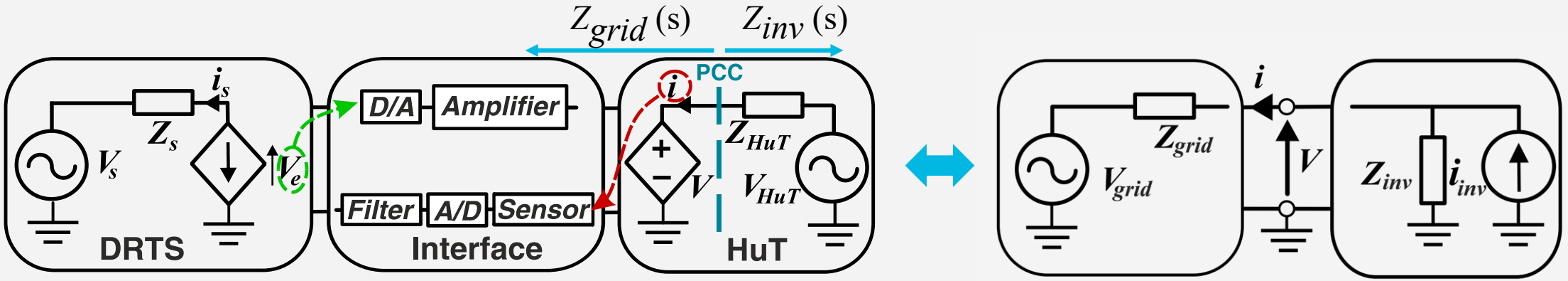
$$V = \overbrace{(V_s + G_{ifb}(s) \ . \ Z_s(s) \ . \ i)}^{V_e} \ . \ G_{ifw}(s)$$

$$i = \underbrace{\frac{1}{G_{ifb}(s) \ . \ Z_s(s)}}_{H_{grid}(s)} V_s - \underbrace{\frac{1}{G_{ifb}(s) \ . \ Z_s(s) \ . \ G_{ifw}(s)}}_{Y_{grid}(s)} V$$



$$V_{grid} = H_{grid}(s) \ . \ V_s$$

STABILITY CRITERION



Existing PHIL Model

Impedance Model

Simulink Model

$$G_{OL} = \frac{Z_{grid}(s)}{Z_{inv}(s)}$$

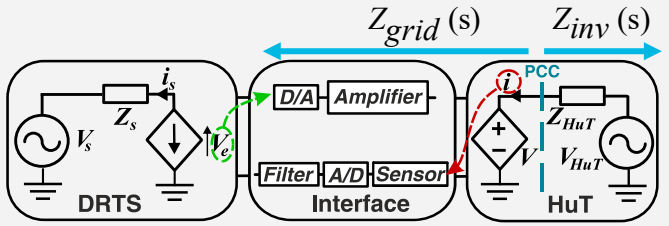
Nyquist Plot

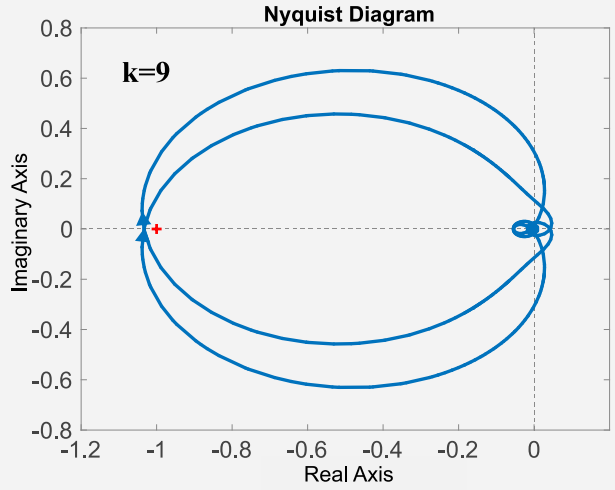
STABILITY VERIFICATION

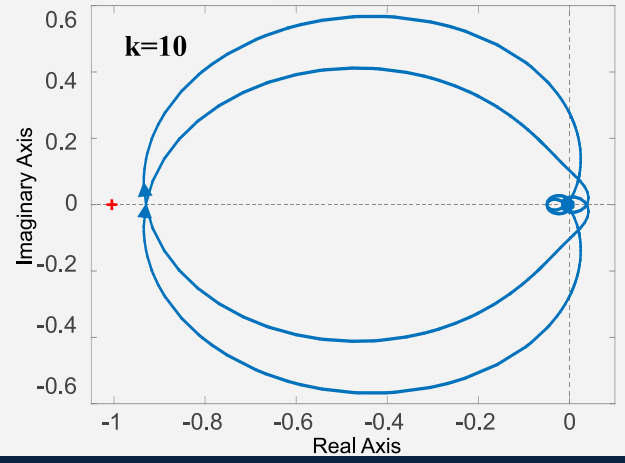
$$G_{OL} = \frac{Z_{grid}(s)}{Z_{inv}(s)}$$

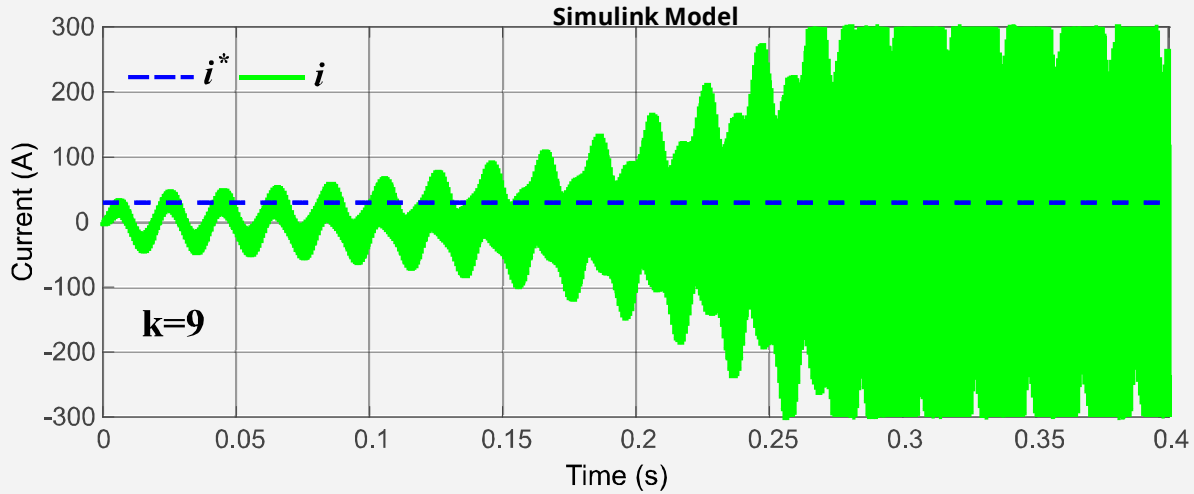
Inductive part of Z_{HuT}

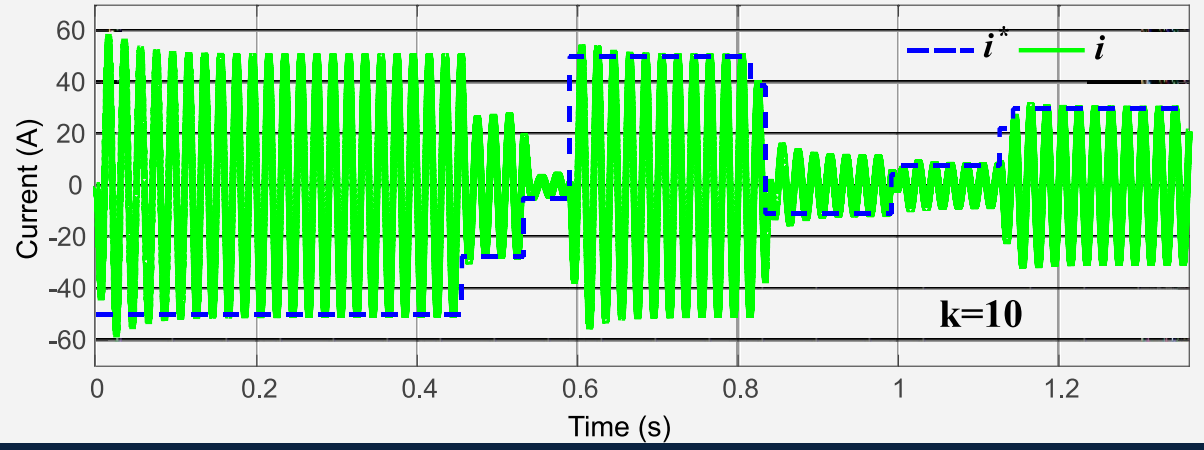
$$k = \frac{Z_L(s)}{Z_S(s)}$$



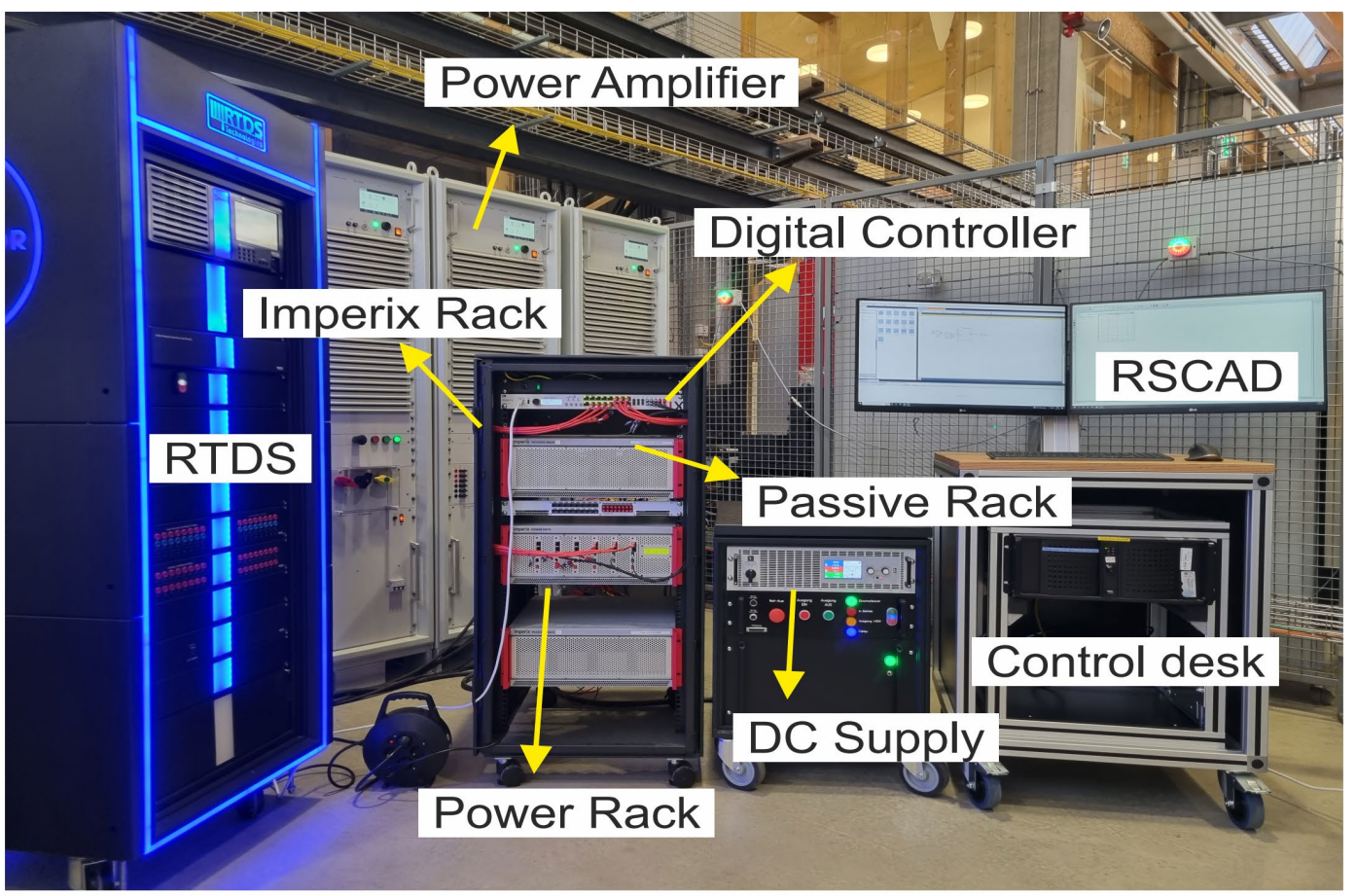




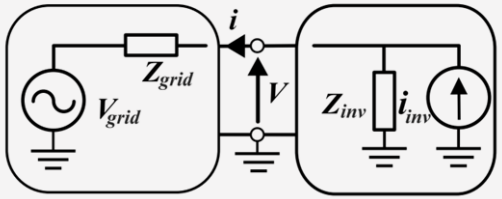


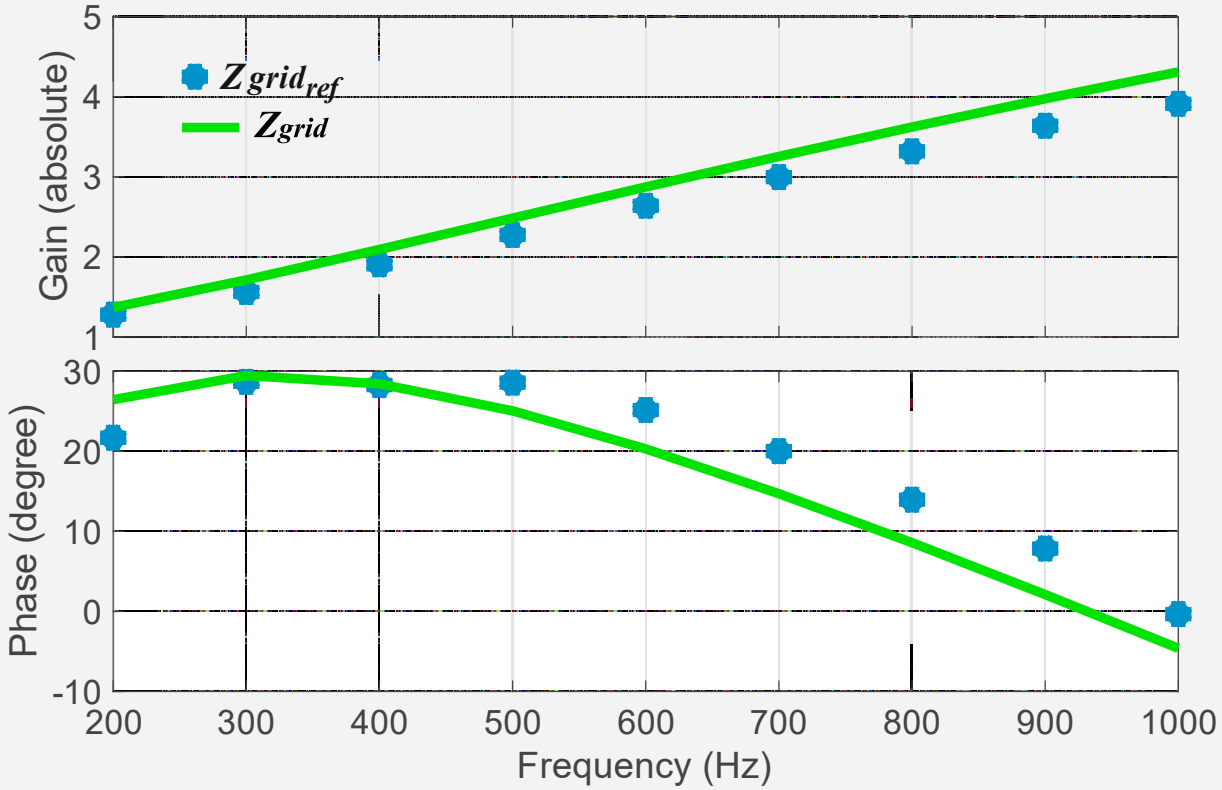


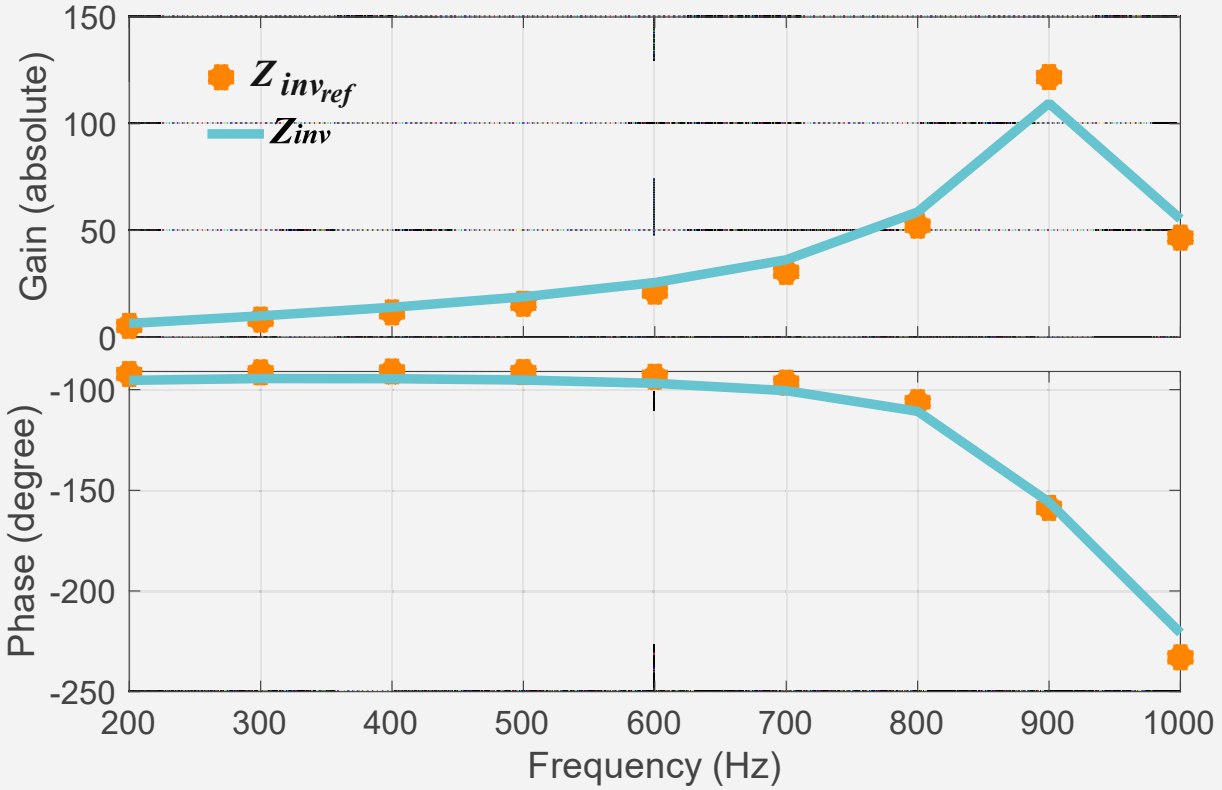
PHIL SETUP AT ENERGY LAB 2.0



IMPEDANCE VERIFICATION







CONCLUSION

- Impedance-based stability, straightforward and accurate
- Impedance information is necessary and sufficient
- Proper approach to ensure stability unknown HuT

THANK YOU!

Any
Questions?

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