

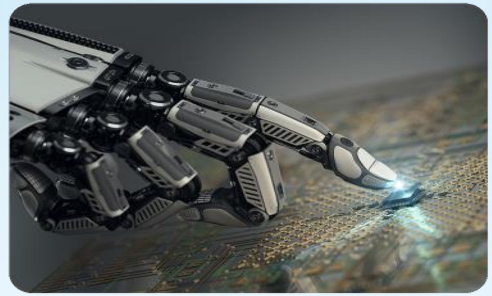

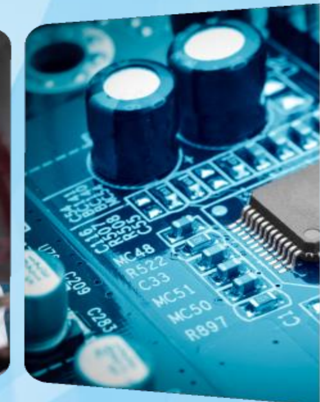

Online measurement and PHIL emulation of power system impedance to test adaptively controlled inverters

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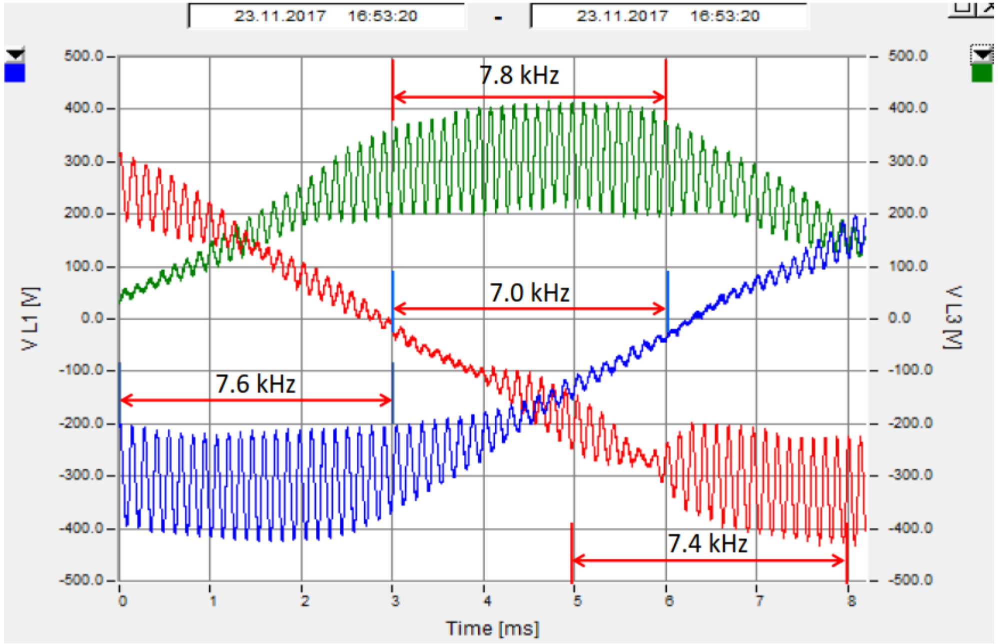
IEEE

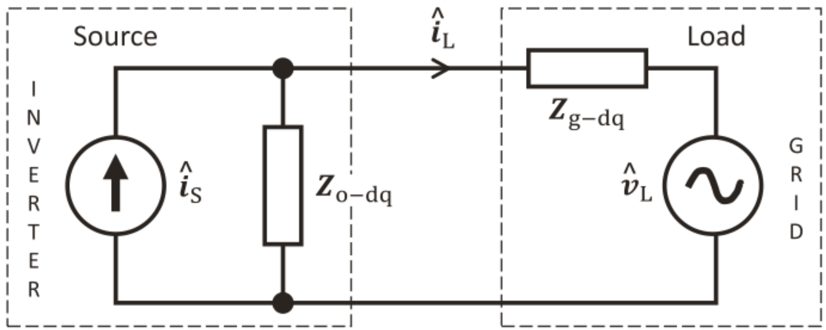
To wake you up: Resonance in LV grid

- So called ”harmonic resonance” is most often related to MV and HV grids
- The voltage waveforms on the right are from a 260 kW power electronic load connected at the end of a LV line
- Converter impedance was measured to be passive
- Maybe caused by low phase margin?
- Capacitive loads seemed to damp the oscillation (By moving the resonant frequency / increasing phase margin?)



Impedance-based interactions

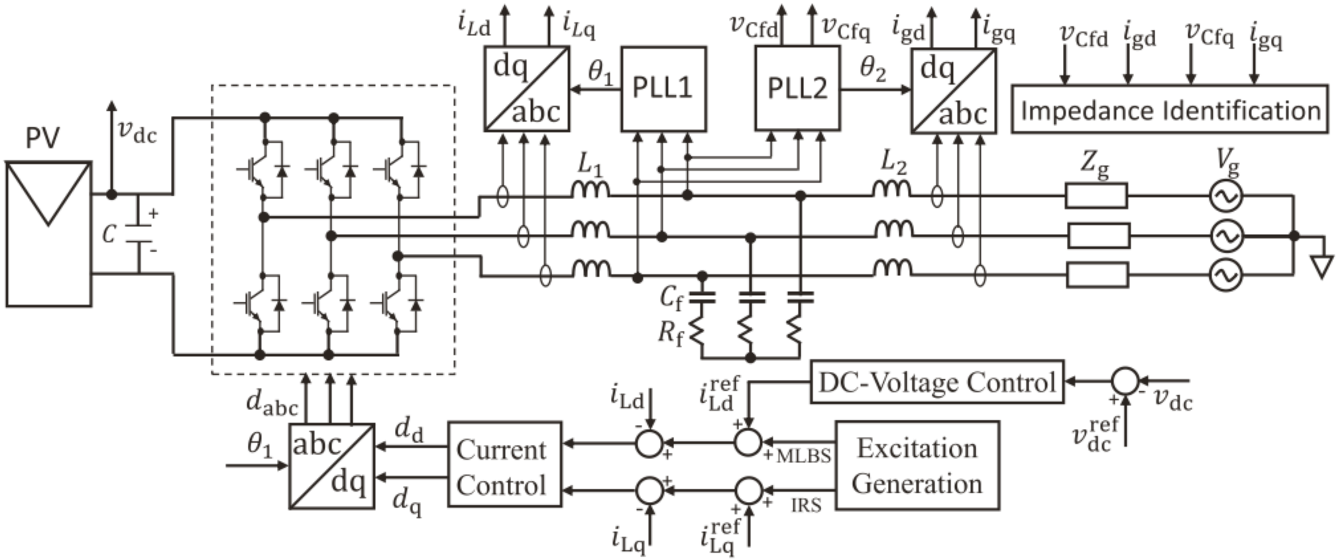
- The inverter and the grid impedance are modeled in synchronous reference frame
- Fundamental AC component is seen as a DC component
- Impedances are modeled as 2x2 transfer matrices
- The most optimal ways to model and execute stability analysis are still open for debate
- However, any method that can give a good estimate on stability margin is useful for preventing resonances



$$\mathbf{Z}_{o-dq}(s) = \begin{bmatrix} Z_{o-dd}(s) & Z_{o-dq}(s) \\ Z_{o-qd}(s) & Z_{o-qq}(s) \end{bmatrix}$$

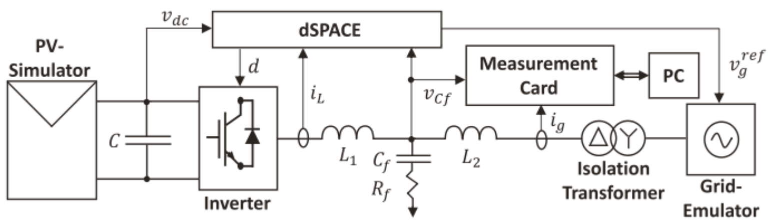
$$\mathbf{Z}_{g-dq}(s) = \begin{bmatrix} Z_{g-dd}(s) & Z_{g-dq}(s) \\ Z_{g-qd}(s) & Z_{g-qq}(s) \end{bmatrix}$$

Grid impedance measurement

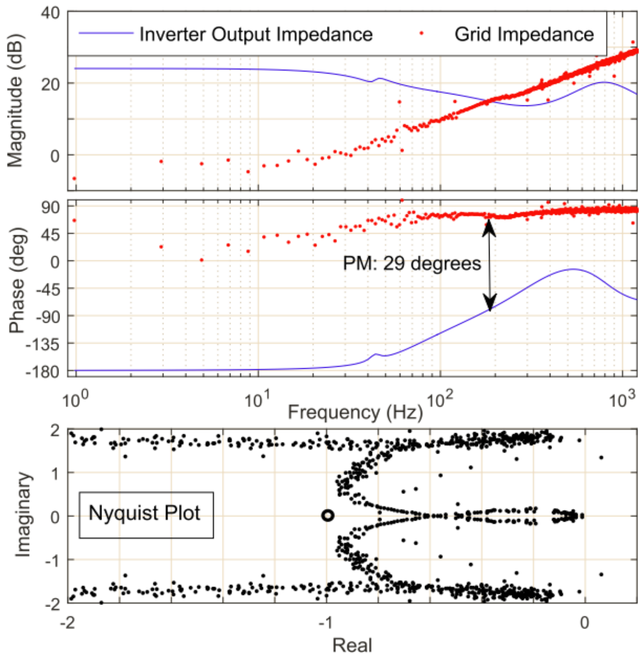


- Grid-connected inverter naturally injects current to the grid
- Small-signal perturbation can be added easily over the current reference value to allow measuring the grid impedance

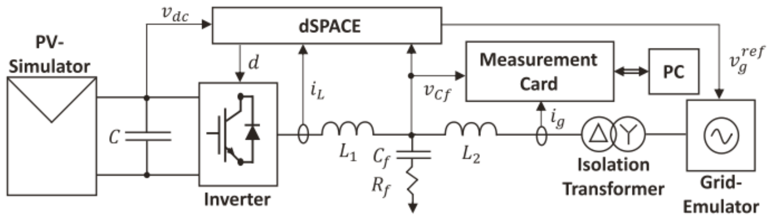
Online impedance-based stability analysis

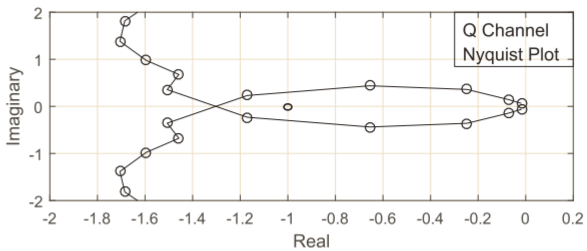


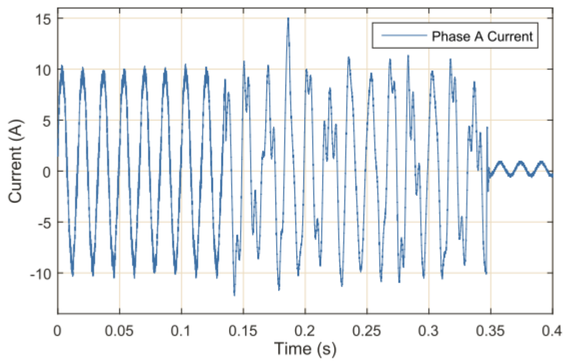
- Grid impedance is measured online
- Inverter impedance is modeled using proven model
- The inverter can estimate the stability margin at its output terminals
- This is the information that would be most useful for adaptive control



Online stability analysis

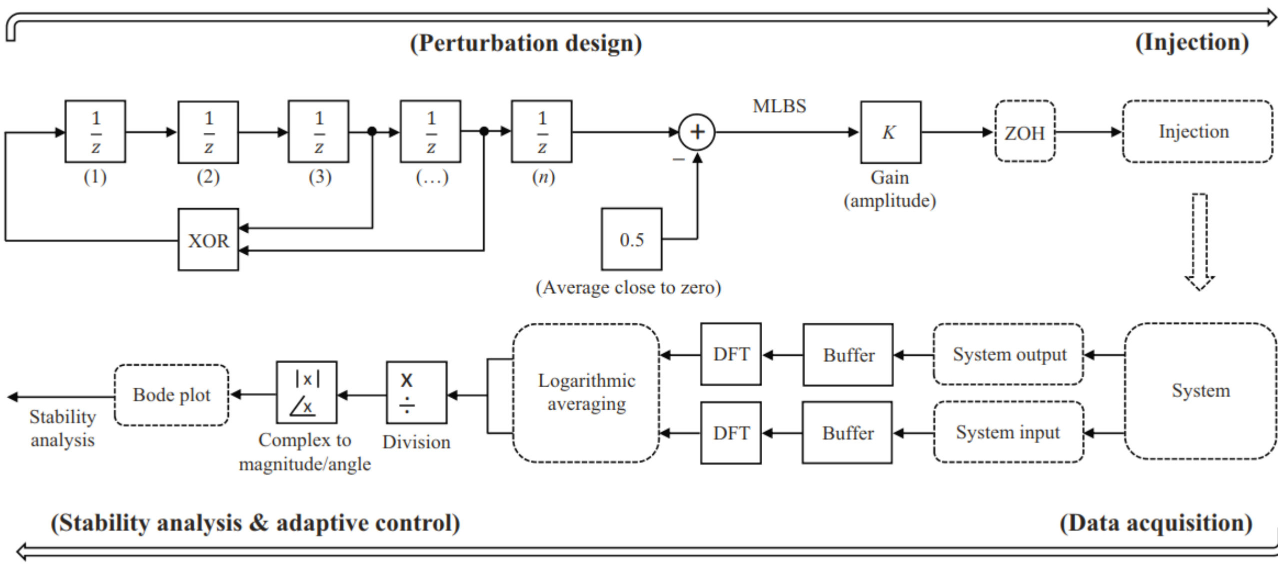


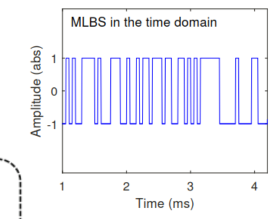


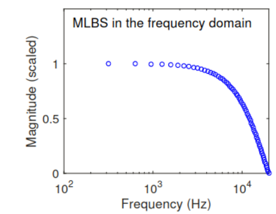


- Grid impedance is measured online
- Inverter impedance is modeled using proven model
- The inverter can estimate the stability margin at its output terminals
- This is the information that would be most useful for adaptive control
- Could be used for post-fault diagnostics as well, since the likely reason for resonance is indicated

PRBS method



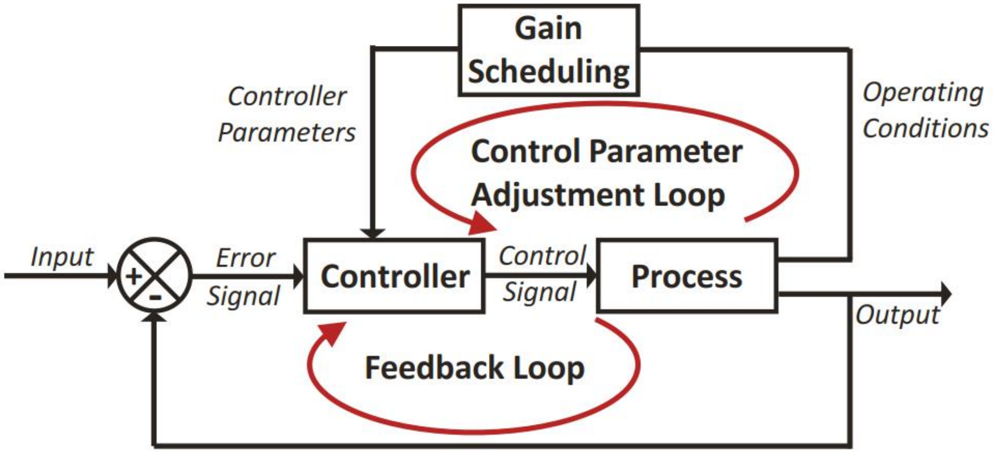




- A wide-bandwidth small-signal perturbation is injected to the system from which the frequency response is extracted

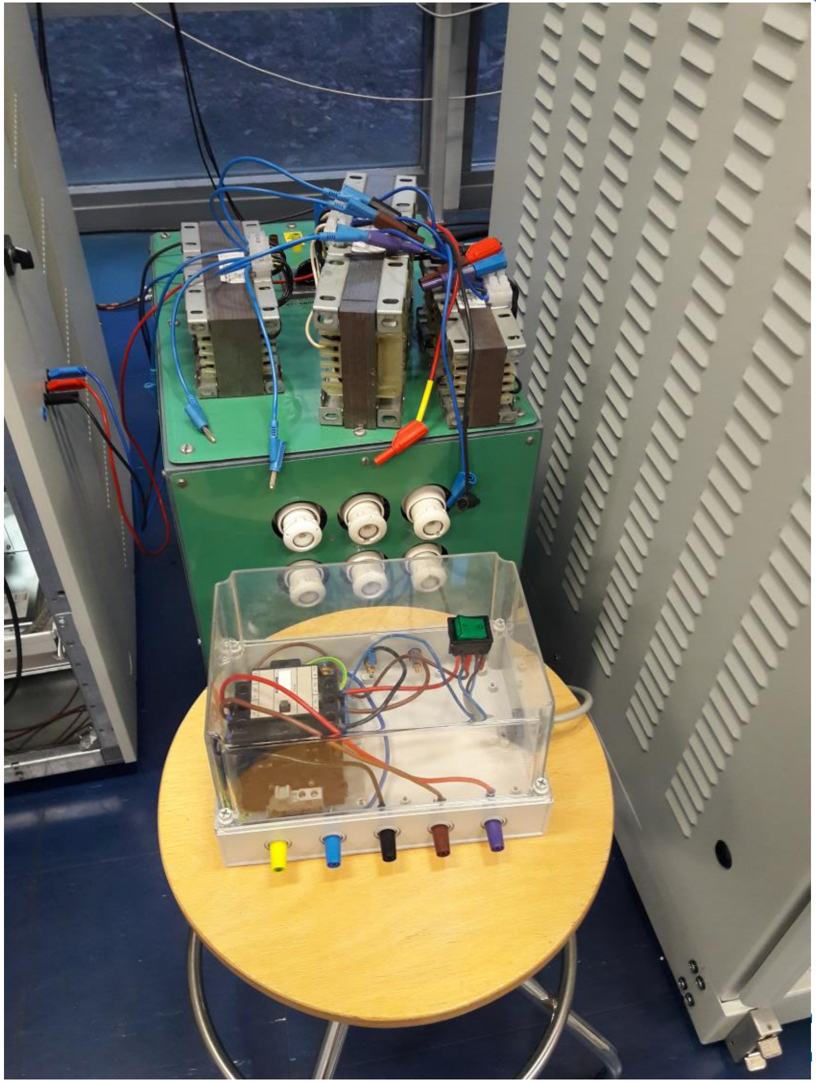
Adaptive control

- Simple idea: ”Controller parameters are fine-tuned online to keep the inverter stable”
- There is no simple answer…
  - What inverter parameter may cause instability?
  - How do grid parameters change?
  - How should the control parameters be adapted to changing grid condition?



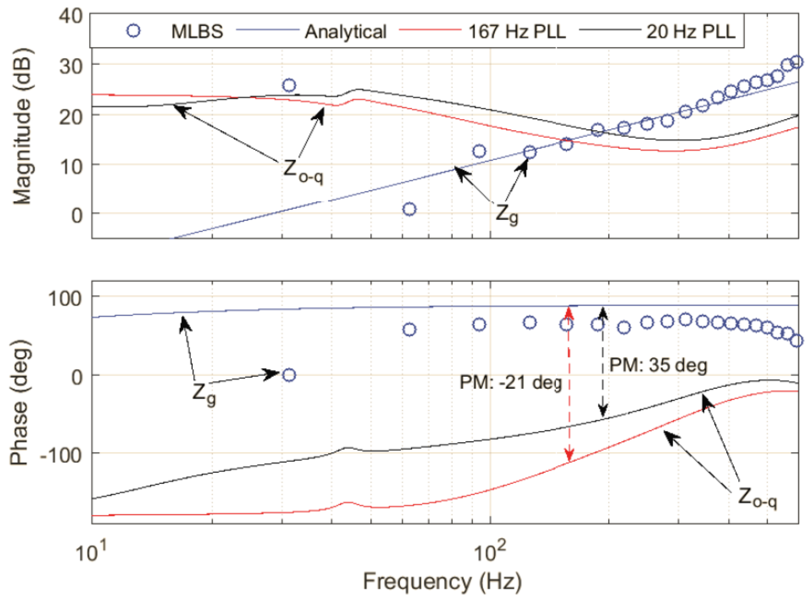
Testing adaptive control

- Adaptive control actively shapes the inverter output impedance according to measured grid impedance
- Brute-force method for testing adaptive control is to use hardware impedance and relays
- Weak grid is often reproduced by connecting a large inductance in series with inverter
- May not be the most realistic method (large transient)

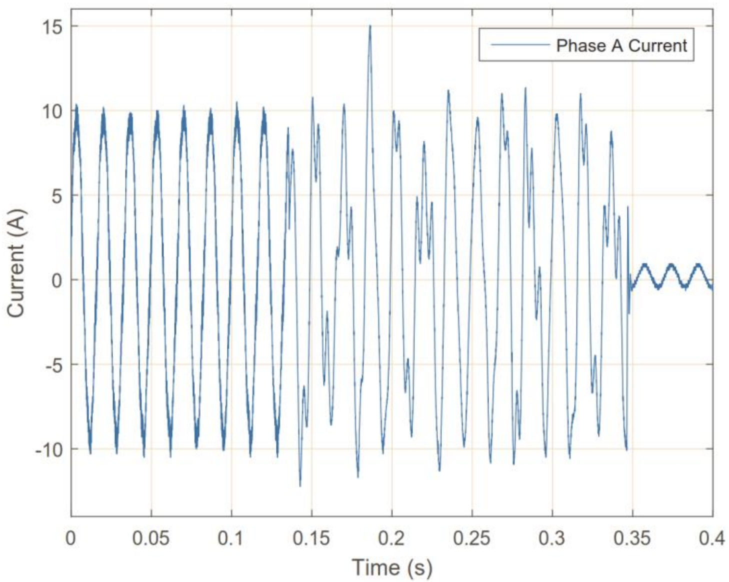


Testing adaptive control

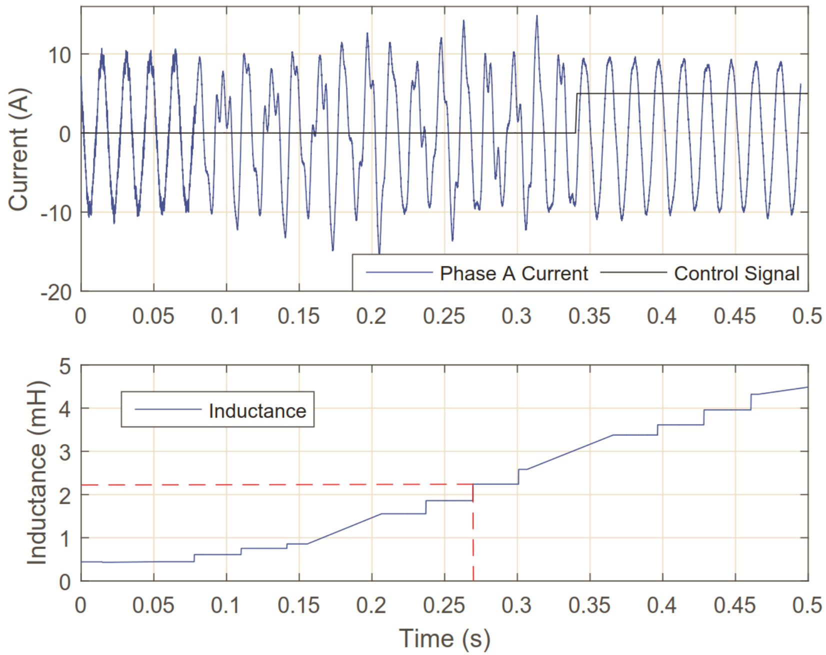
- High bandwidth PLL is known to interact with large inductive grid impedance
- The simple solution in this case is to lower the PLL bandwidth
- In the example case suitable PLL parameters were pre-calculated offline and collected as a gain scheduling table
- Real grid impedance may be something else (e.g. frequency-dependent losses)



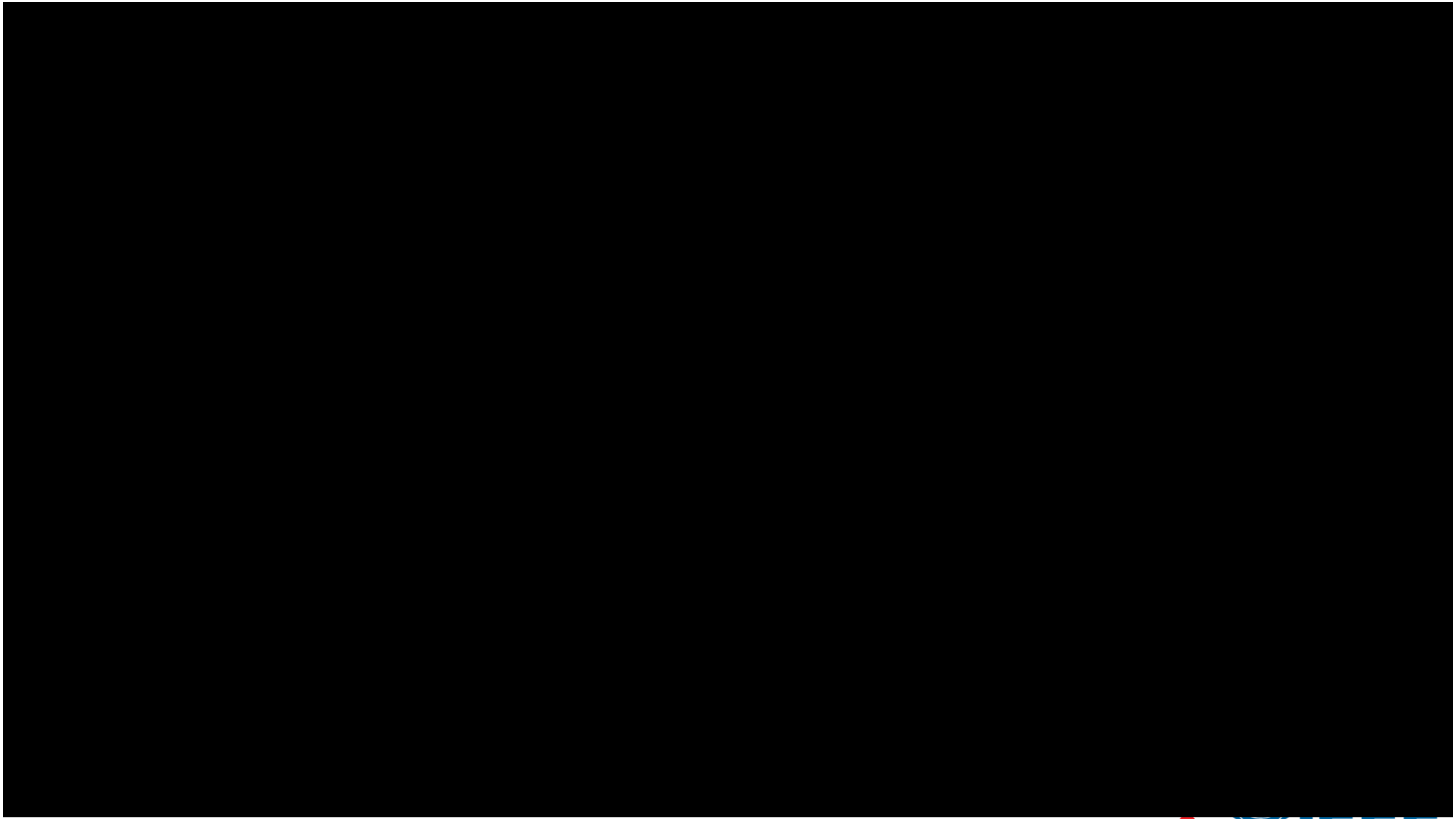
Testing adaptive control



No adaptivity: Inverter trips due to overcurrent. PLL bandwidth remains high after grid inductance increases.



Adaptive control: Increase in grid inductance is sensed. PLL bandwidth is decreased based on gain scheduling principle.



Our PHIL setup in Tampere

Hardware

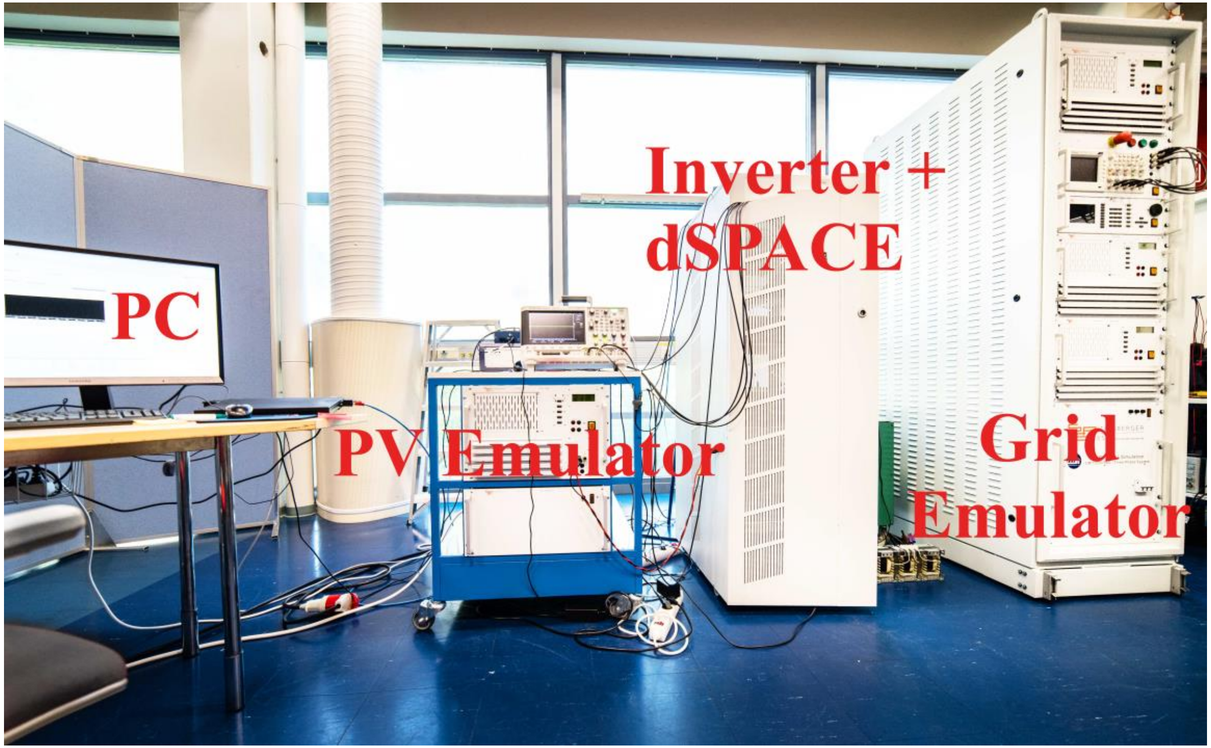
15 kW linear 3-phase voltage amplifier from Spitzenberger & Spies

7 kW PV simulator based on linear amplifier from Spitzenberger & Spies

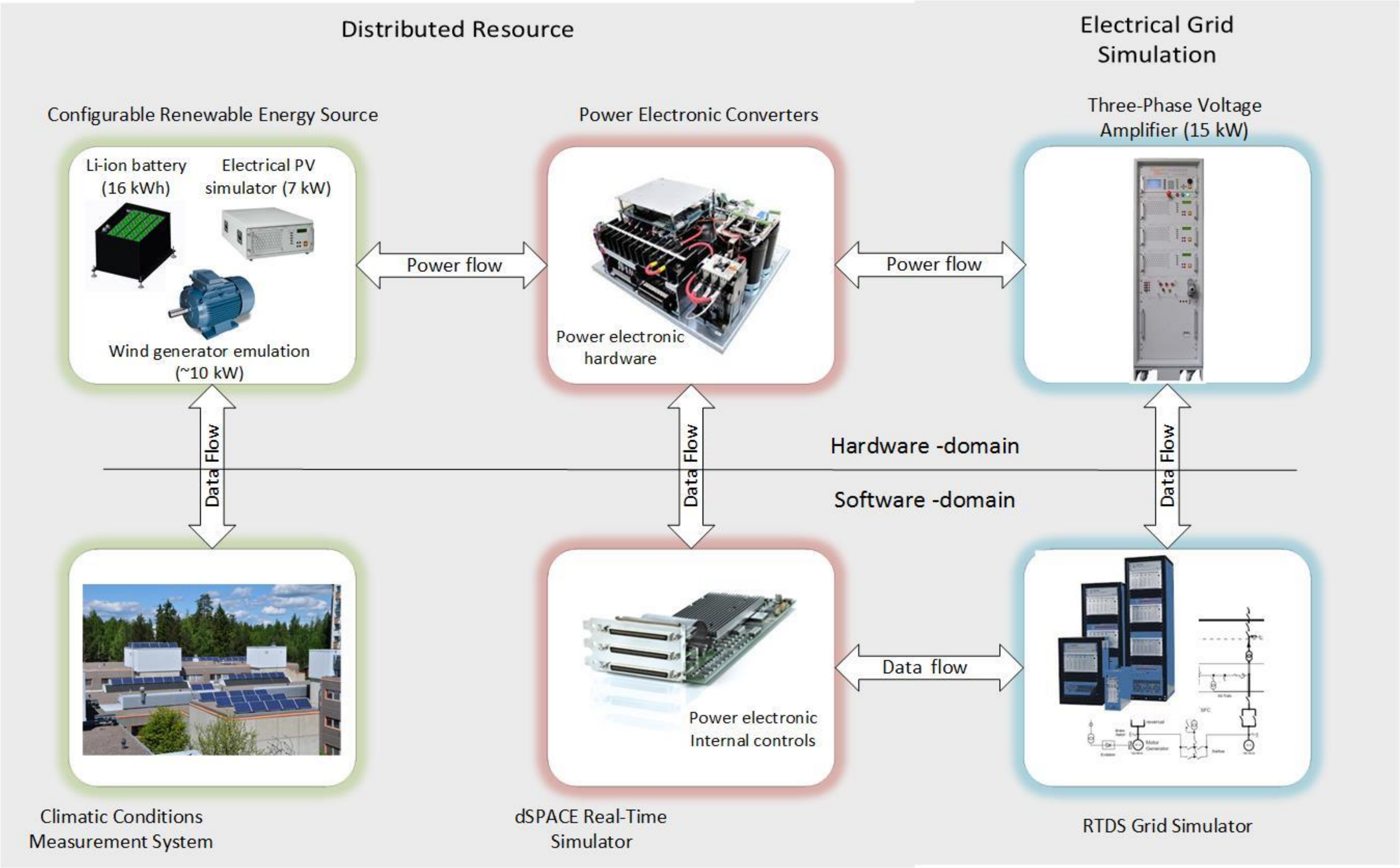
10 kW IGBT-based three-phase two-level inverter from Myway

dSPACE DS1003 control platform

RTDS grid simulator (not shown in the figure)

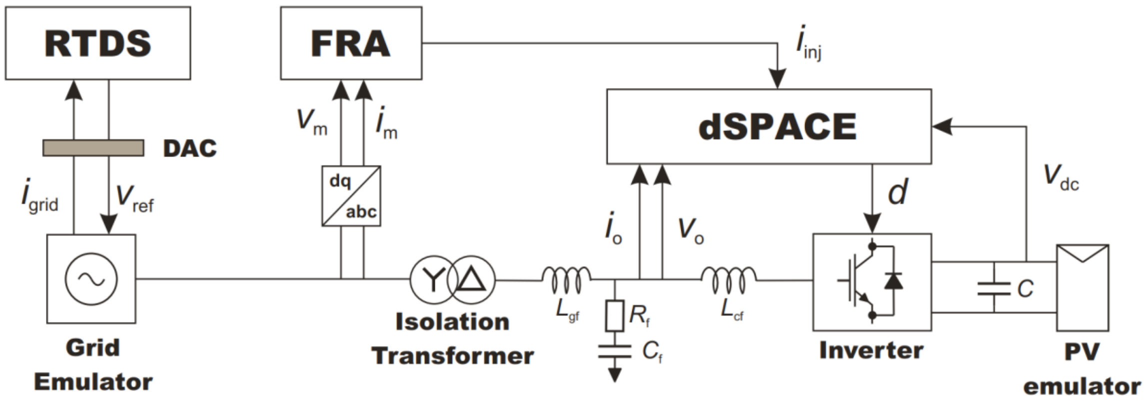


Our PHIL setup in Tampere



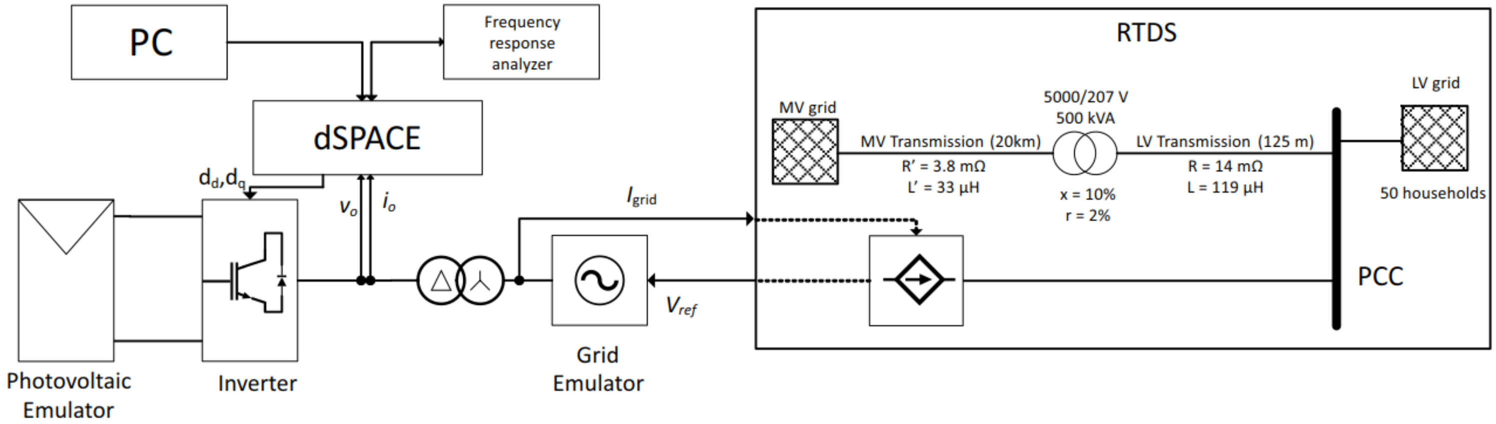
Grid impedance emulation

- 3-phase voltage amplifier is connected to RTDS emulator
- Model of the power system is running in RTDS
- Delays are minimized using optical connection (are not negligible)
- The main goal is to make the inverter see a more realistic grid impedance (which also varies dynamically)



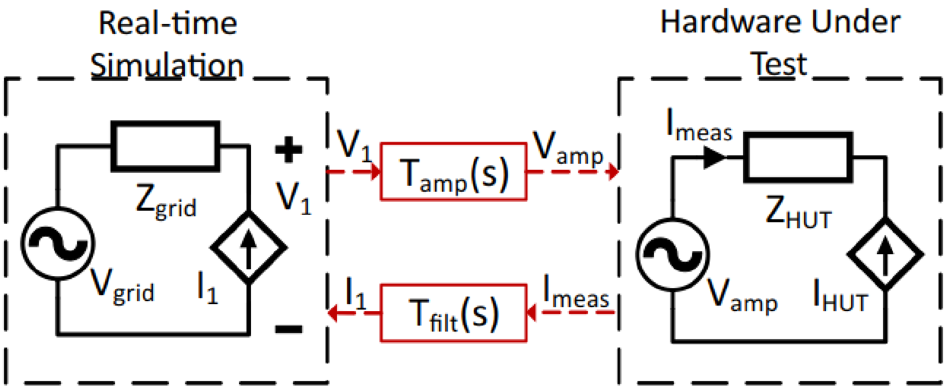
Grid impedance emulation

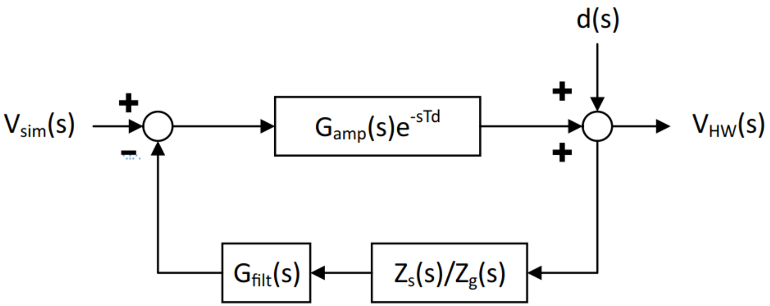
- Main goal is to relieve power electronic engineers from complex modeling tasks related to power system impedance
- The power system can be simulated using suitable tools such as RTDS, if the impedance can be reproduced accurately by the voltage amplifier (not an easy task!)



Grid impedance emulation

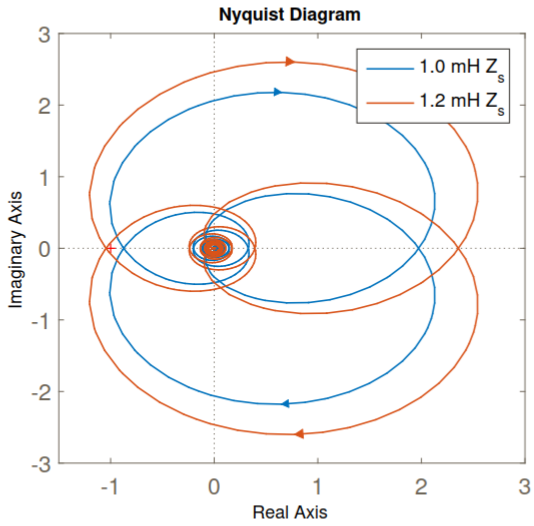
- Interface algorithm between amplifier and RTDS has major impact on stability (ideal transformer method, ITM, used here)
- Currents are measured and sent to RTDS
- Voltage response is computed by the RTDS and sent back as the voltage reference of the voltage amplifier
- Total delay is 136.6 us, which may destabilize the PHIL setup

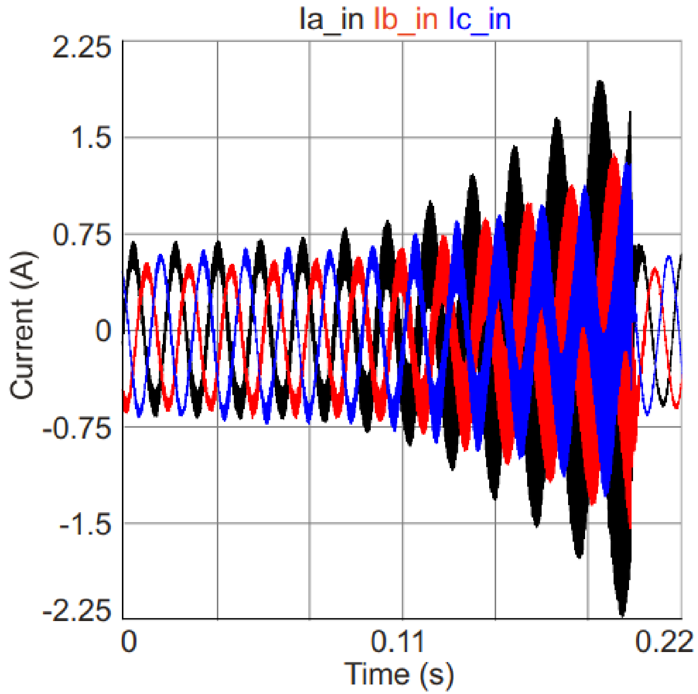




Grid impedance emulation

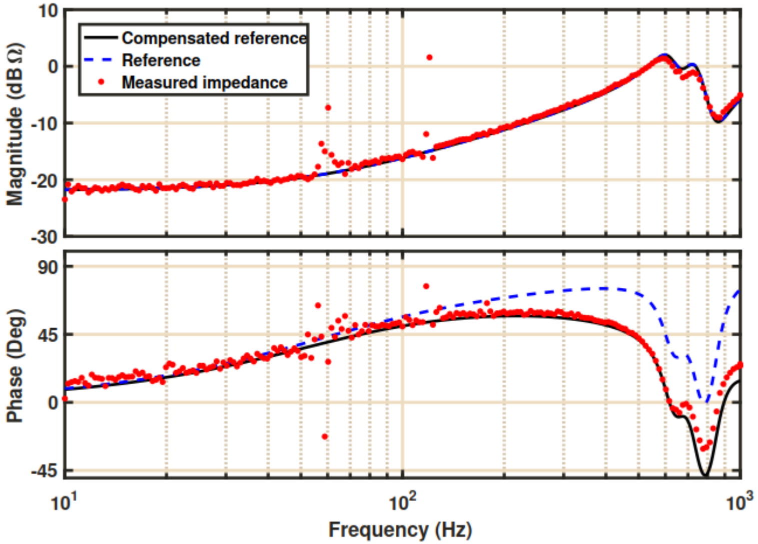
- When using ideal transformer method, the hardware side impedance should be higher than the software side impedance
- Stability of the PHIL setup can be determined by using impedance models





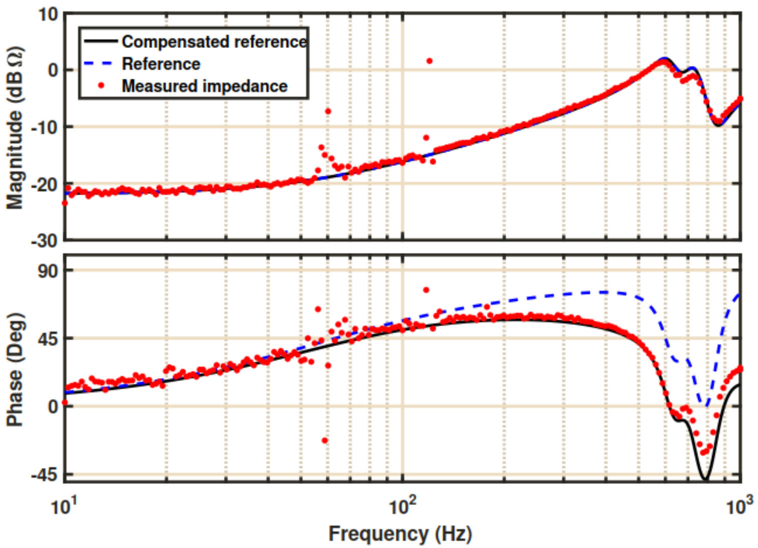
Grid impedance emulation

- Inherent delay can cause error in the phase of the emulated impedance
- Magnitude in the test case remains accurate up to 1 kHz
- Phase starts to deviate around 100 Hz
- There is still a lot of work to be done to improve the accuracy of the phase of the emulated grid impedance!



Future work

- Pushing the PHIL setup to its limits
  - Maximum impedance magnitude
  - Resonant grid impedance
  - Phase accuracy
- How do faults affect the power system impedance seen by the inverter?
- How and how fast does the power system impedance change during a fault?
- How do other power system components affect the impedance seen by the inverter?
  - Synchronous generators
  - Transformers (saturation, frequency dependent losses)
  - Other power converters



Related publications

Tommi Reinikka, Henrik Alenius, Tomi Roinila and Tuomas Messo, "Power Hardware-in-the-Loop Setup for Stability Studies of Grid-Connected Power Converters," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), pp. 1704 – 1710, 2018

Roni Luhtala, Tuomas Messo, Tommi Reinikka, Jussi Sihvo, Tomi Roinila and Matti Vilkko, "Adaptive control of grid-connected inverters based on real-time measurements of grid impedance: DQ-domain approach," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 69 – 75, 2017

Tomi Roinila, Tuomas Messo, Roni Luhtala, Rik Scharrenberg, Erik de Jong, Alejandra Fabian and Yin Sun, "Hardware-in-the-Loop Methods for Real-Time Frequency-Response Measurements of on-Board Power Distribution Systems," IEEE Transactions on Industrial Electronics, 2018 (Early Access)

Roni Luhtala, Tomi Roinila and Tuomas Messo, "Implementation of Real-Time Impedance-Based Stability Assessment of Grid-Connected Systems Using MIMO-Identification Techniques," IEEE Transactions on Industry Applications, vol. 54, no. 5, pp. 5054 – 5063, 2018

Roni Luhtala, Tuomas Messo and Tomi Roinila, "Adaptive Control of Grid-Voltage Feedforward for Grid-Connected Inverters based on Real-Time Identification of Grid Impedance," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), pp. 547 – 554, 2018

Tuomas Messo, Roni Luhtala, Aapo Aapro and Tomi Roinila, "Accurate Impedance Model of Grid-Connected Inverter for Small-Signal Stability Assessment in High-Impedance Grids," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), pp. 3156 – 3163 , 2018

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