PHIL simulation for DER and smart grids: best practices and experiences from the ERIGrid project

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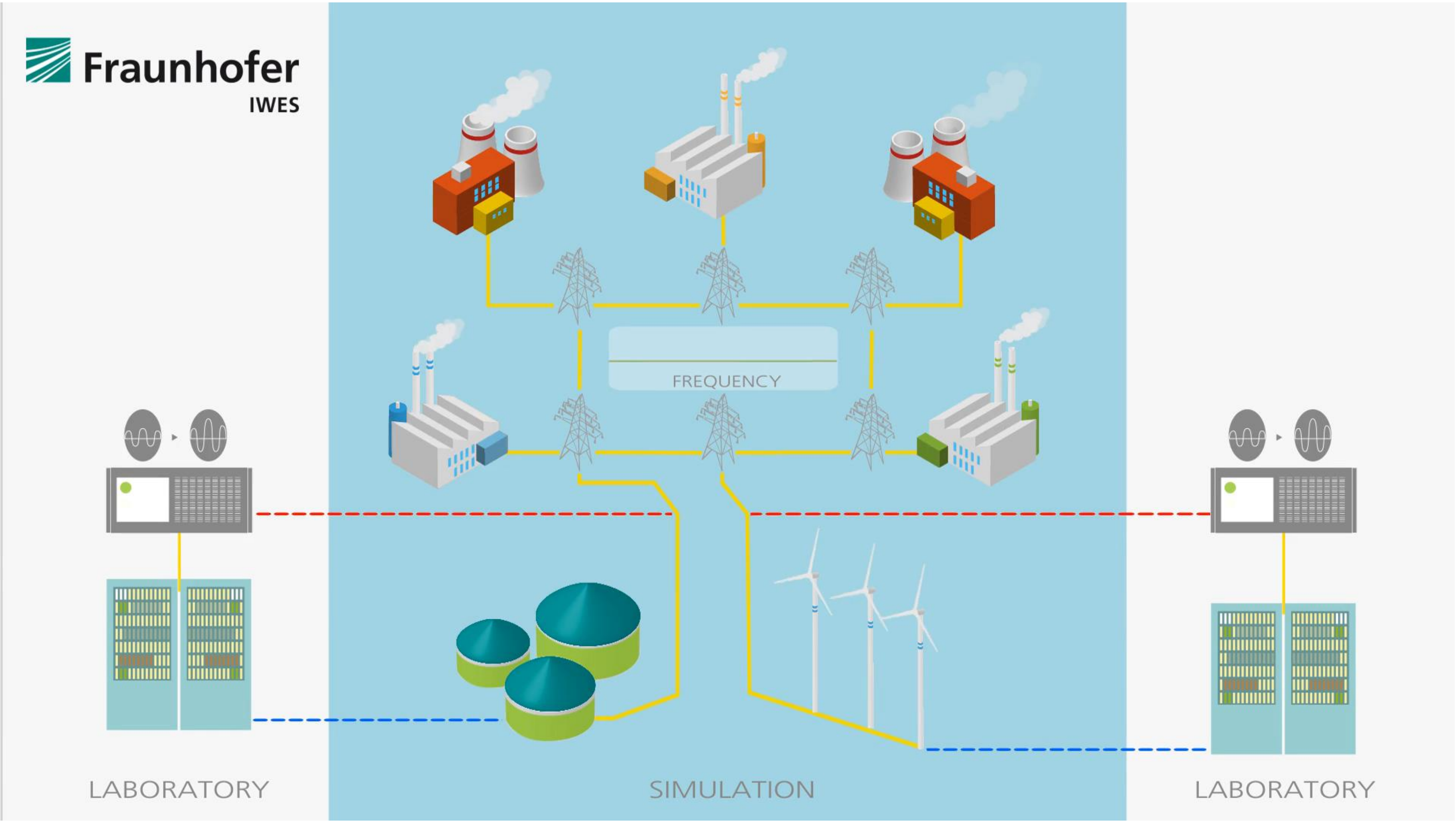
EU H2020 Programme GA No. 654113

Overview

- Characteristics of PHIL simulation
- Stability, accuracy issues, interface topologies and stabilisation methods
- PHIL tests that show the value of the approach: DER inverters providing ancillary services, voltage-frequency control, microgrids, etc
- Improved Hardware in the Loop (HIL) methods in the ERIGrid project
- Live demonstration of HIL tests
- Discussion

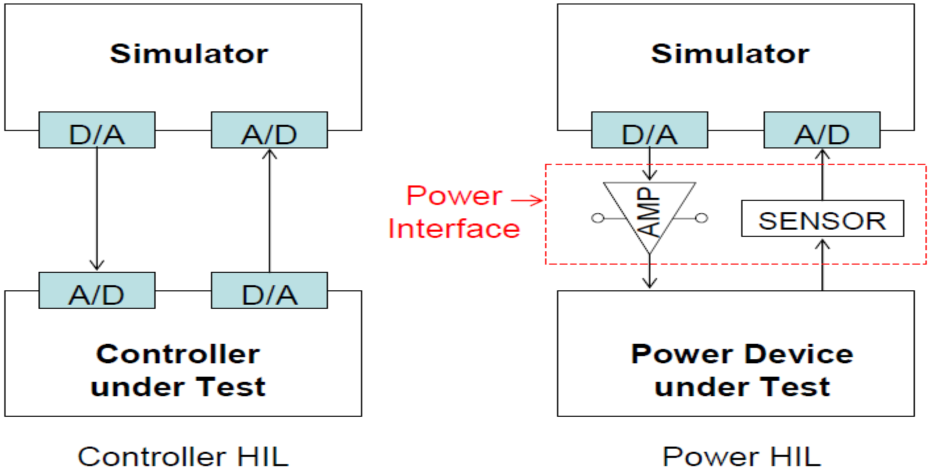
Introduction

What is Hardware-in-the-Loop?



What is Power Hardware in the Loop simulation?

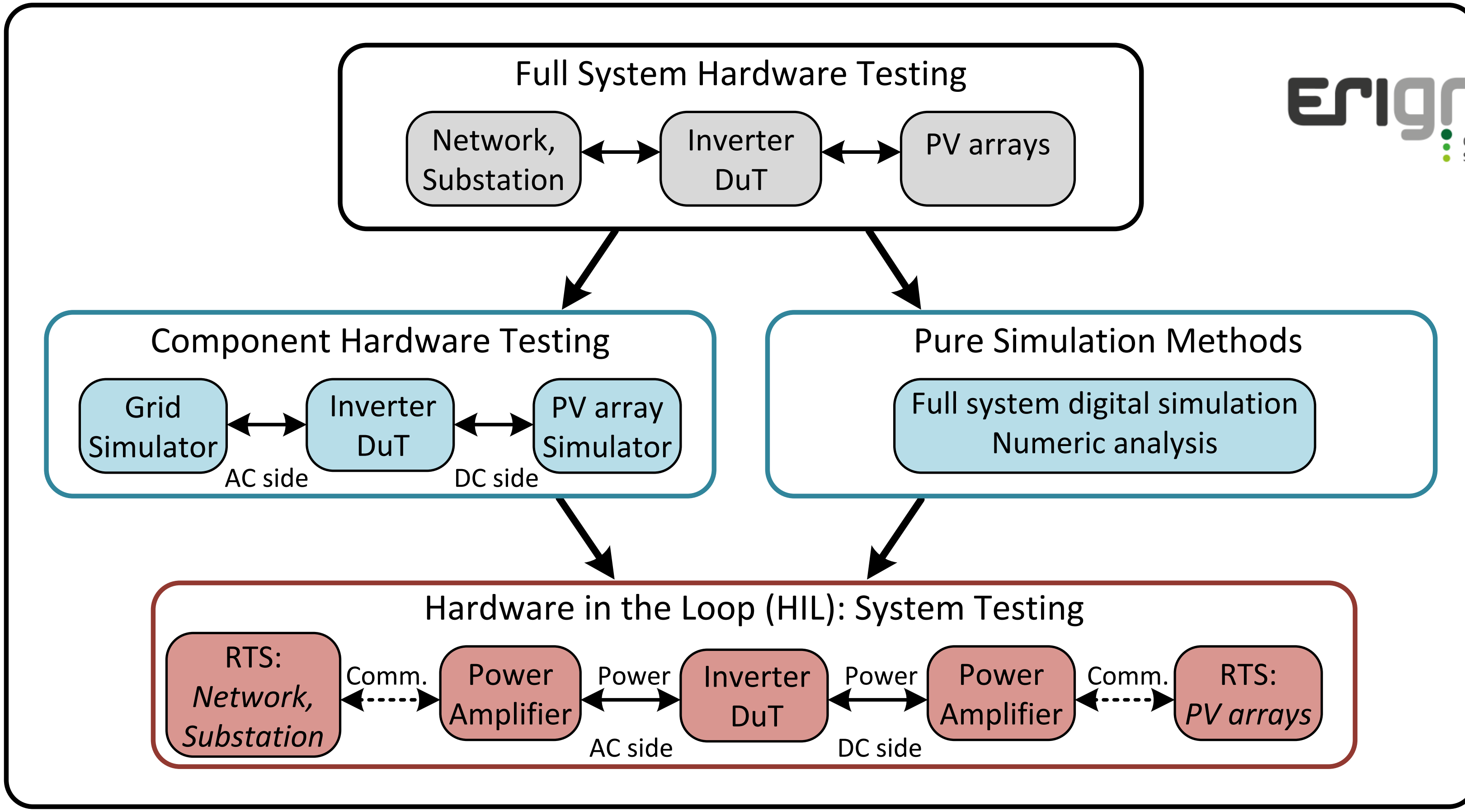
Power Hardware-in-the-Loop (PHIL) is a method that is used for testing a **hardware power component** in realistic conditions, while a part of the system is simulated in a Digital Real Time Simulator (DRTS)



Main Components:

- Digital Real Time Simulator (DRTS)
- Power Amplifier
- A/D and D/A Converters
- Sensors
- Hardware under Test (HUT)

Ren, Wei, Michael Steurer, and Thomas L. Baldwin. "Improve the stability and the accuracy of power hardware-in-the-loop simulation by selecting appropriate interface algorithms." IEEE Transactions on Industry Applications 44.4 (2008): 1286-1294.



- Experimental setups: low flexibility, cost, maintenance, damage
- Standardised tests: predefined profiles, complex interactions are not taken into account
- Study of phenomena: digital simulations (flexibility, low cost), accuracy of the models. Challenges due to the DG integration

Why PHIL for Power System Analysis and testing

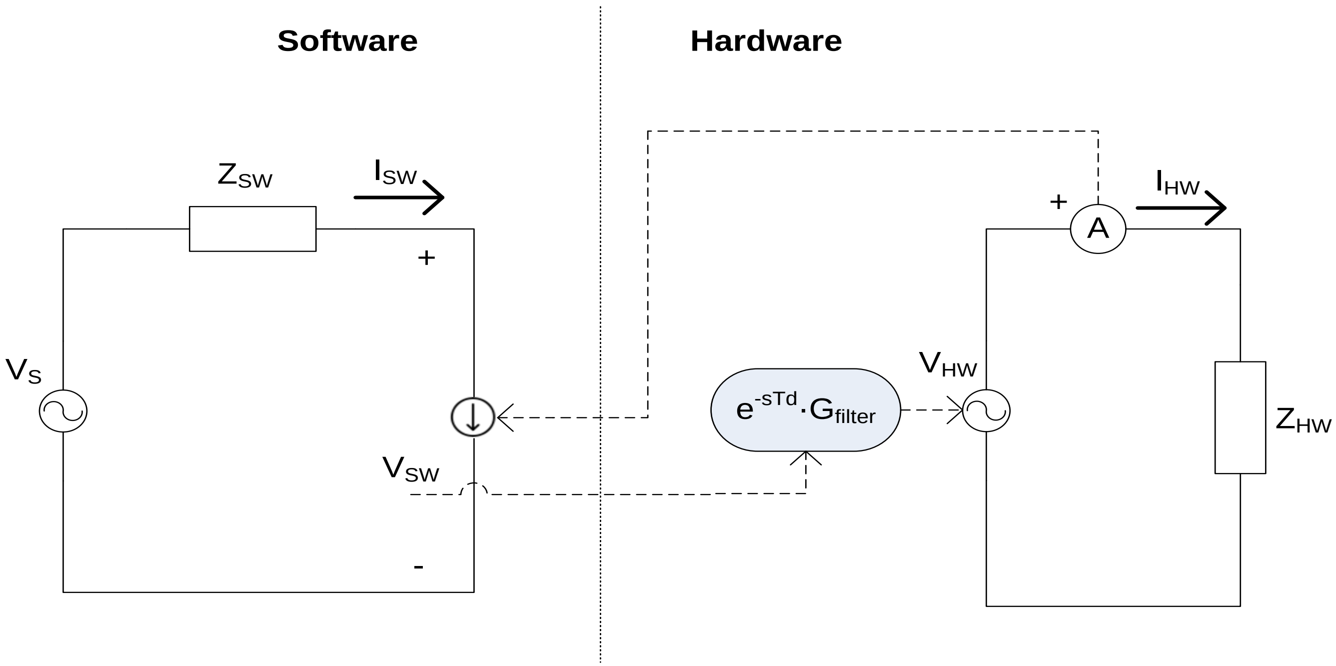
- PHIL supports the development of prototypes and innovative methods and technologies

Advantages and Issues of HIL Technologies

+ Combines the advantages of simulation and hardware testing
+ Lab-based investigations are closer to field testing
+ Supports the validation of simulations results. Can even show interactions that are not visible in digital simulation
+ De-risks field testing

- High implementation effort
- Accuracy and realism of Hardware/Software interface has to be proven

Stability of PHIL simulation

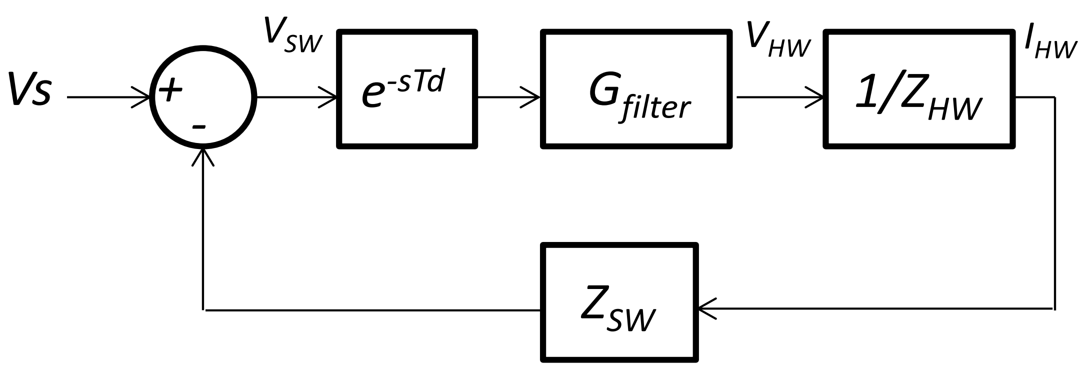


$$V_{HW} = V_{SW} \cdot e^{-sTd} \cdot G_{filter}$$

$$I_{HW} = \frac{V_{HW}}{Z_{HW}}$$

$$I_{SW} = I_{HW}$$

$$V_{SW} = Vs - I_{SW} \cdot Z_{SW}$$



$$G_{OL}(s) = \frac{Z_{SW}(s)}{Z_{HW}(s)} e^{-sTd} \cdot G_{filter}(s)$$

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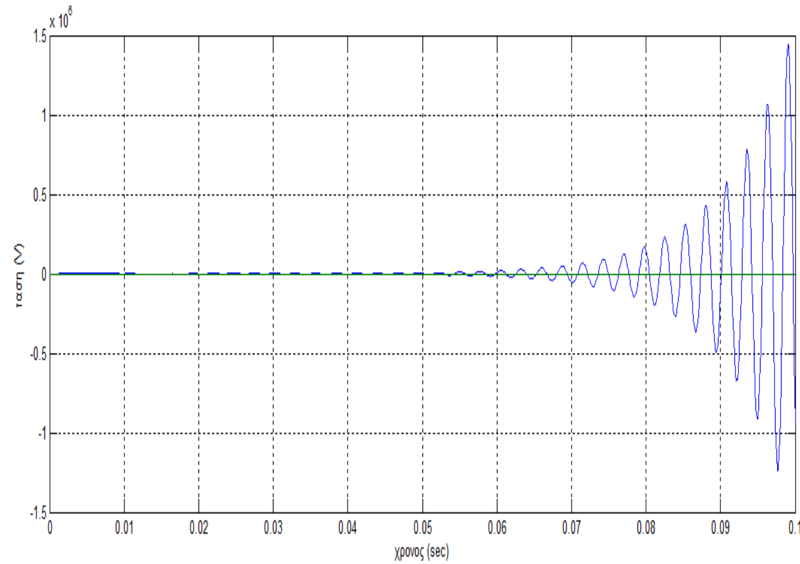
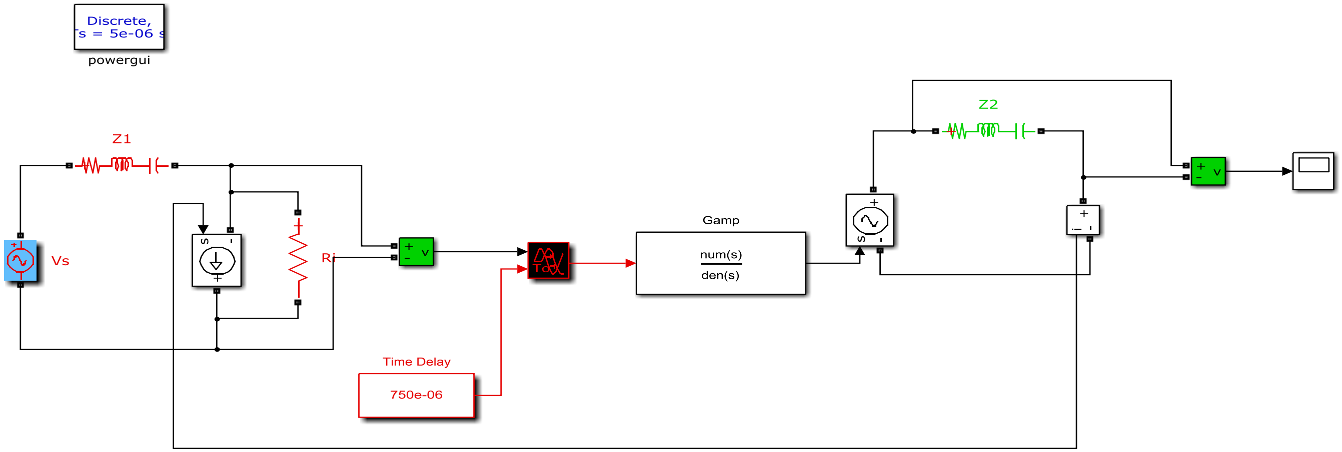
Stability of PHIL simulation: Evaluation Methods

Stability Evaluation Methods:

- Nyquist plot: easy to implement on software
- Bode stability criterion
- Routh criterion: e.g. Pade approximation
- Root Locus: graphical representation
- Dynamic simulation circuit

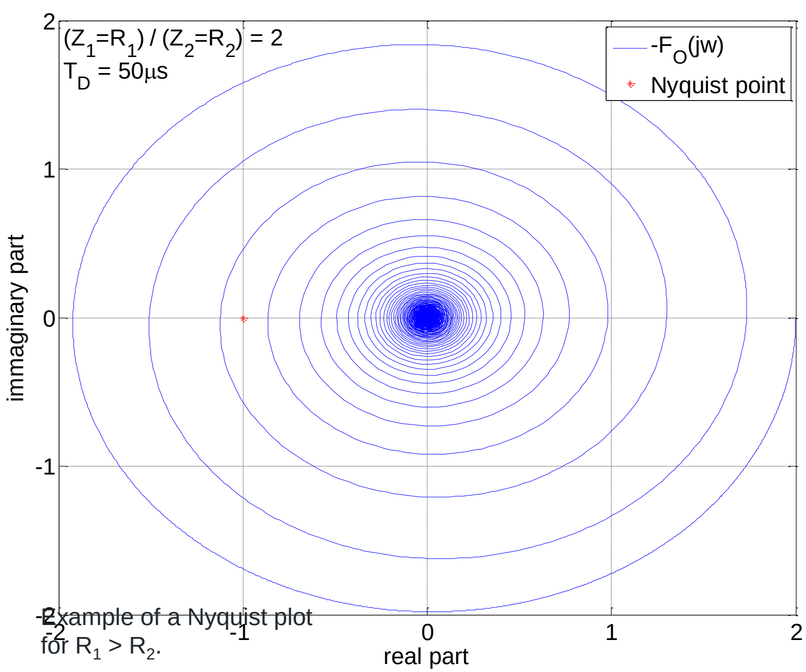




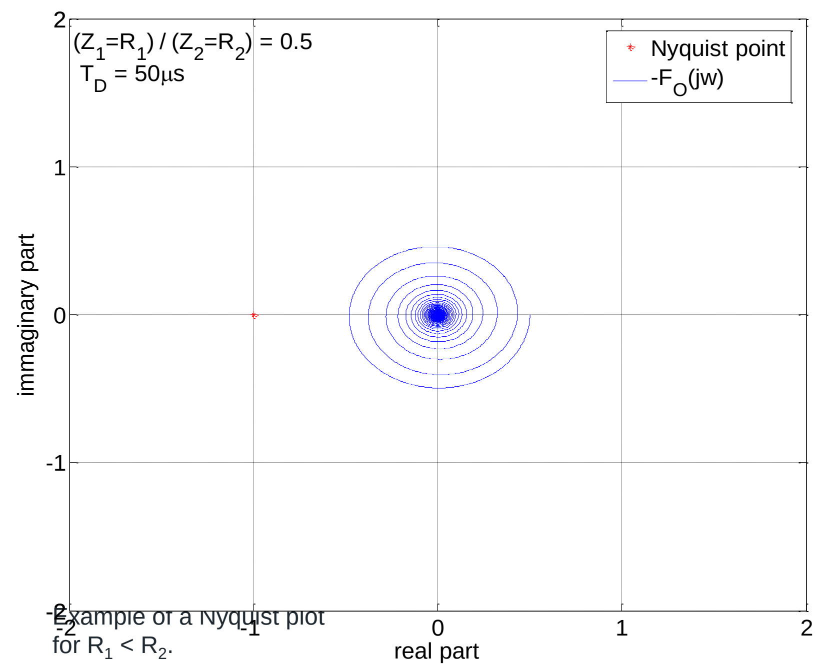
PHIL Simulation: Stability Evaluations

Connecting European Smart Grid Infrastructures

- Simulation step time: 50 µs (T_D)
- Nyquist plot of open loop TF for 2 cases:
  - $Z_1 < Z_2$ (instable, encircled Nyquist point (-1,0j)
  - $Z_1 > Z_2$ (stable control system, hardware resistance bigger than software resistance)



Example of a Nyquist plot for $R_1 > R_2$.



Example of a Nyquist plot for $R_1 < R_2$.

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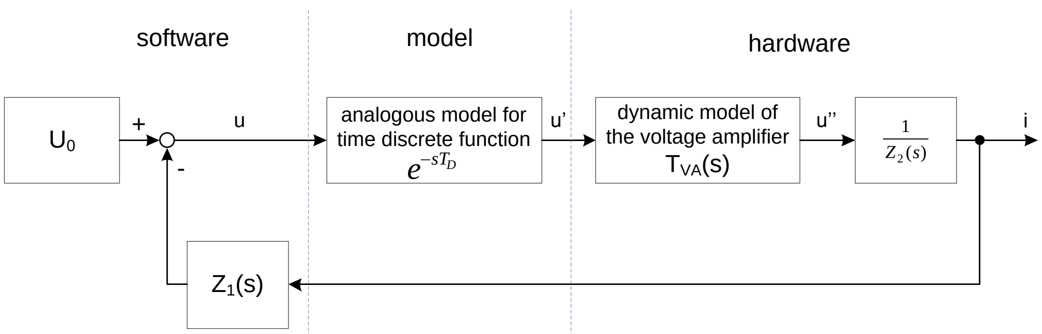
PHIL Simulation: Stability Evaluations

Analysis:

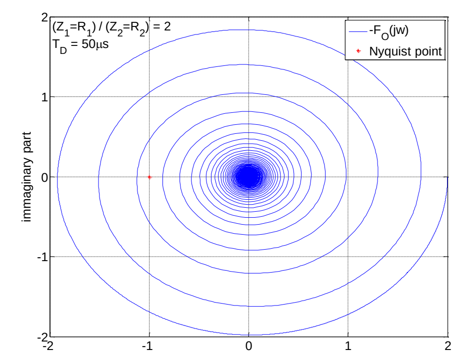
- Assuming advantageous assumtions as idealized used equipment (voltage amplifier / current measurement; $T_{VA}(s) = T_{ME}(s) = 1$; ITM as PI)
- Stability cannot be guaranteed this discussed basic system (settings $R_1>R_2$)

Conclusions:

- No stability for this PHIL system ($R_1>R_{2,}$ T_S=50µs)
- Countermeasures to achieve simulation stability (-> *feedback current filtering*)
- Introducing complex load impedances ($\underline{Z}_1/\underline{Z}_2$) the simulation stability depends on both impedances as well as the Nyquist criterion on stability



Control theoretic depiction of system.



Nyquist plot for R_1/R_2.=2

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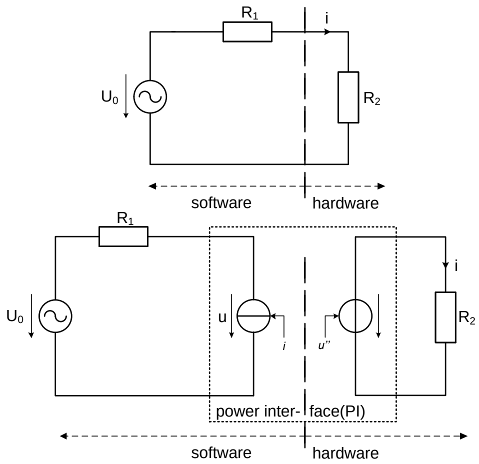
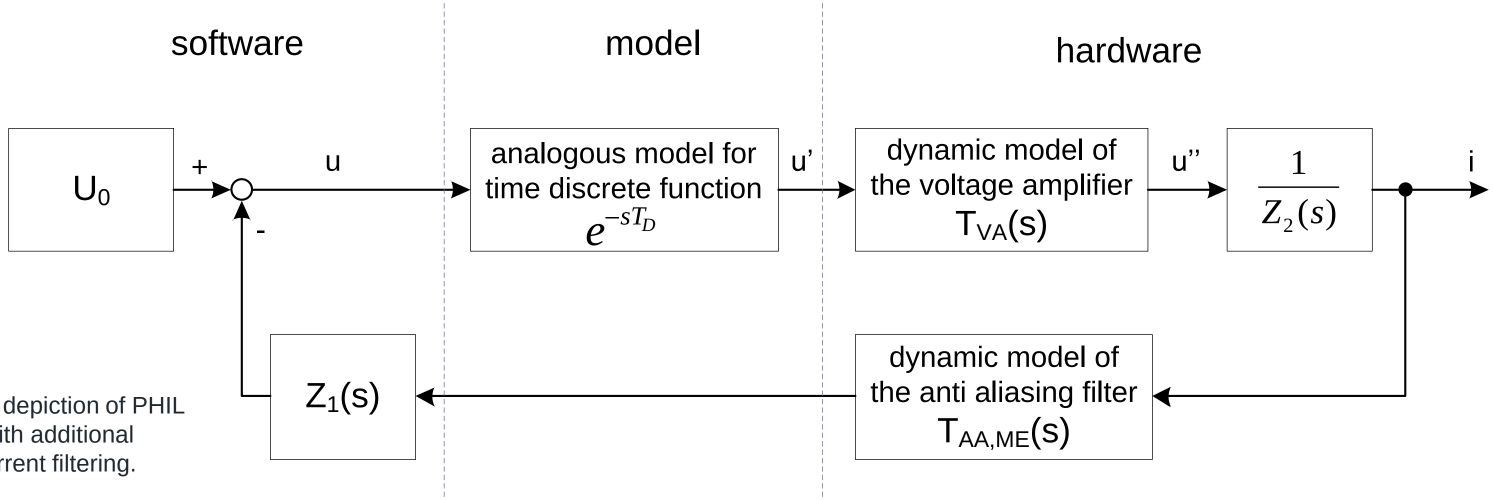
PHIL Simulation: Current Filtering



- In case of a pure real impedances (R_1, R_2), a simple first order low pass filter can be used in the current feedback closed loop ($T_{FILTER} = \frac{1}{1+s/2\pi f_c}$)
- Stability behaviour is modified due to this introduction of a feedack filter!

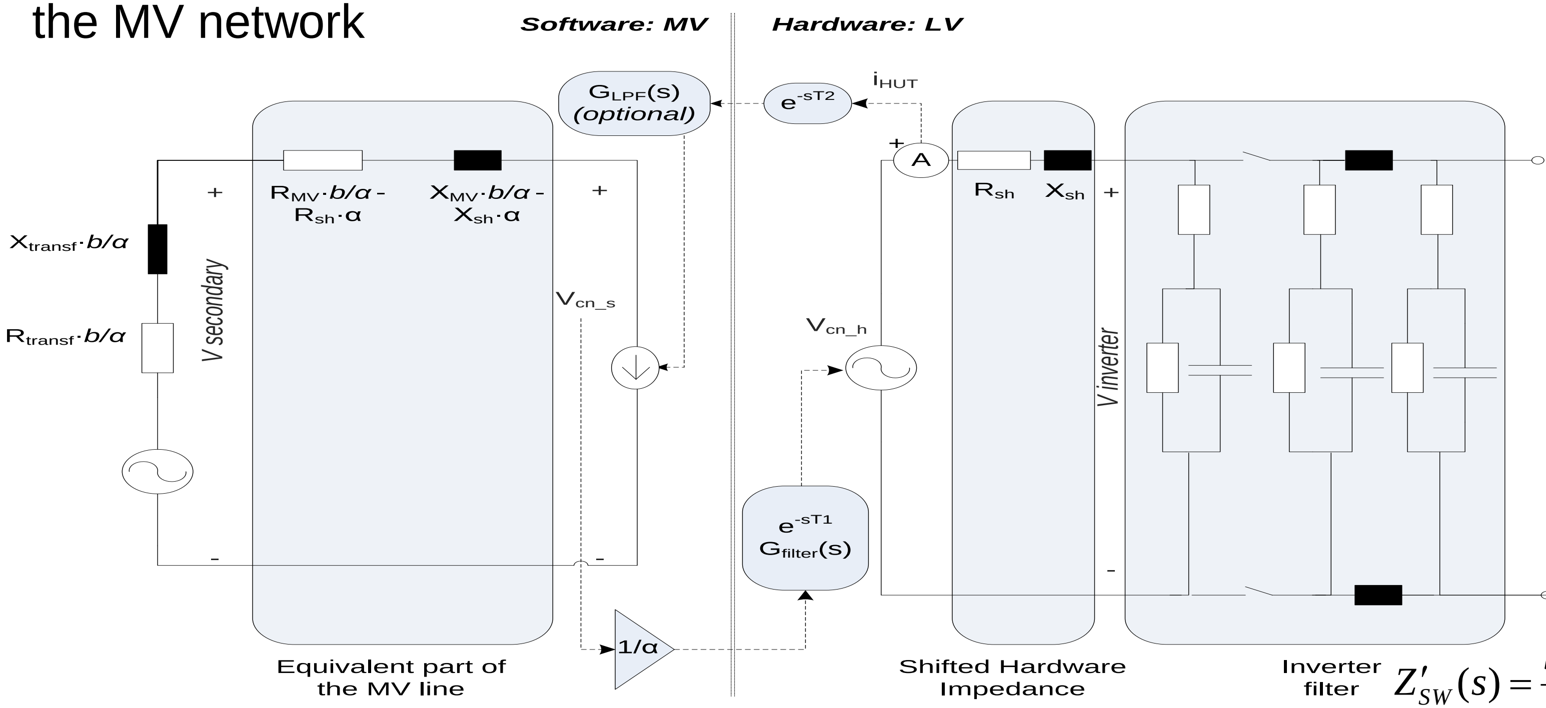


Control loop depiction of PHIL simulation with additional feedback current filtering.

Shifting impedance method

- Shifting part of the software impedance on the hardware side. Stability can be achieved without compromising accuracy: if necessary a “smaller” feedback filter can be used

- PHIL allows scaling of the software and hardware: A smaller hardware LV PV inverter can be used to evaluate the integration of a large PV park connected to the MV network



$$a = \frac{V_{SW}}{V_{HW}}$$

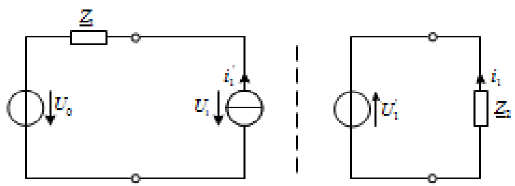
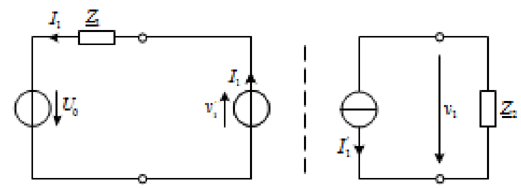
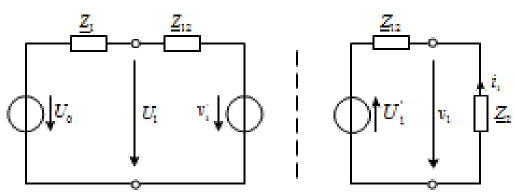
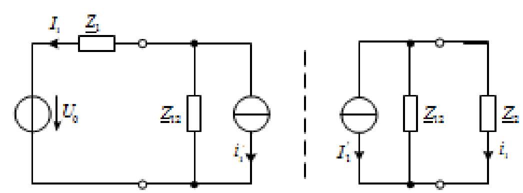
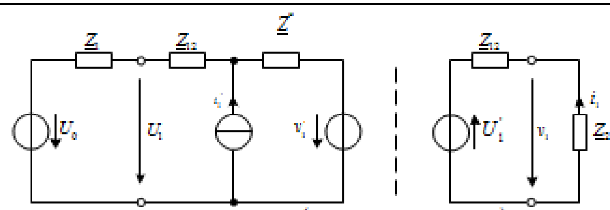
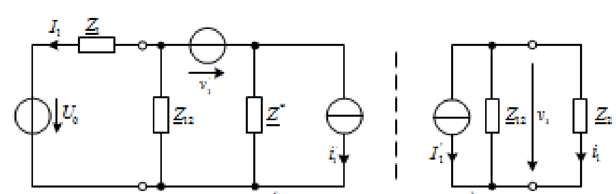
$$b = \frac{S_{HuT\_full}}{S_{HuT\_red}}$$

$$Z'_{SW}(s) = \frac{b}{a} Z_{SW}(s) - a \cdot Z_{sh}(s)$$

*P. Kotsampopoulos, F. Lehfuss, G. Lauss, B. Bletterie, N. Hatziargyriou, “**The limitations of digital simulation and the advantages of PHIL testing in studying Distributed Generation provision of ancillary services**”, IEEE Transactions on Industrial Electronics, Sept. 2015*

PHIL Methodology

- Analysis of PHIL Interface Topologies

	Interface (voltage type)	Dual Interface (DIA) – (current type)
ITM (Ideal Transformer Model)	 $F_0(s)=-T_{VA}(s)\,T_C(s)\frac{Z_1(s)}{Z_2(s)}e^{-sT_d}$	 $F_0(s)=-T_{CA}(s)\,T_V(s)\frac{Z_2(s)}{Z_1(s)}e^{-sT_d}$
PCD (Partial Circuit Duplication)	 $F_0(s)=-T_{VA}(s)\,T_V(s)\frac{Z_1(s)\,Z_2(s)}{(Z_1(s)+Z_{12}(s))(Z_2(s)+Z_{12}(s))}e^{-sT_d}$	 $F_0(s)=-T_{CA}(s)\,T_C(s)\frac{Z_{12}^2(s)}{(Z_1(s)+Z_{12}(s))(Z_2(s)+Z_{12}(s))}e^{-sT_d}$
DIM (Damping Impedance Method)	 $F_0(s)=-T_{VA}(s)\frac{Z_1(s)(T_V(s)\,Z_2(s)-T_C(s)\,Z^*(s))}{(Z_1(s)+Z(s)^*+Z_{12}(s))(Z_2(s)+Z_{12}(s))}e^{-sT_d}$	 $F_0(s)=-T_{VA}(s)\frac{Z_{12}^2(s)(T_C(s)\,Z^*(s)-T_V(s)\,Z_2(s))}{(Z_1(s)Z(s)^*+Z_{12}(s)Z(s)^*+Z_1(s)Z_{12}(s))(Z_2(s)+Z_{12}(s))}e^{-sT_d}$

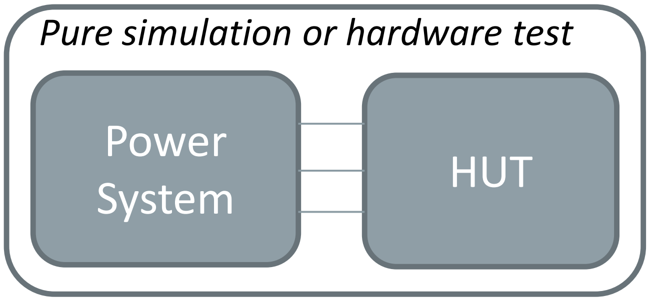
Accuracy of PHIL simulation

- PHIL simulations need to be accurate for producing valid results.
- The accuracy needs to be assessed in order to improve the system accuracy if possible.
- The accuracy of PHIL simulation depends on:
  - The time delay of the implementation.
  - Any filtering used (for different purposes: stability, anti-aliasing, noise).
  - The accuracy of the simulated models.
  - The bandwidth of the simulation and amplifier.
  - The gain introduced by the different components on a PHIL setup.
  - The measurement accuracy.

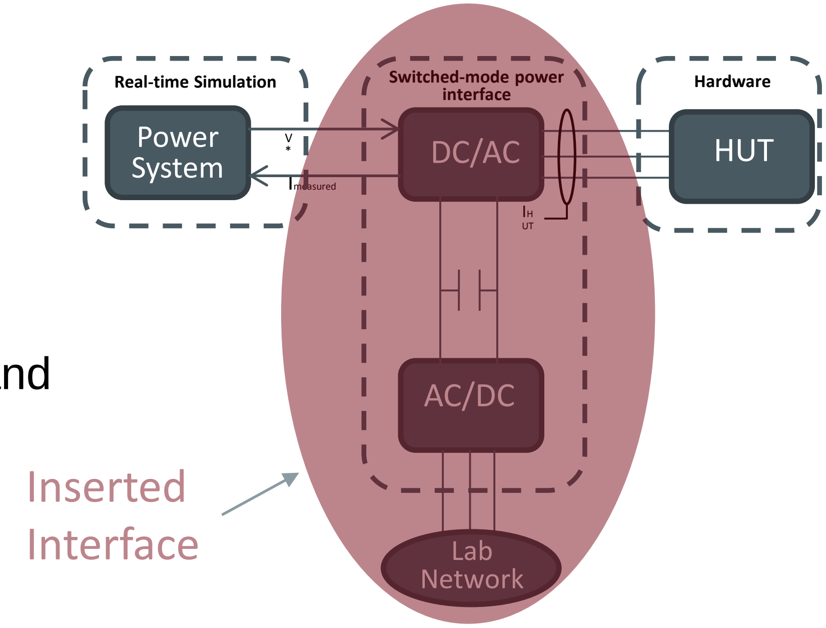
Accuracy of PHIL simulation

- The power interface is the main source of inaccuracies on PHIL, because of the power amplifier but also its interconnection with the other components.
  - ***Linear amplifier:*** very low time-delay, large losses at high powers, can have bandwidth limitations.
  - ***Switched-mode amplifier:*** large time-delay, complex control can add inaccuracies (filters, resonances), can have bandwidth limitations.
  - ***Analog communication:*** large time-delay, filters required (anti-alising).
  - ***Digital communication:*** very low time-delay.
  - ***Measurements:*** Can add some delay and gains.
  - ***Filters:*** large time-delay.

1. Ideal Scenario



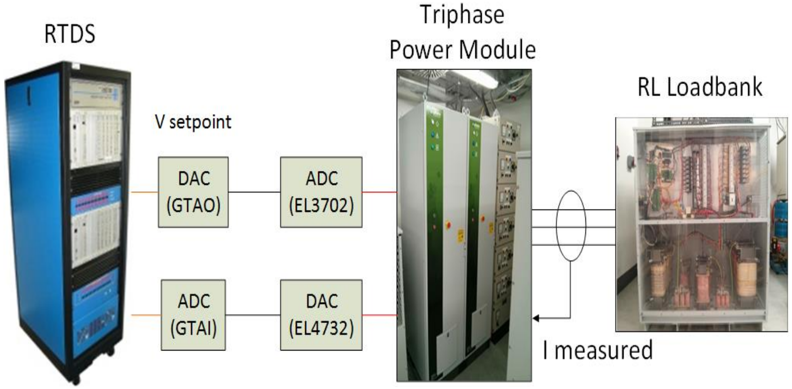
2. PHIL Scenario

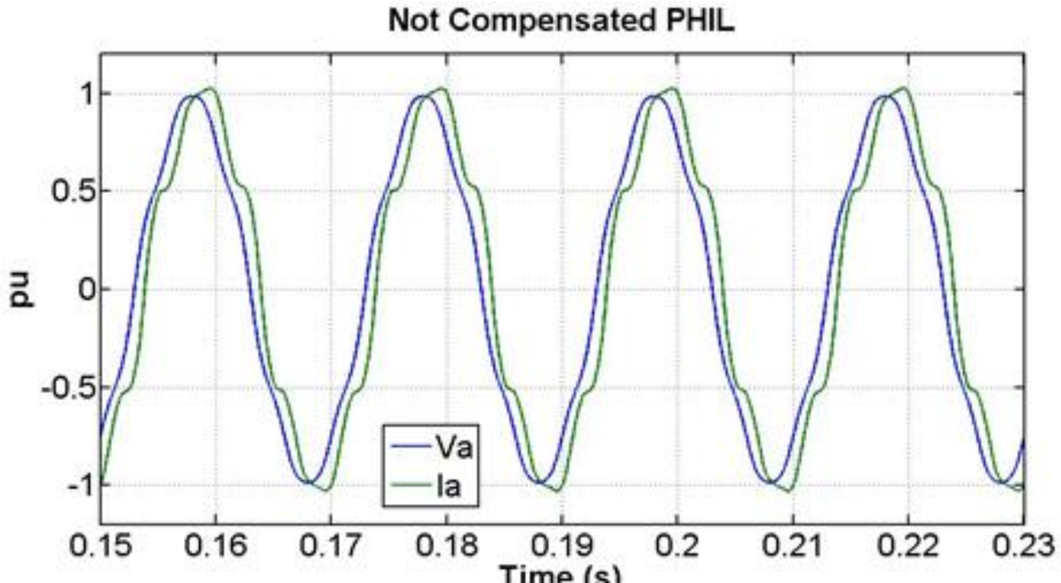


Accuracy of PHIL simulation

An example of a PHIL implementation without dealing with accuracy aspects is presented below.

- Resistive HUT (*V* and *I* should be in phase),
- 5^{th} and 7^{th} harmonics present.
- Total Td≈900us
- Notch filter used



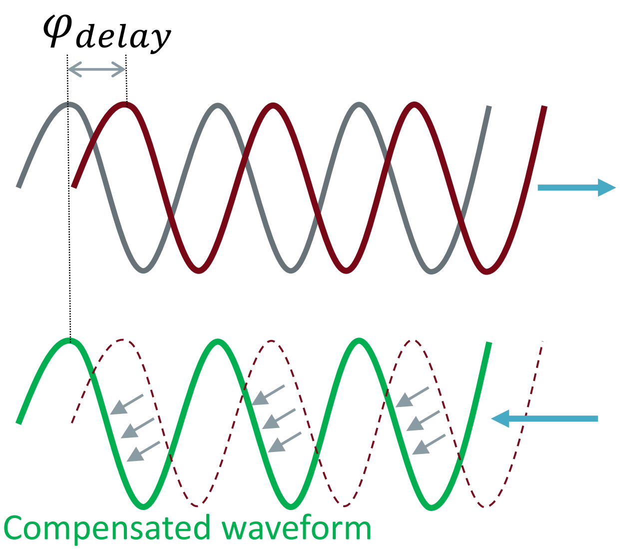


- ❖ Therefore, each PHIL implementation should be assessed and these inaccuracies should be compensated.
- ❖ This can be done by compensating time delays or avoiding unnecessary filters.

Improving stability and accuracy of PHIL simulation

University of Strathclyde Glasgow

- **<u>Accuracy improvements:</u>**
  - Time delay compensation of the power interface reference signal



$$X(w) = [A1, \varphi_1; \ldots; An, \varphi_n]$$

$$X'(w) = [A1, (\varphi_1 + \varphi_{delay}); \ldots; An, (\varphi_n + n \cdot \varphi_{delay})]$$

Time to frequency domain

Phase Shift

❖ Apparent phase difference is compensated with this method.
❖ Accurate during steady state and dynamic scenarios.
❖ Filtered transient behaviour due to DFT needs to be considered.

Improving stability and accuracy of PHIL simulation

Other approaches have been proposed in literature:

- Use of other interface algorithms (Damping Impedance Method)
- Multi-rate simulation
- Introduction of high pass filters parallel to the input and the output of the power amplifier
- Use of leading transfer functions
- Other

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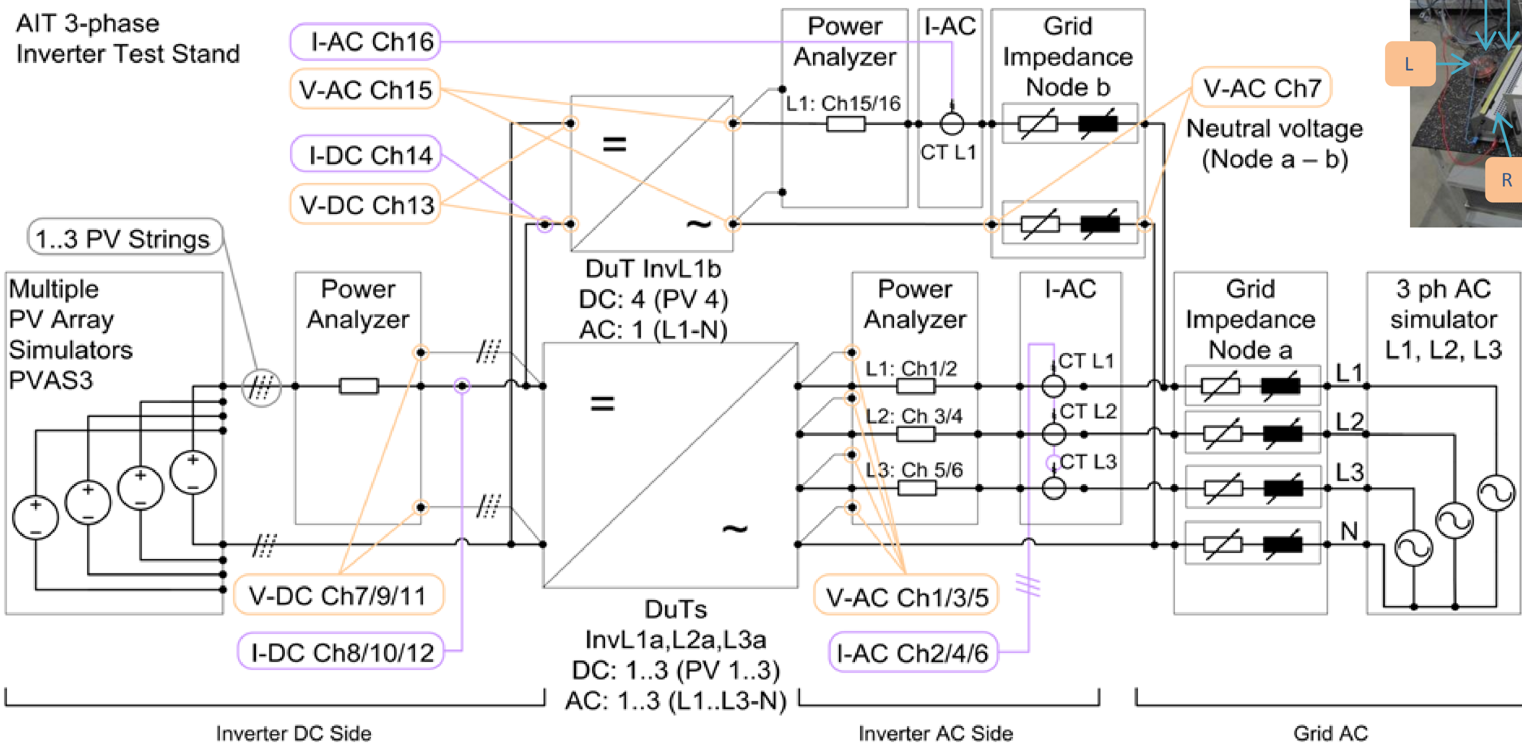
Limitations

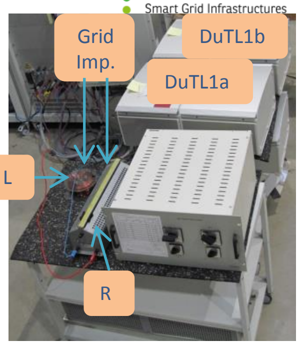
- Some of the limitations of PHIL simulations are:
  - The bandwidth of the power amplifiers can limit the accuracy under transient scenarios and high harmonic conditions.
  - The bandwidth of the real time simulators can limit the accuracy of models with high switching frequencies.
  - Difficult mathematical assessment of the stability under complex scenarios
  - Interactions between switched-mode power interface and HUT.
- However:
  - Only limited scenarios would require very high bandwidth .
  - Empirical assessment of the stability is possible for complex scenarios
  - Advanced converter controls of switched-mode power interfaces can reduce the interactions of the HUT with the interface.

PHIL experiments of the ERIGrid partners

Comparison Hardware Testing and Digital Simulation

Hardware Experiment





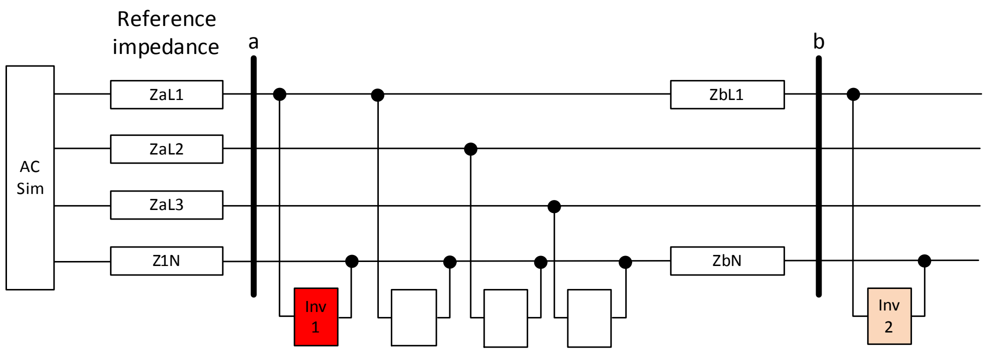
Laboratory Test Stand:

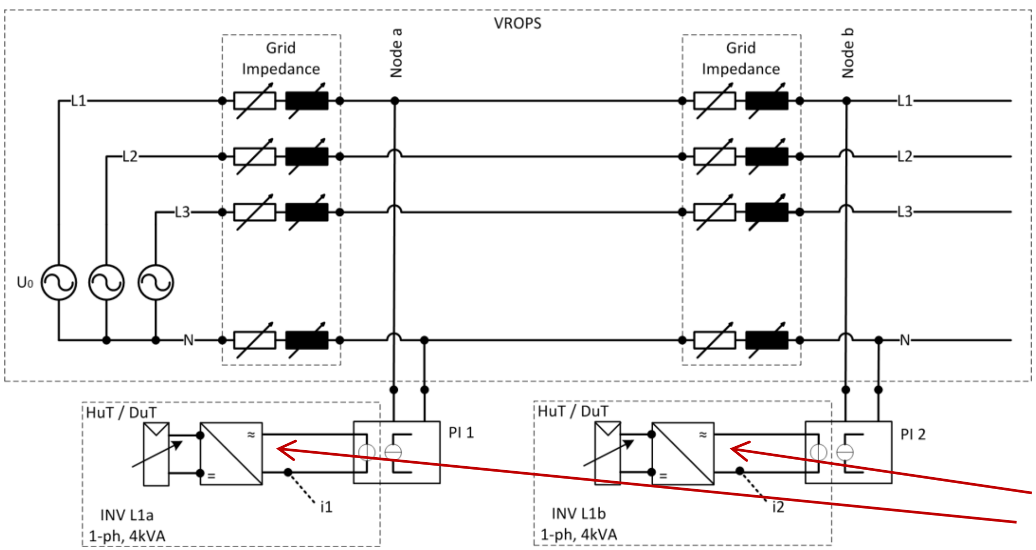
- AC / DC measurments (U, I, P, Q, S, f, …)
- Linear sources (AC: SPS; DC: PVAS)
- Grid impedances (free programmable)
- 4-wire power measurement

grid impedance settings (hardware experiment)

-	Parameter of Impedances		
Name	Location	R (Ω)	X (Ω)
$Z_{aL1,2,3}$	grid – node a	0.24	0.15
Z_{aN}	grid – node a	0.16	0.10
Z_{bL1}	node a – b	0.53	1.025
Z_{bN}	node a – b	0.427	0.549

PHIL Experiment (Use case 1)





Software Simulation Part:

- Entire LV grid topology and 3-ph grid simulation
- Complete Grid impedances (Node a/b) emulation of line and neutral impedances

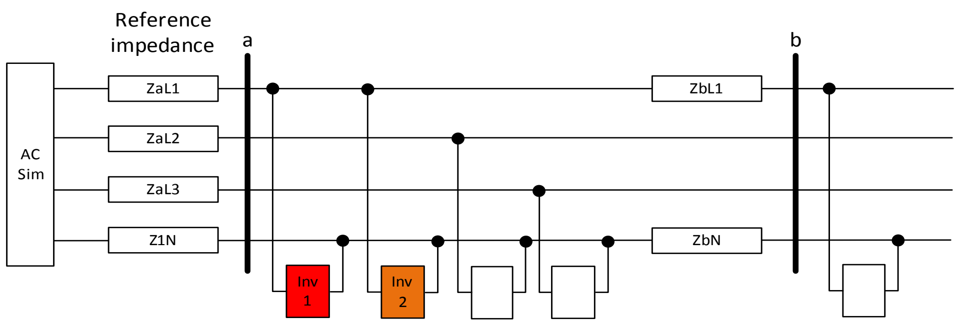
Hardware Part:

- PV inverters
  - 1-ph units (4kW, 230V/50Hz)
  - PQ control method implemented: Q(U)
  - Sourced by PV array simulators (PVAS3) in hardware

→ Conclusion:

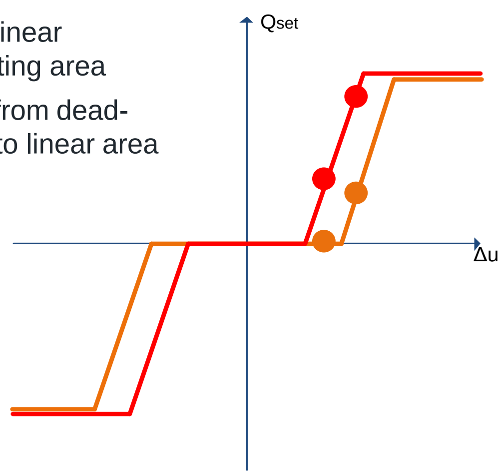
only DUTs (INV Lx) in hardware required for PHIL compared to numerical simulation

PHIL Experiment (Use case 2)



Inv1: linear operating area

Inv2: from dead-band to linear area



Typical Q(U) diagram of PV inverters connected at the same PCC

Simulation :

- Both inverters connected to the same node (Node-a)
- No Coupling via grid impedances
- Investigations on the behaviour on different Q(U) curves

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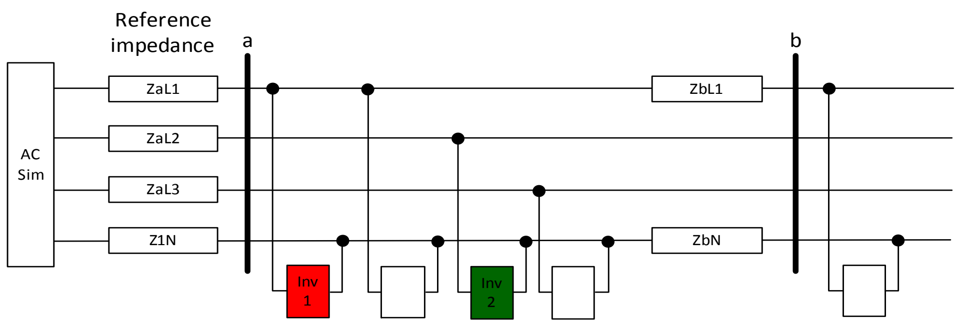
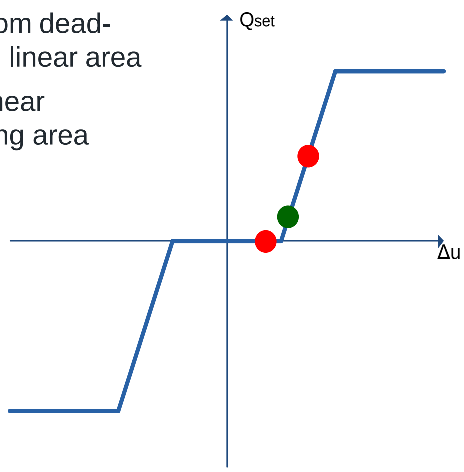
PHIL Experiment (Use case 3)



Inv1: from dead-band to linear area

Inv2: linear operating area



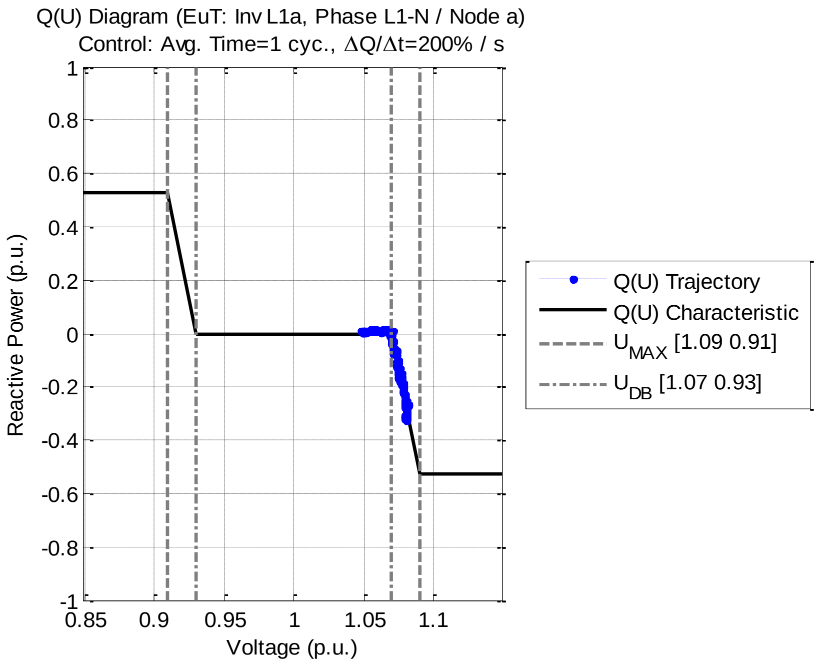
Typical Q(U) diagram of PV inverters coupled via N-grid impedance

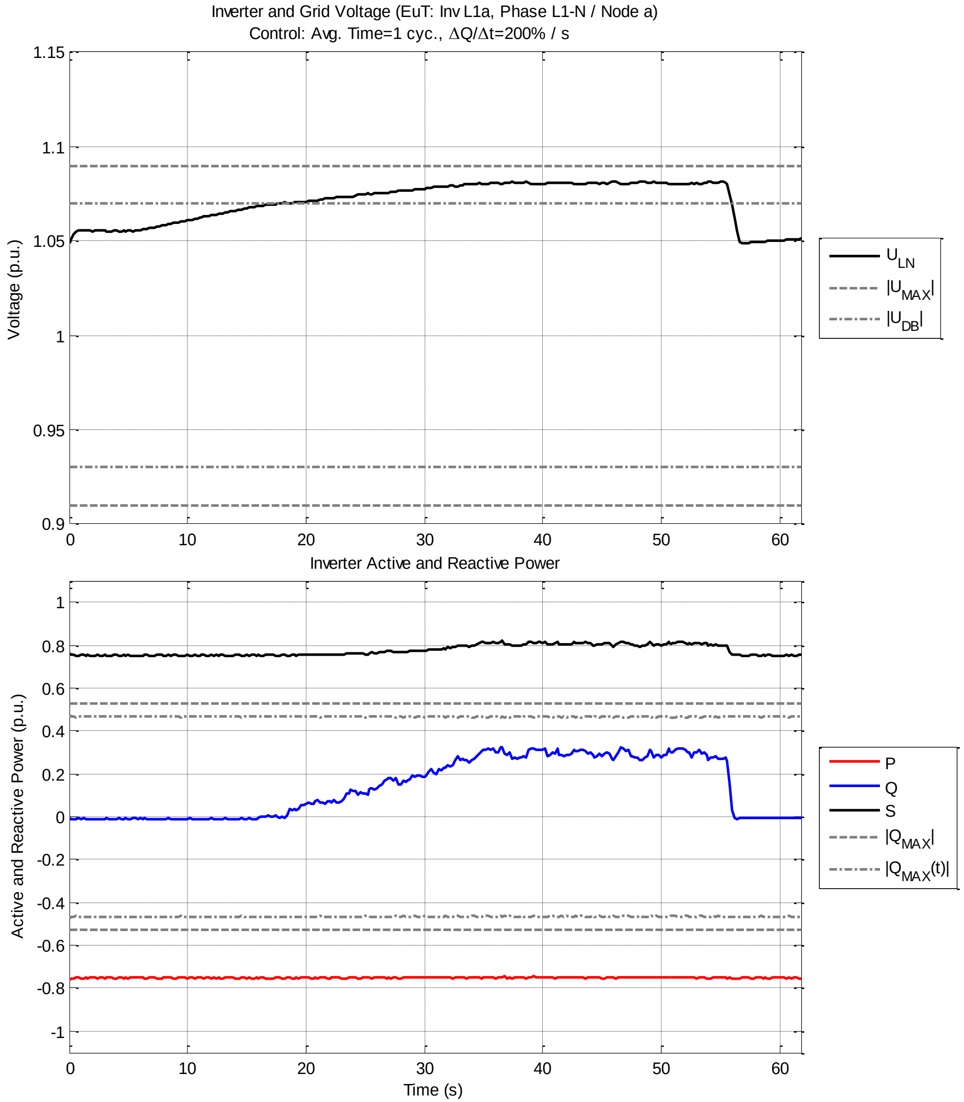
Simulation :

- Both inverters connected to the same node (Node-a)
- Coupling via Z_{bN} (impedance Node a-b)
- Investigations on interaction / interference of the two PV inverters (PQ control)

PHIL Experiment (PQ control)

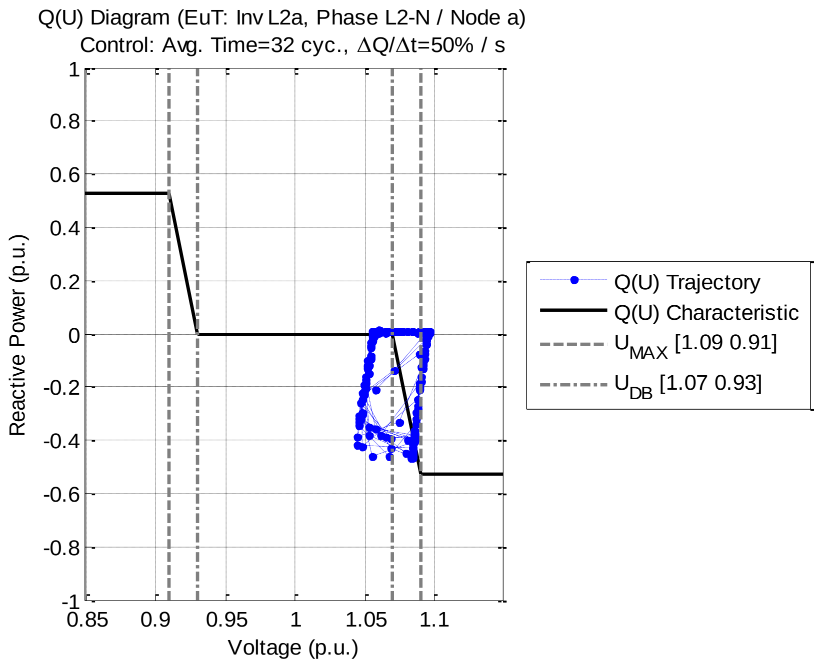
Use case 1: slow raise of grid voltage (controlled states)

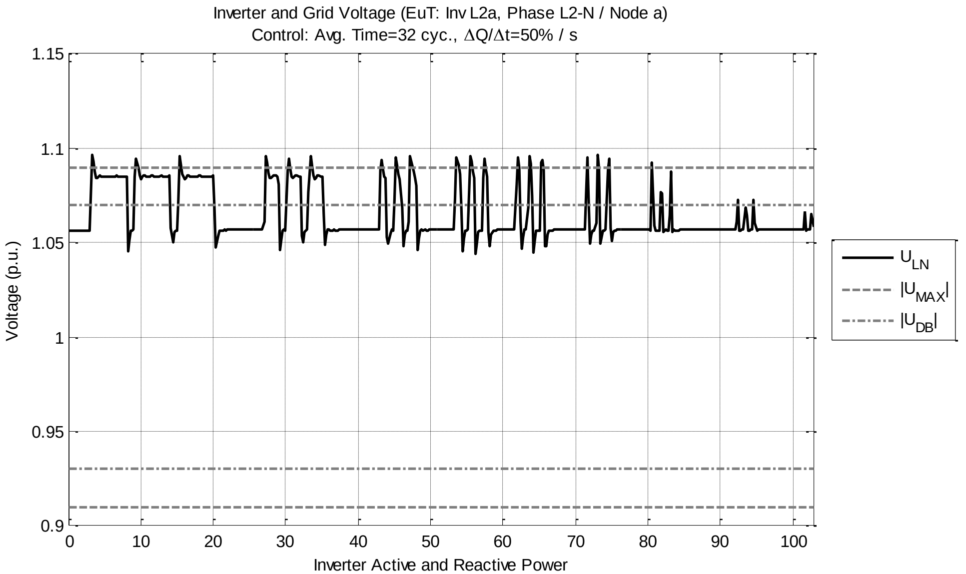


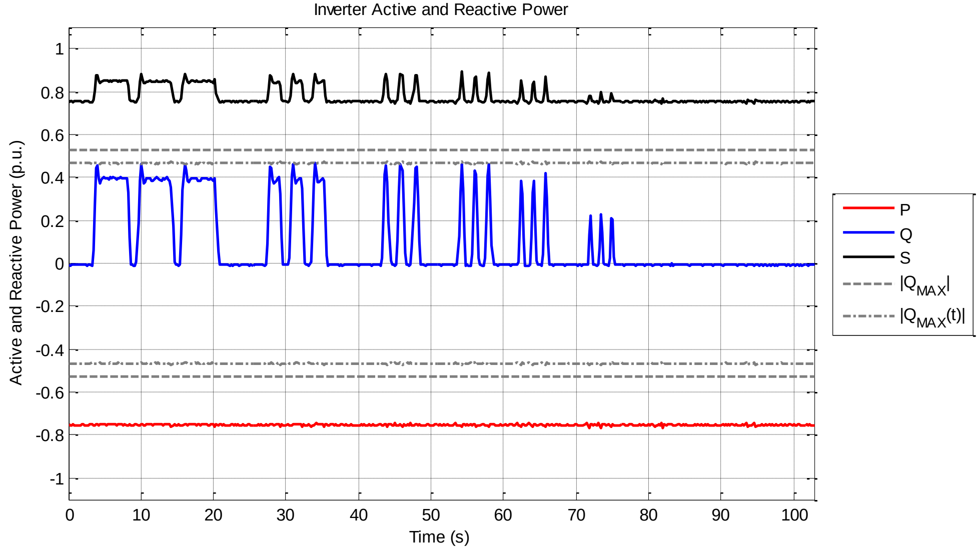


PHIL Experiment (PQ control)

Use case 2: dynamic voltage changes (uncontrolled states)

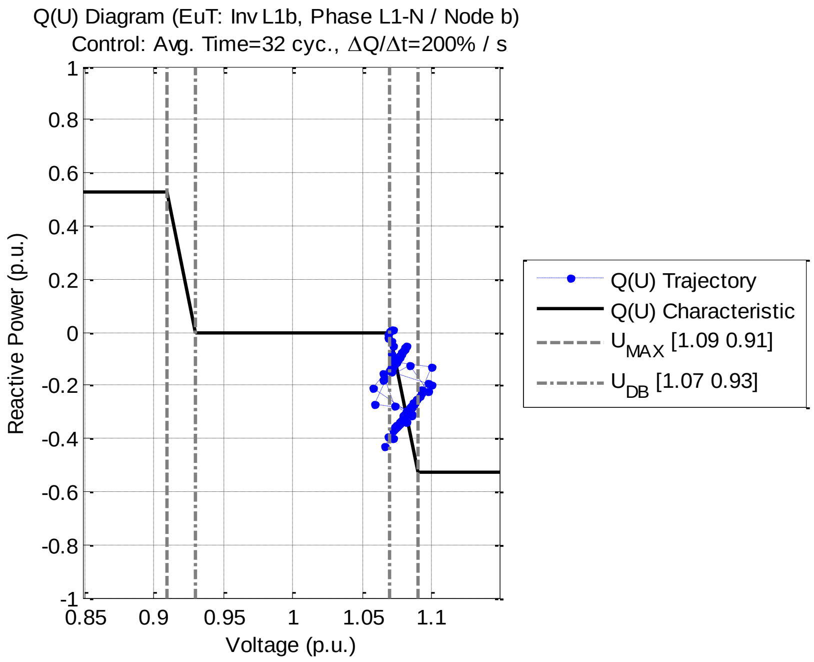


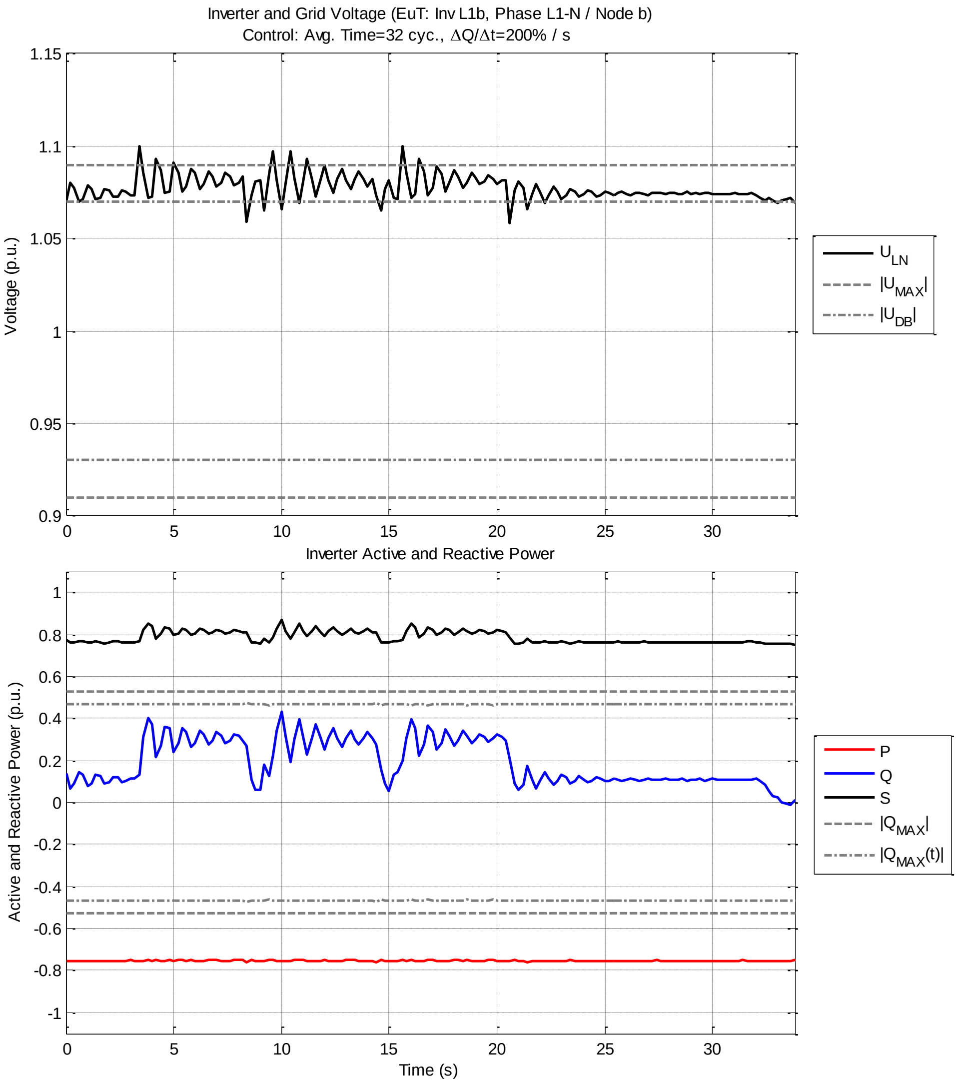




PHIL Experiment (PQ control)

Use case 3: instabilities of PQ control (uncontrolled states)





PHIL Experiment (Ancillary Services)

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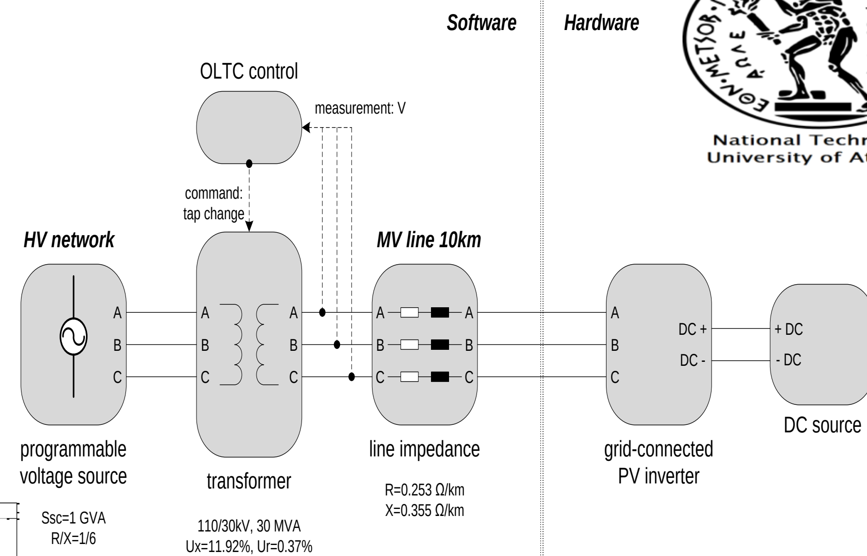
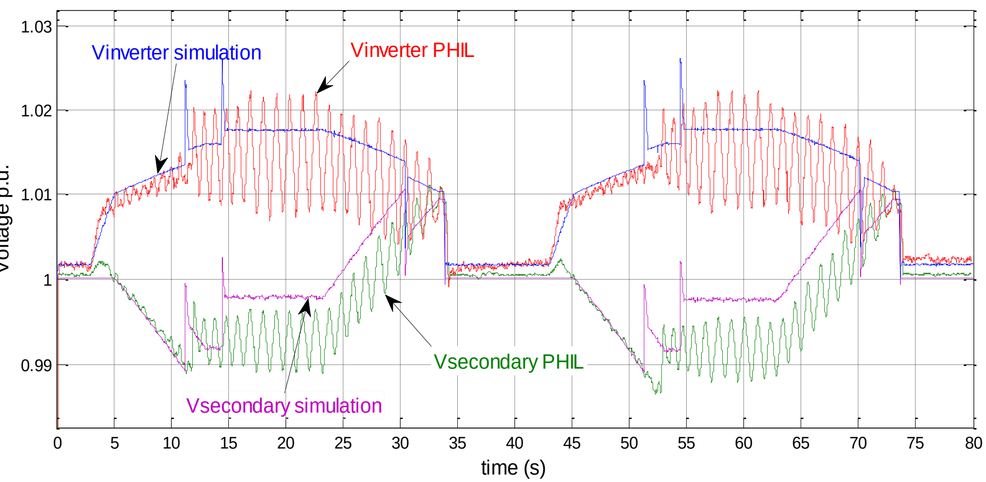
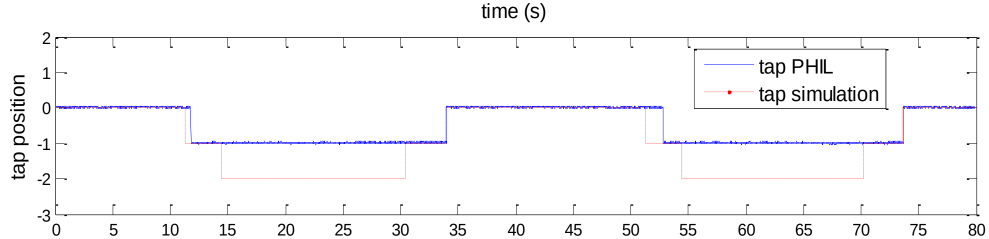
National Technical University of Athens

Comparison PHIL and Numerical Simulation:

- OLTC transformer & PV inverter; Concept for upscaling the power in PHIL experiments
- Hardware inverter operating with Q(U) or cosφ(P) characteristic
- Recurring tap-changes where observed







→ Conclusion: Differences between PHIL and software simulation detected!! Oscillations (due to instability of the Q(U) controller) were not visible at the software simulation

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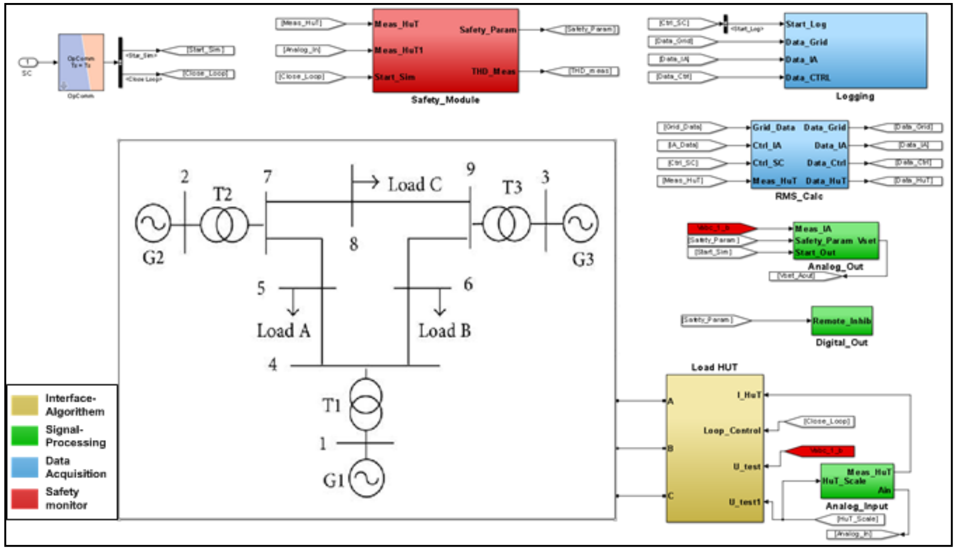
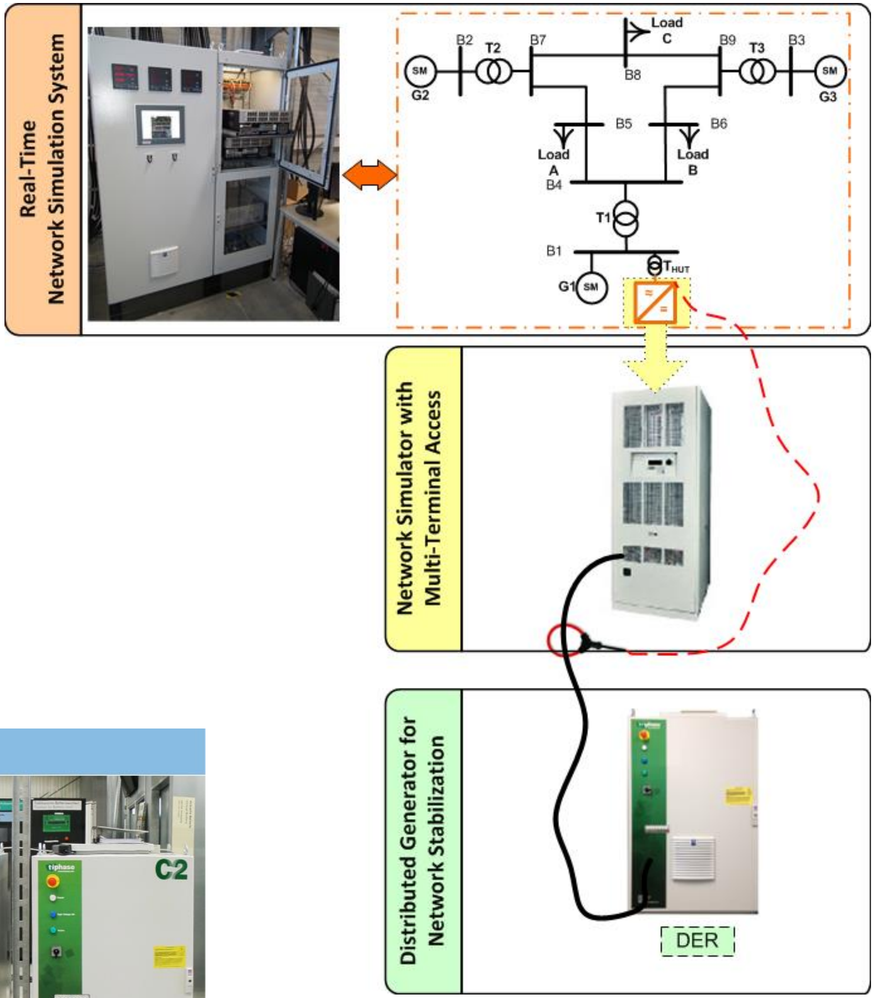
Innovative Testbed Design:

PHIL Testbed @ Fraunhofer SysTec

Implementation on RT-target





Power Amplifier

Real-time Simulation System

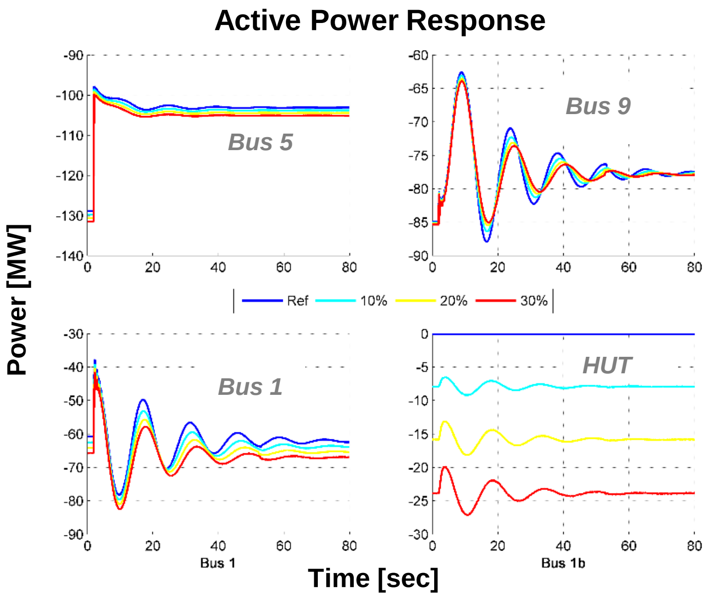
DER

Implementation at laboratory

Power System Stability Studies

Test Case 1: Virtual Inertia

- IEEE 9-Bus System with extension of machine governors
- HUT is one unit of a simulated Windpark model
- Windpark Scaling as Gen1 replacement
  - By 0%, 10%, 20%, 30% S of Gen1
- 25% Load shedding of Load A
  @ Bus 5 (125MW / ~10% of S_{Grid})

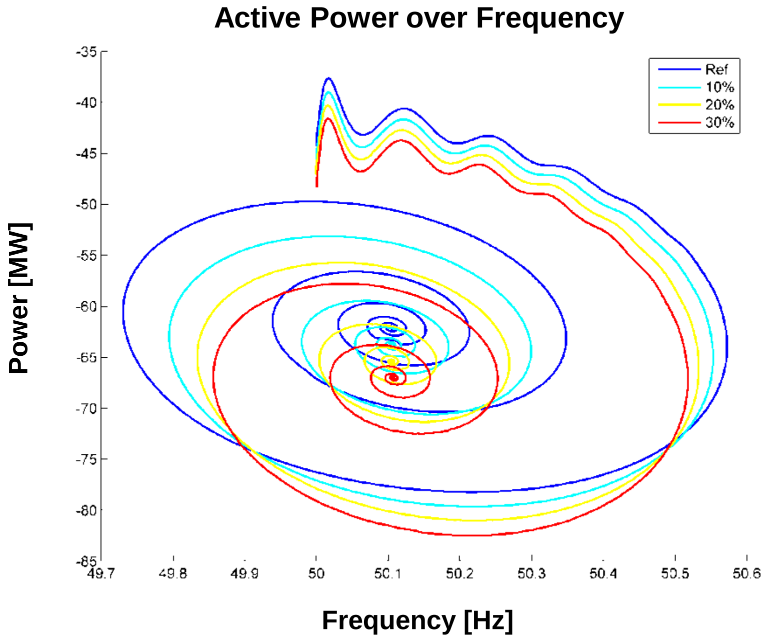


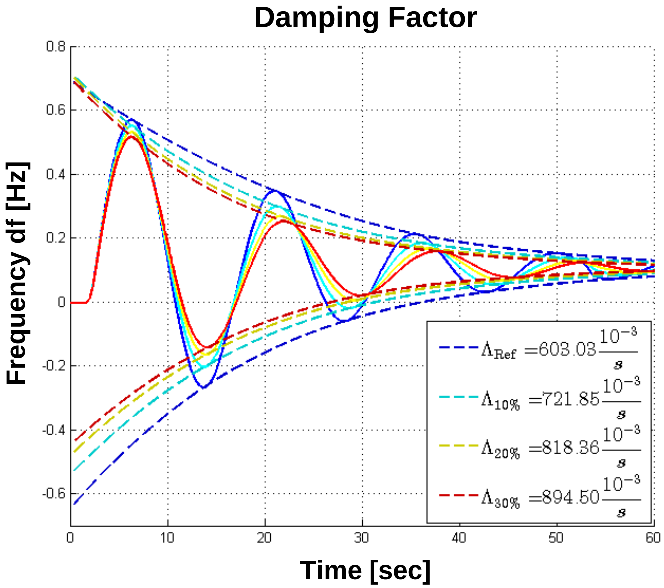
EU H2020 Programme GA No. 654113

Power System Stability Studies

Test Case 1: Virtual Inertia

Power Over Frequency and Logarithmic Decrement of Frequency





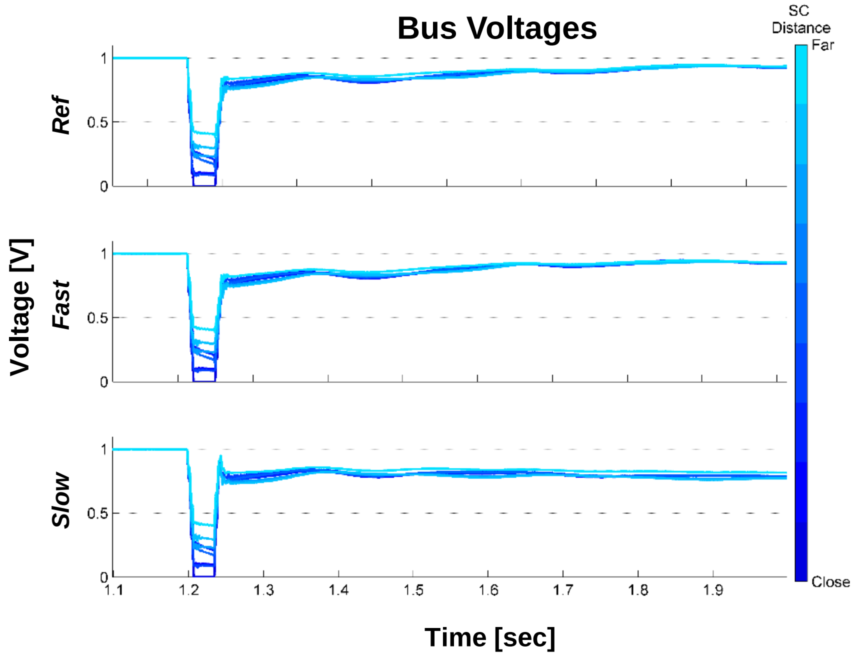
Virtual Inertia Improves Stability:

- Endorsement of virtual inertia for Power System Stability
- Higher impact/contribution shows higher frequency stability support

Power System Stability Studies

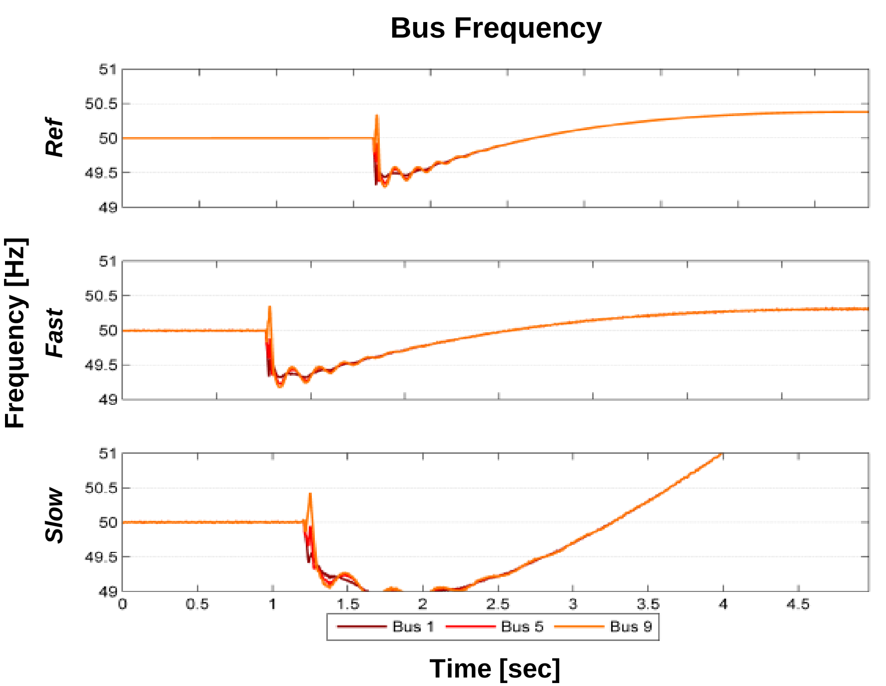
Test Case 2: Power Recovery Rate after LVRT

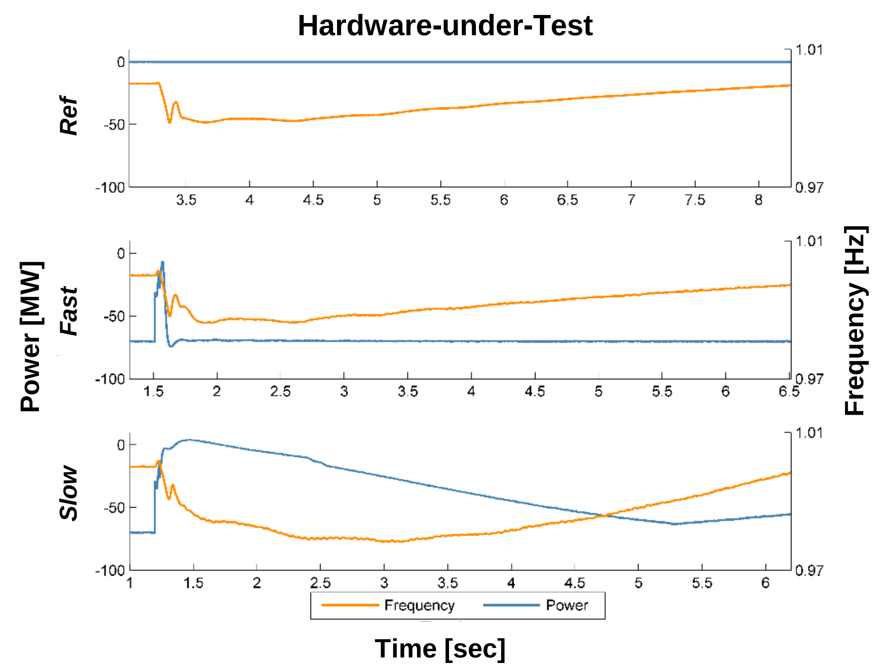
- IEEE 9-Bus System with extension of machine governors
- HUT is one unit of a simulated Windpark model
- Windpark replaces power of Gen1
- Short Circuit at Bus 8
  1. Without Windpark (Ref.)
  2. Fast power recovery rate after LVRT
  3. Slow recovery rate according FGW-TR 3 grid code (10%/s)



Power System Stability Studies

Test Case 2: Power Recovery Rate after LVRT





Benefits of fast Recovery Rates:

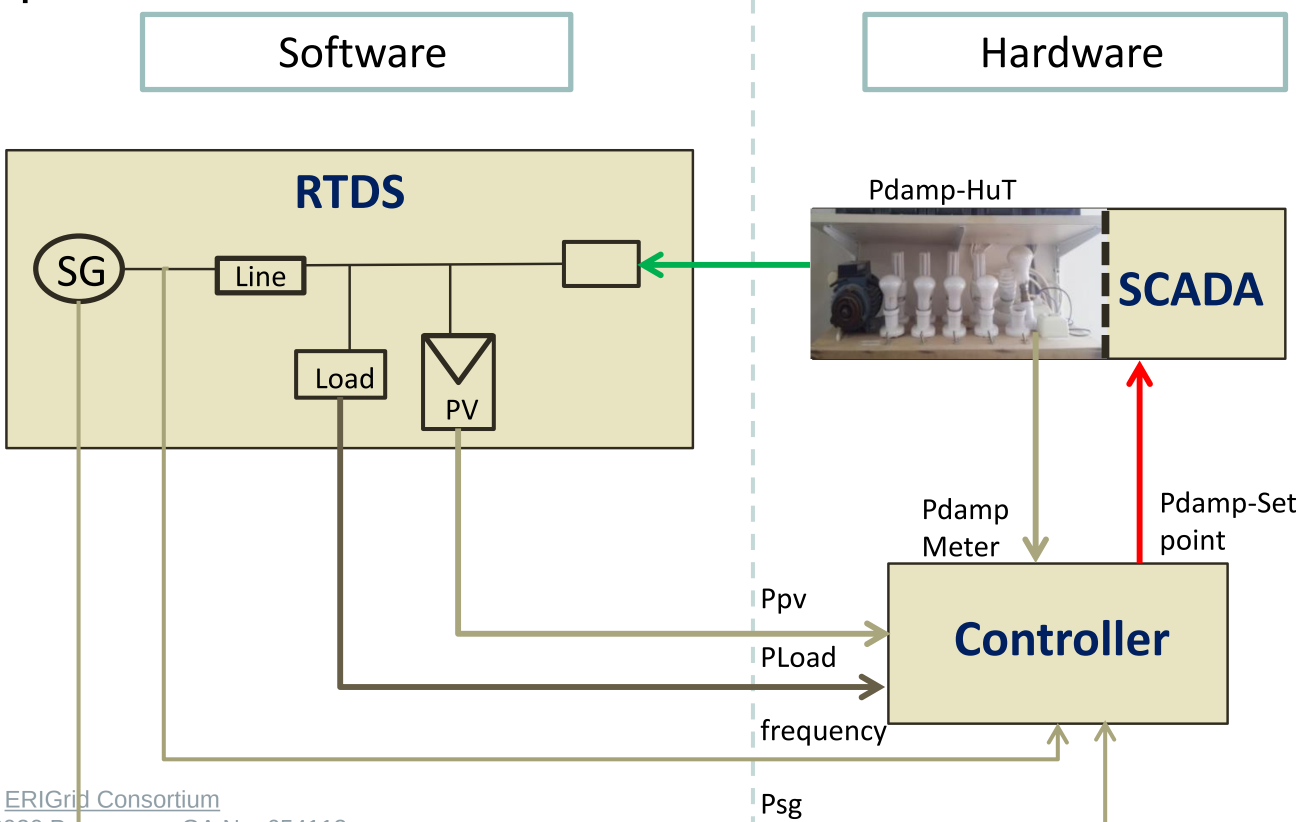
- Faster rates improve short-term voltage stability
- DER can provide fast recovery rates

CHIL/PHIL testing of off-grid microgrid controller

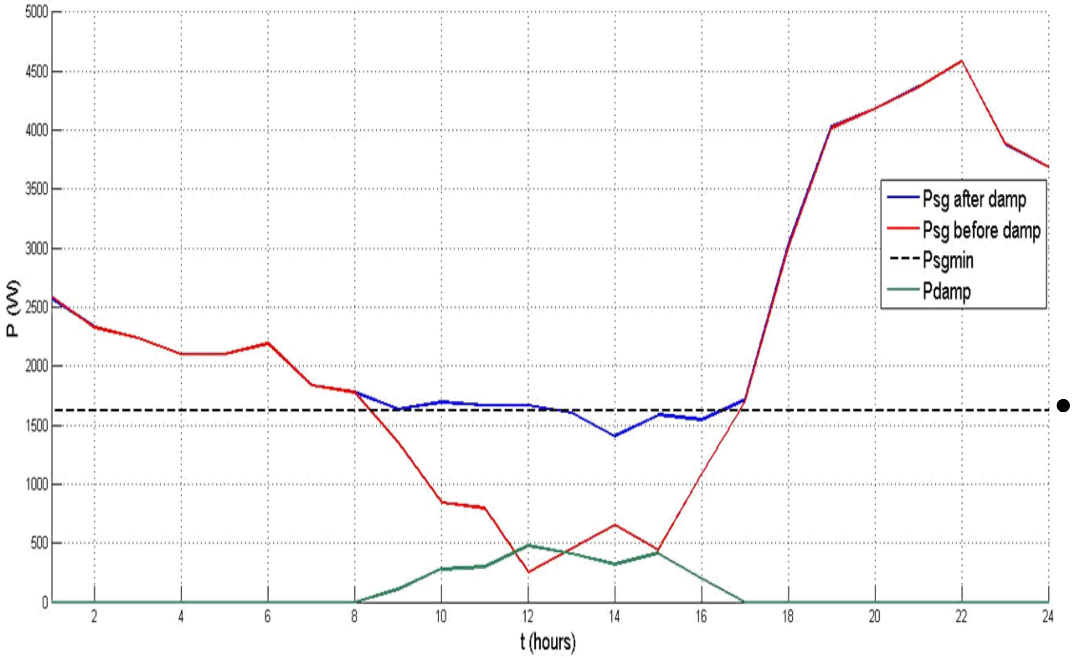
- Testing of central controller of off-grid systems:

Diesel Generator-PV-loads

- The controller activates damp loads in order to respect the minimum load ratio (30% of nominal power) of the Diesel generator, due to high PV penetration

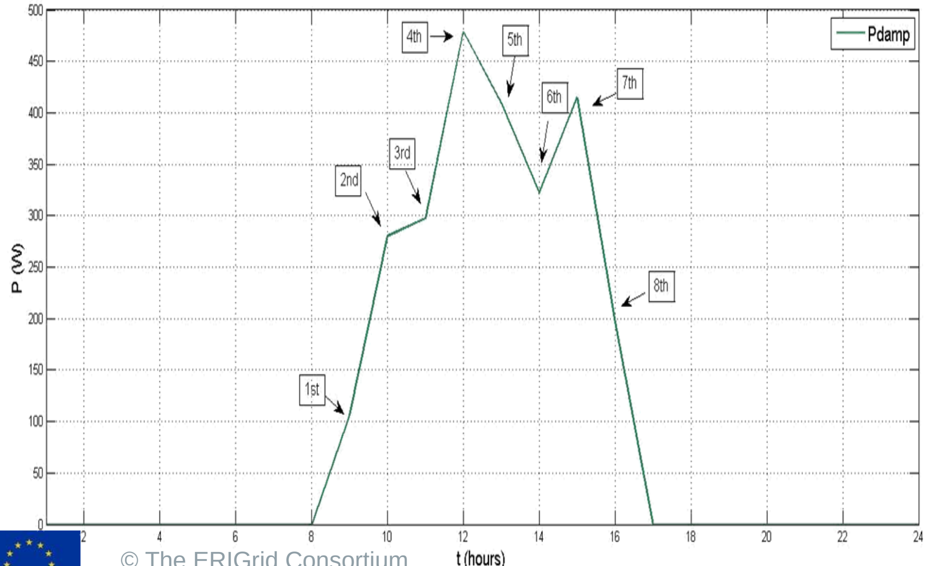


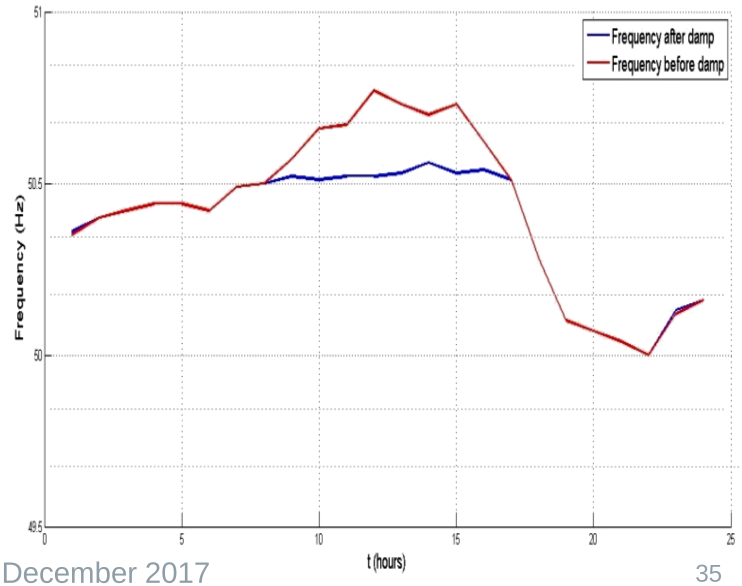
CHIL/PHIL testing of off-grid microgrid controller



National Technical University of Athens

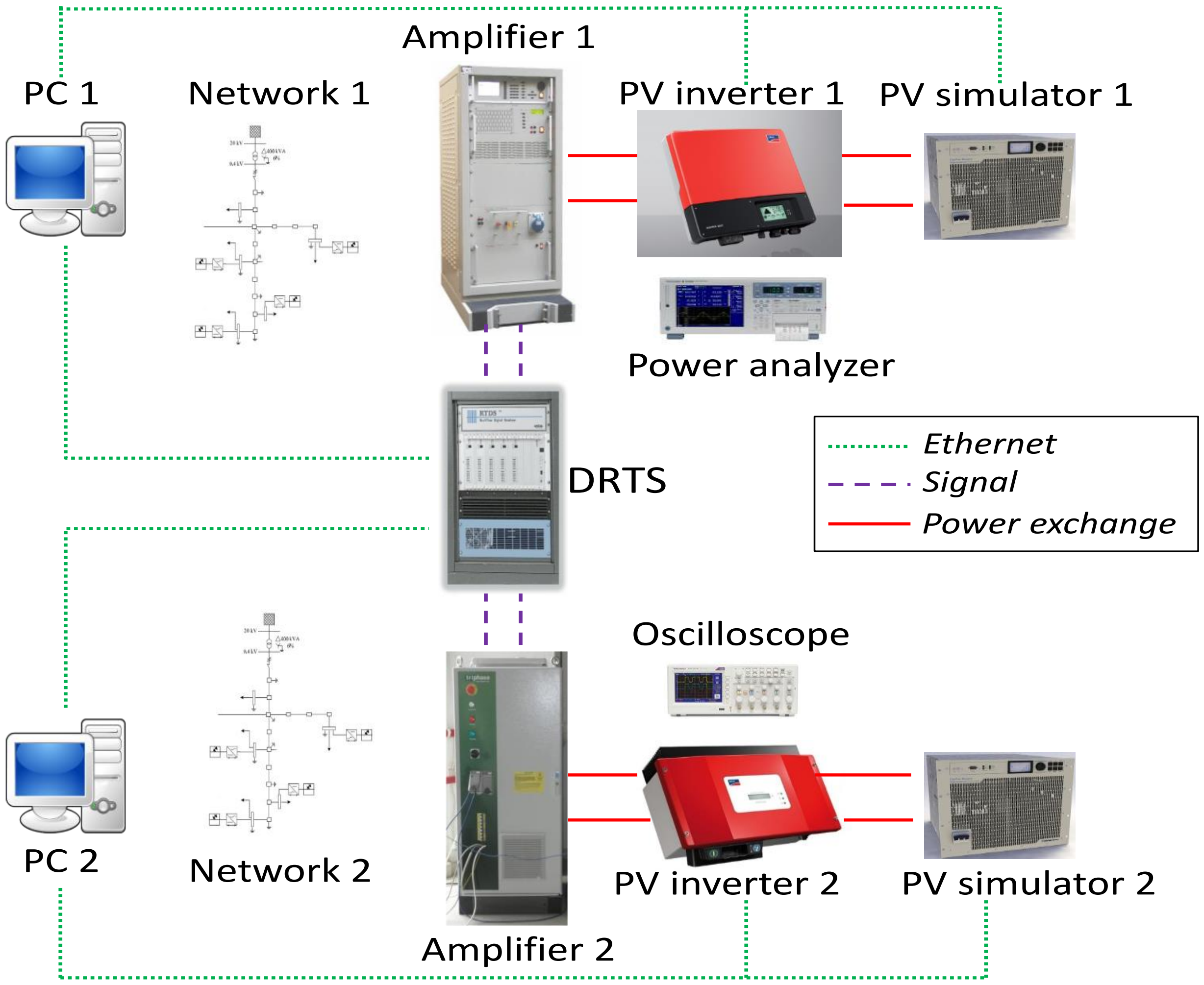
- The non ideal operation of the damp load shows the benefit of using the CHIL/PHIL approach





PHIL simulation for laboratory education

- Hands on experience for students (back to the lab)
- Double PHIL configuration (small groups of students). Equipment that was not available was simulated



*P. Kotsampopoulos, V. Kleftakis, N. Hatziargyriou, "**Laboratory Education of Modern Power Systems using PHIL Simulation**", IEEE Transactions on Power Systems, Sept. 2017*

PHIL simulation for laboratory education

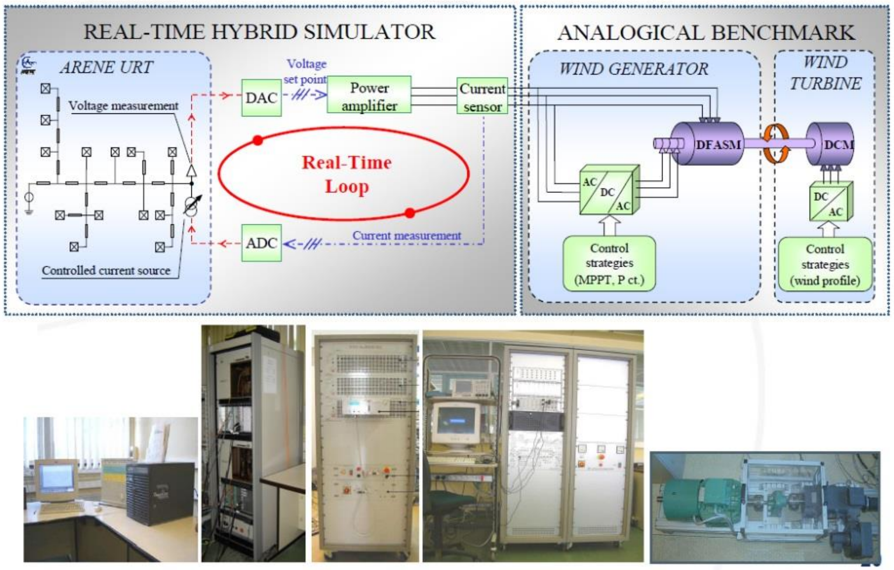
National Technical
University of Athens

1st Work bench

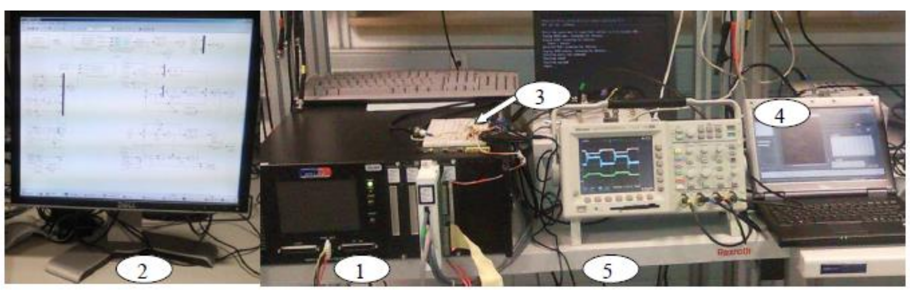
2nd Work bench

Integration of DER and non-conventional loads to smart grid

Wind Energy Analogical Benchmark

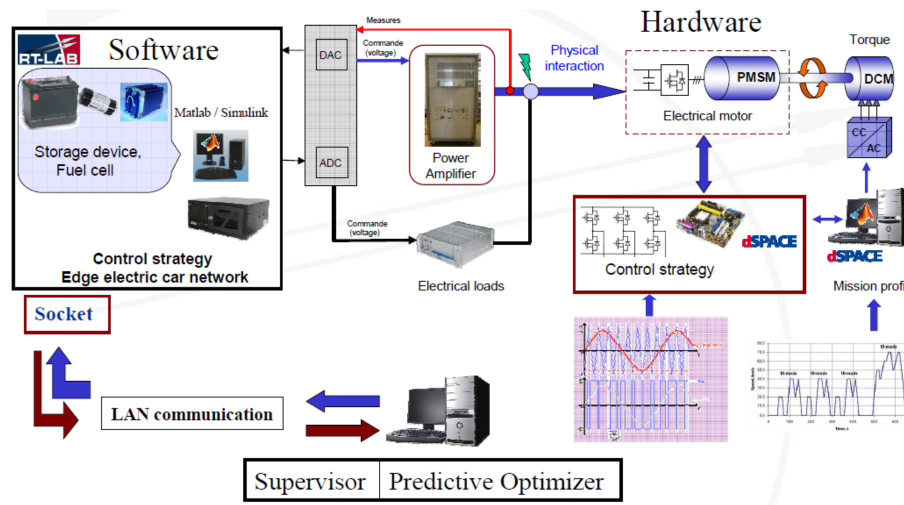


HIL Test-bed for PV integration to grid

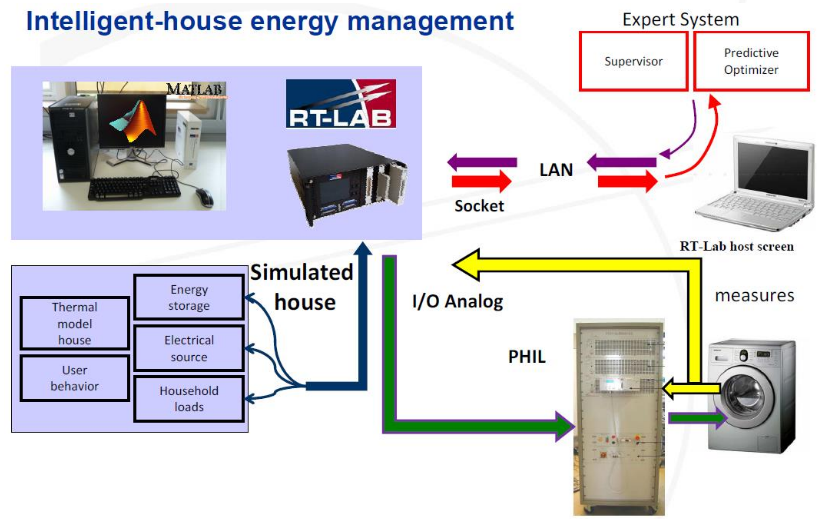


The test bench: 1 – RT-lab target (HILBox 4U), 2 – RT-Lab host screen (Simulink environment), 3 – PIC18F252 microcontroller (HUT),4 – microcontroller host (laptop), 5 – scope

PHIL of Electrical Vehicle to Grid



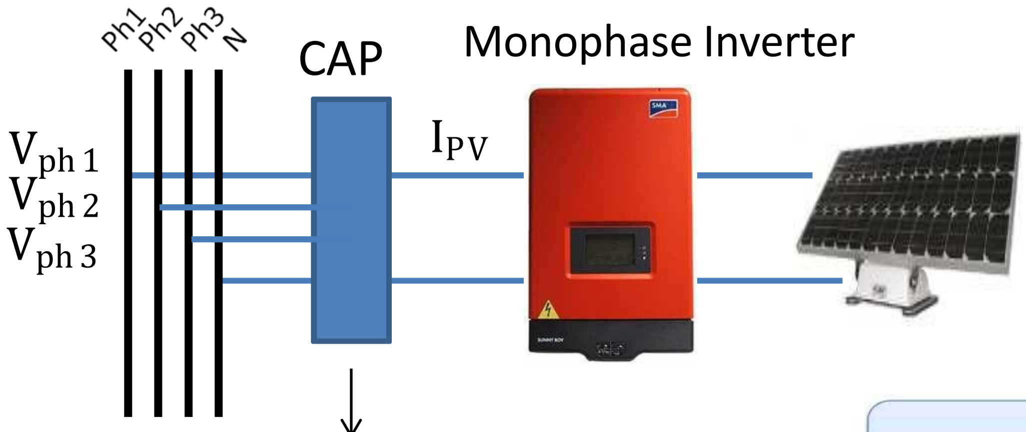
Intelligent-house energy management

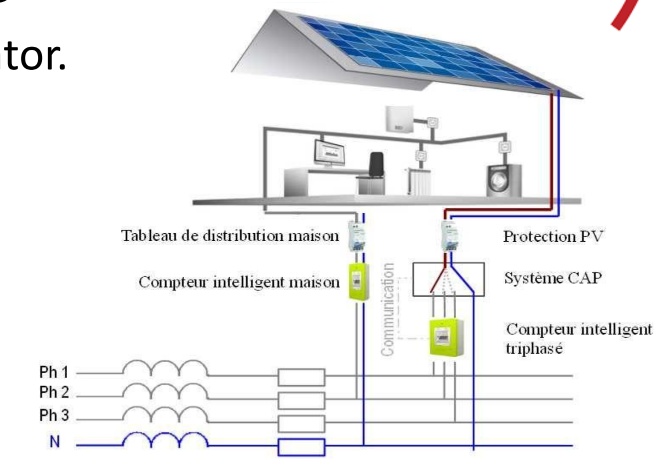


EU H2020 Programme GA No. 654113

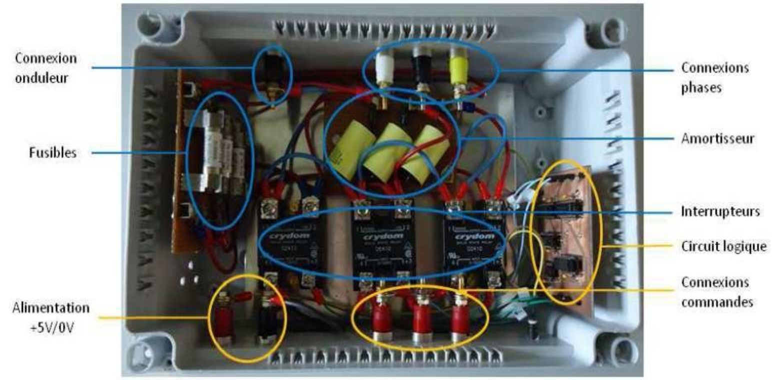
Limit the impact of DER integration to the grid via phase switching

Proposition: DER connection via a 3 positions commutator.

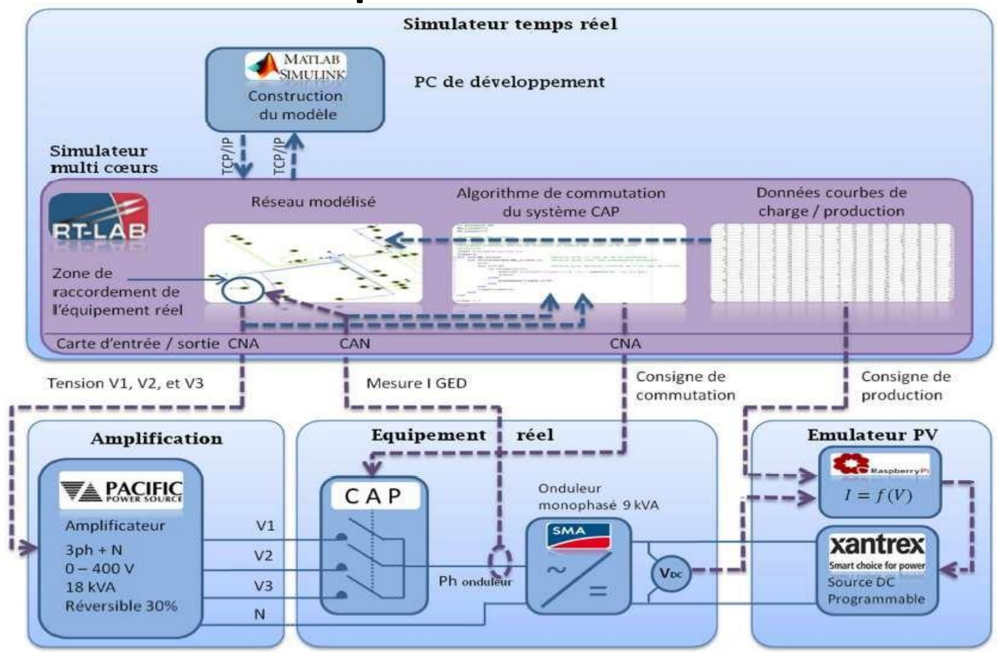




Patented by Grenoble INP



PHIL implementation



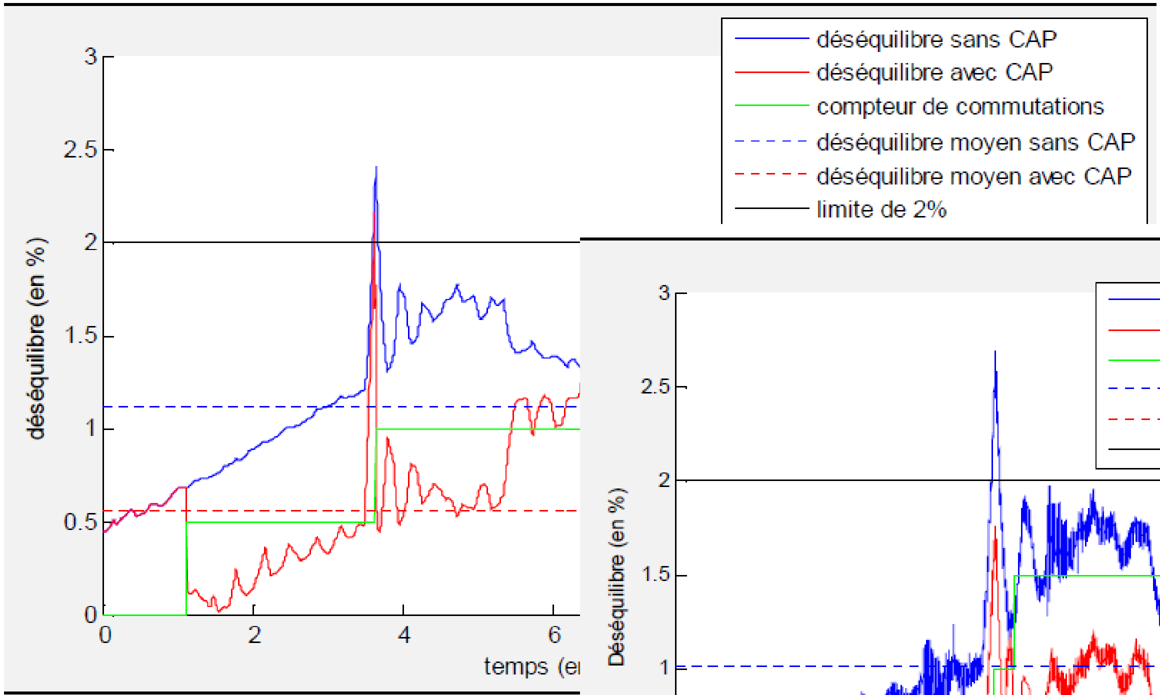
A. MERCIER *et al*, **Best phase connection for DGs using individual Smart Meter data,** IEEE PES General Meeting, July 2014

Integration of DER and non-conventional loads to smart grid

Study on impact of massive integration of DER and EV to the grid

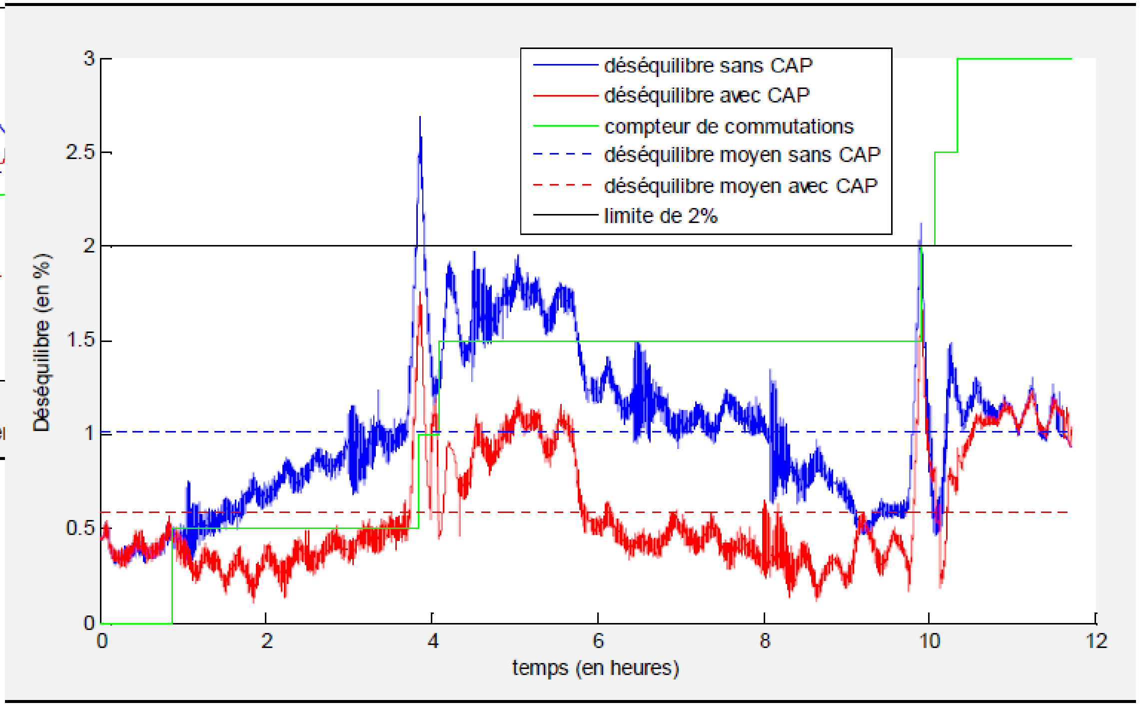
Limiting the impact of installations through phase switching

Experiment Results



PHIL Experiment

Numerical Simulation



ERIGrid: Improved Real-time Simulation and HIL Methods

- **Two main activities:**
  - **1) Improvement of RT simulation and HIL Methods.**
    - <u>Extending HIL capacity:</u>
      - Integration of HIL to Co-simulation framework.
    - <u>Improving Power-HIL testing performance:</u>
      - Stability analysis of PHIL experiments.
      - Time delay assessment and compensation for improving PHIL experiments.
  - **2) Standardization and Interoperability of HIL Experiments.**
    - Definition of a general framework for smart grid testing using Hardware-in-the-loop methods.
    - Contribution to IEEE Workgroup on Hardware-in-the-loop.

V.H. Nguyen *et al*, **Real-Time Simulation and Hardware-in-the-Loop Approaches for Integrating Renewable Energy Sources into Smart Grids: Challenges & Actions**, Inproceedings of the IEEE PES ISGT Asia 2017, Auckland, New Zealand, Dec 2017.

ERIGrid: Extending HIL Capacity

Integration of HIL to co-simulation framework:

- **Why?**
  - Need for understanding mutual impact of communications and power systems.
  - Testing multi vector energy scenarios.
  - Compatibility with larger models or different software running in different time steps.
  - Holistic simulation must consider continuous and discrete event aspects.

- Integration of HIL to co-simulation framework allows us to have a complete view of the behavior with different domains.

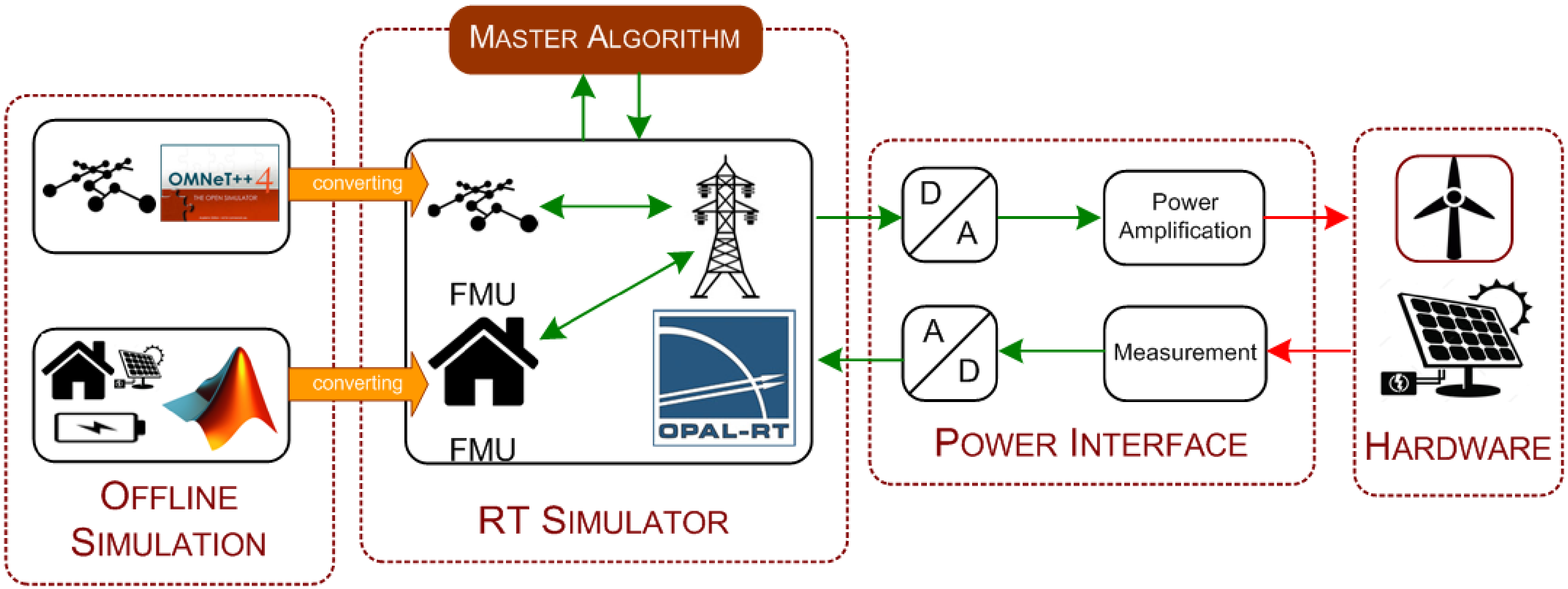
V.H. Nguyen *et al*, **Using Power-Hardware-in-the-Loop Experiments together with Co-simulation for the Holistic Validation of Cyber-Physical Energy Systems**, Inproceedings of the IEEE PES ISGT Europe 2017, Torino, Italy, Sep 2017

ERIGrid : Extending HIL Capacity

3 approaches for integration of HIL to co-simulation framework

1. « Offline » Cosimulation Approach

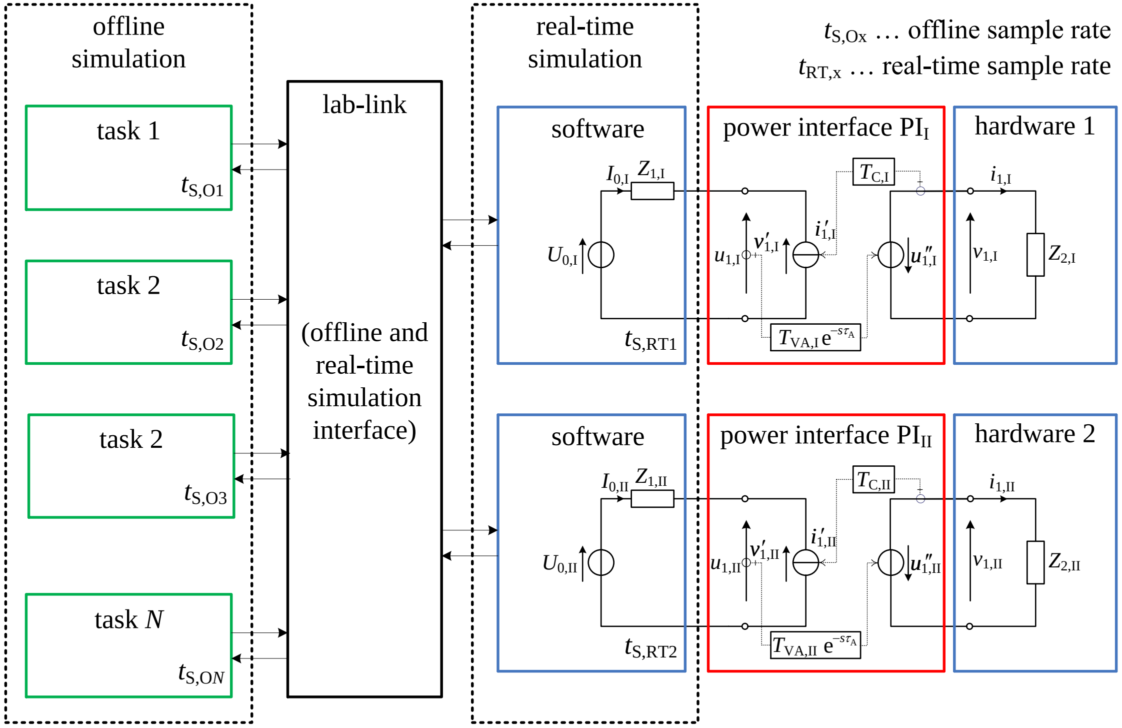
- Offline simulation is converted to FMU and integrated directly to the RT simulator's model -> forced to run at RT simulators time steps.
- Need of comptability verification (some RT simulators require to compile the FMU)



ERIGrid : Extending HIL Capacity

2. « Online » Cosimulation Approach – Without Synchronization

- Lab-link Architecture.



Sample rates of subsystems linked via lab-link:

a) offline tasks: $t_{S,O(N\text{-}1)}$ > 100 ms; operating sample rates [100 ms; 2 s]

b) lab link: : $t_{S,LL}$ > 1 ms; operating sample rates [100 ms; 2 s]

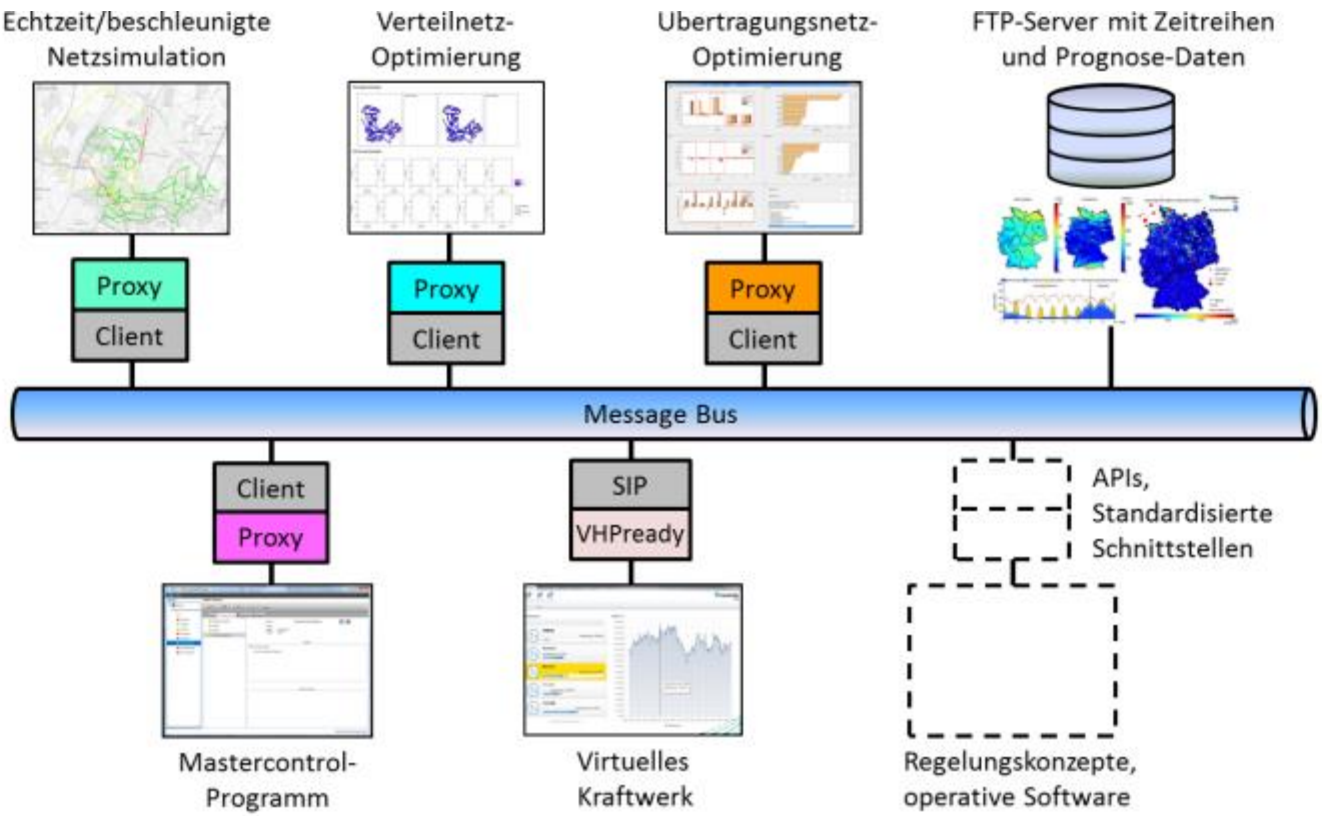
c) real-time simulation: $t_{S,RT}$ < 1ms (up to 100ns); operating sample rates [100 ns; 1 ms]

F. Lehfuss *et al* , **A Novel Approach to Couple Real Time and Co-Simulaton to Evaluate the Large Scale Grid Integration of Electric Vehciles**, IEEE Vehicle Power and Propulsion Conference, Belfort, France, Dec 2017.

ERIGrid : Extending HIL Capacity

3. « Online » Cosimulation Approach – With Synchronization

- OPSim Solution



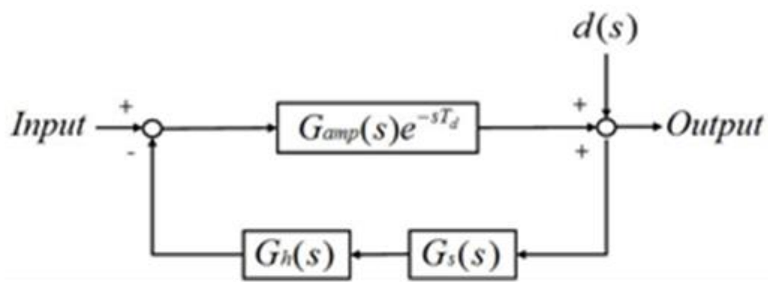
- Synchronization via conservative approach.
- The environment maybe extended with physical laboratory-based domains.
- Can communicate with OPAL RT via asynchronous interface.

ERIGrid : Improving PHIL testing Performance

- **Determining marginal parameters for to achieve Stability of PHIL test**

Considering Bode stability criterion, a stable PHIL simulation the following conditions should be satisfied:

1. $|G_s(s)G_{amp}(s)e^{-sTd}G_h(s)| \leq 1$
2. $\angle G_s(s) + \angle G_{amp}(s) + \angle G_h(s) - \omega T_d = \pi$

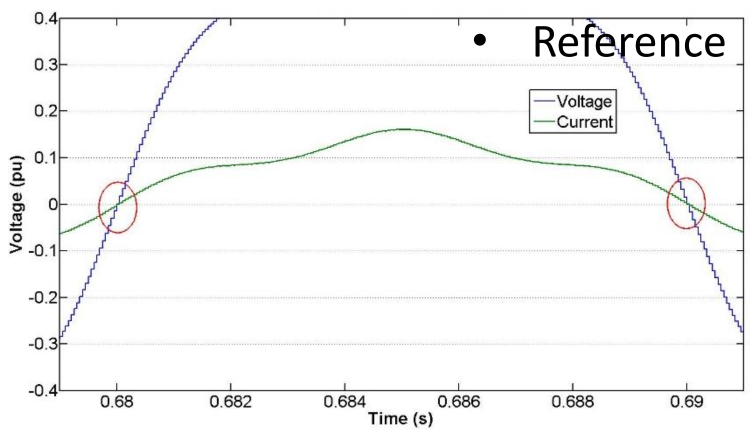


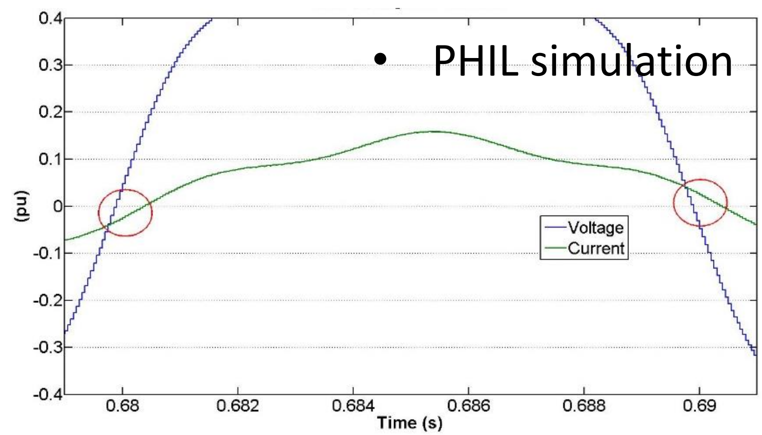
❖ Method successfully applied to the shifting impedance method and feedback filter.

*A. Markou, V. Kleftakis, P. Kotsampopoulos, N. Hatziargyriou, "**Improving existing methods for stable and more accurate Power Hardware-in-the-Loop experiments**", 26th IEEE International Symposium on Industrial Electronics (ISIE), 2017*

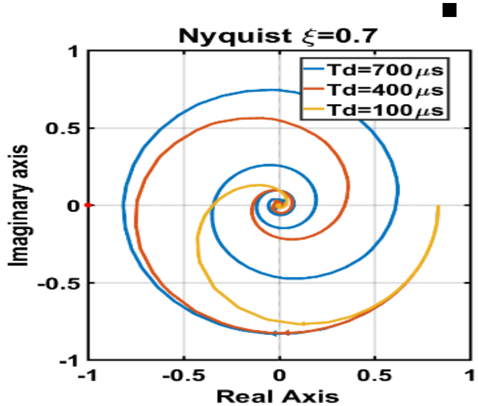
ERIGrid : Improving PHIL testing Performance

- **<u>Time delay</u>** an important cause of inaccuracies and stability issues in PHIL.
  - **Effect on Accuracy**





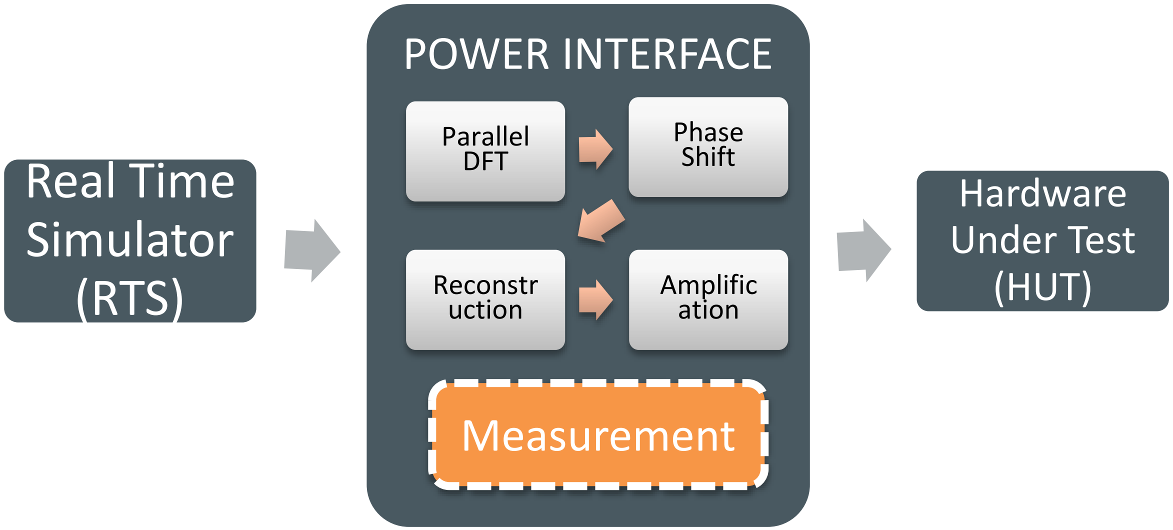
  - **Effect on Stability**



When the time delay is increased the stability margin is reduced, being closer to encircle the instability point (-1,0).

ERIGrid : Improving PHIL testing Performance

- **<u>Time delay compensation in PHIL tests</u>**



- Improves stability and accuracy of PHIL.
- Relatively low computation using parallel DFT.
- Compensation of fundamental and harmonics components.

E. Guillo-Sansano, A. J. Roscoe and G. M. Burt, "**Harmonic-by-harmonic time delay compensation method for PHIL simulation of low impedance power systems**," *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST).*

ERIGrid activities on standardization of HIL approach

- The methodological and technical improvements of ERIGrid workgroup are formalized and presented in various research papers.
- The group works closely with the IEEE Task force on hardware-in-the-loop.
- A « yellow paper » on Hardware-in-the-loop technique is being prepared by ERIGrid to propose to the Task force.

P. C. Kotsampopoulos *et al,* **Laboratory Education of Modern Power Systems Using PHIL Simulation**, IEEE Transaction on Power Systems, vol 32 (5), 2016.

M. Maniatopoulos *et al,* **Combined control and power hardware in-the-loop simulation for testing smart grid control algorithms**, IET Generation, Transmission & Distribution, vol 11 (12), 2017.

R. Brandl, **Operational Range of Several Interface algorithms for different Power Hardware-In-The-Loop setups**, Energies, vol 10 (1946), 2017

V.H. Nguyen, **On Conceptual Structuration and Coupling Methods of Co-Simulation Frameworks in Cyber-Physical Energy System Validation**, Energies, Vol 10, 2017.

Conclusions

- Research on smart grids require advanced testing and simulation methods for its validation.
- PHIL de-risks field tests by enabling reality-close testing in controlled laboratory environments.
- At some cases PHIL simulation can reveal interactions which are not visible at pure digital simulations.
- More research is needed on the stability and accuracy of PHIL simulation.
- Standardized approach for performing PHIL is required.
- Combining HIL and co-simulation can be an important step towards the holistic testing of smart grid systems.

THANK YOU FOR YOUR ATTENTION

Project website: www.erigrid.eu

Educational-training material: www.erigrid.eu/education-training