



**SMART
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CHIL and PHIL simulation: key features and applications

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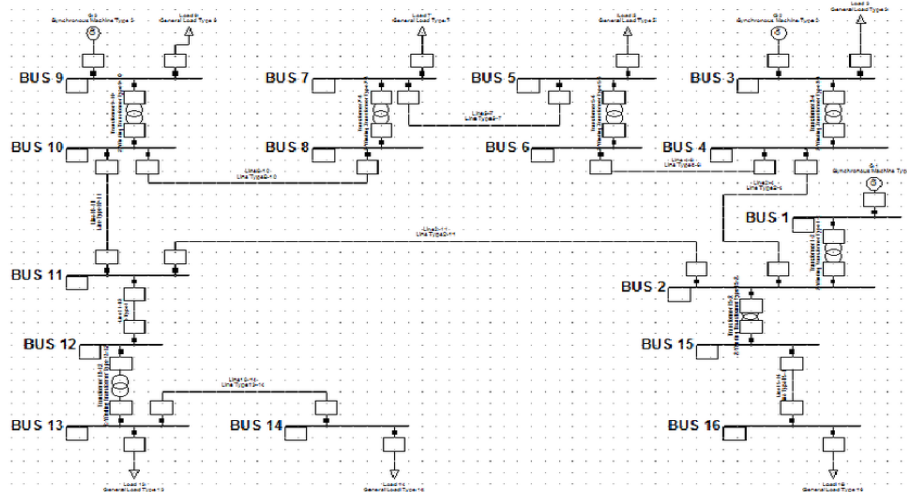
Overview

- Introduction to Hardware in the Loop simulation
- Controller Hardware in the Loop simulation (CHIL):
 - Testing relays, power electronic converter controllers and supervisory controllers
- Power Hardware in the Loop simulation (PHIL):
 - Stability, accuracy and interfacing
 - Testing of DER inverters

Conventional Approaches in the power system analysis, research, testing and validation

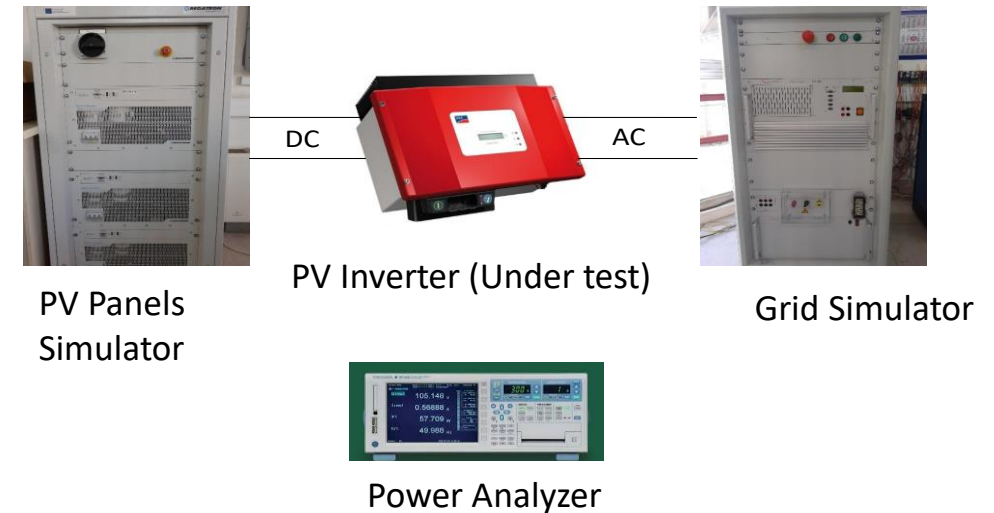
Digital Simulation

- Analysis of phenomena
- Mathematical models
- High flexibility, low cost
- The accuracy depends on the accuracy of the models



Conventional Hardware testing

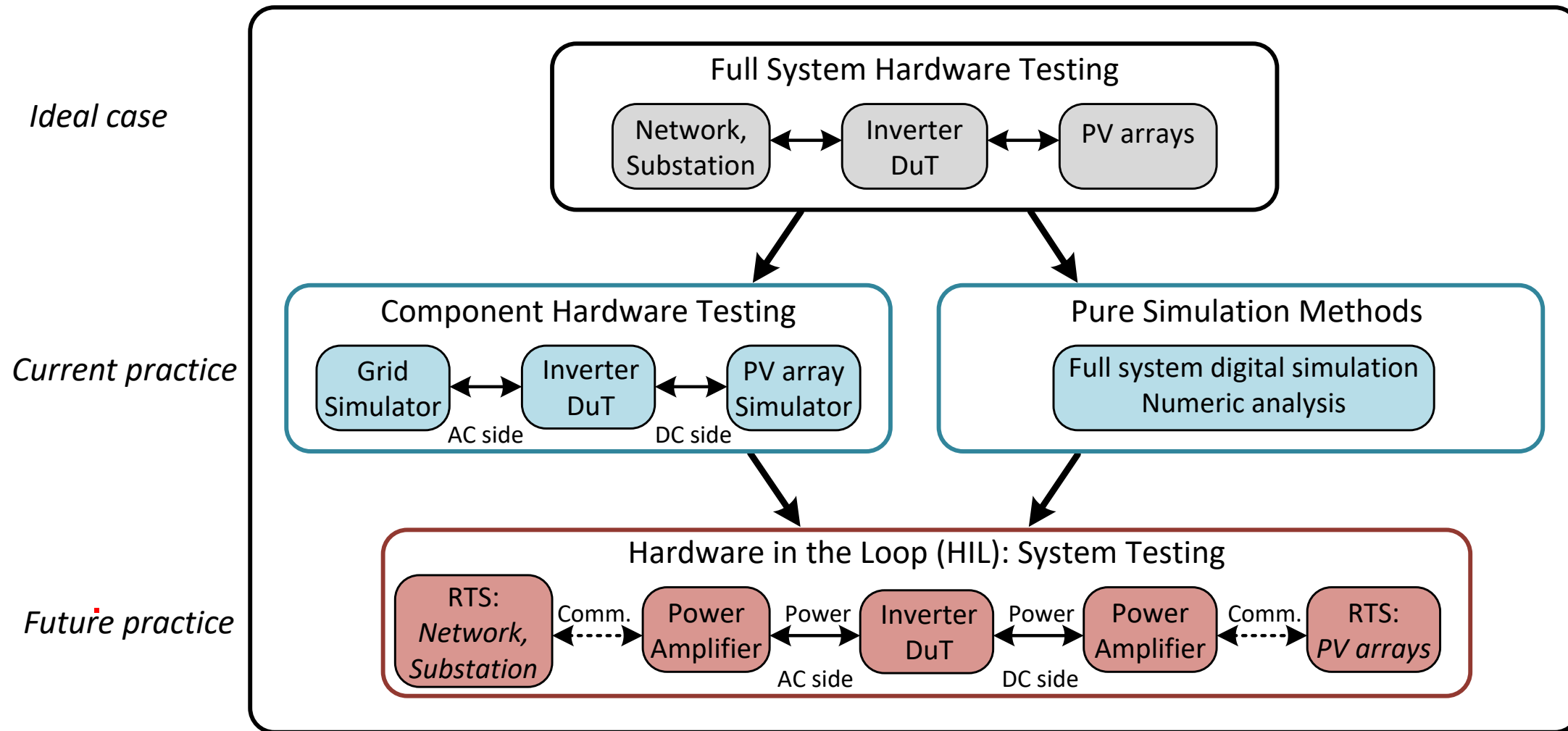
- Pre defined profiles
- Limited interaction



Laboratory experimental set-ups

- Typically specific functions
- Low flexibility, maintenance, damage, cost

Evolution of power system analysis and testing



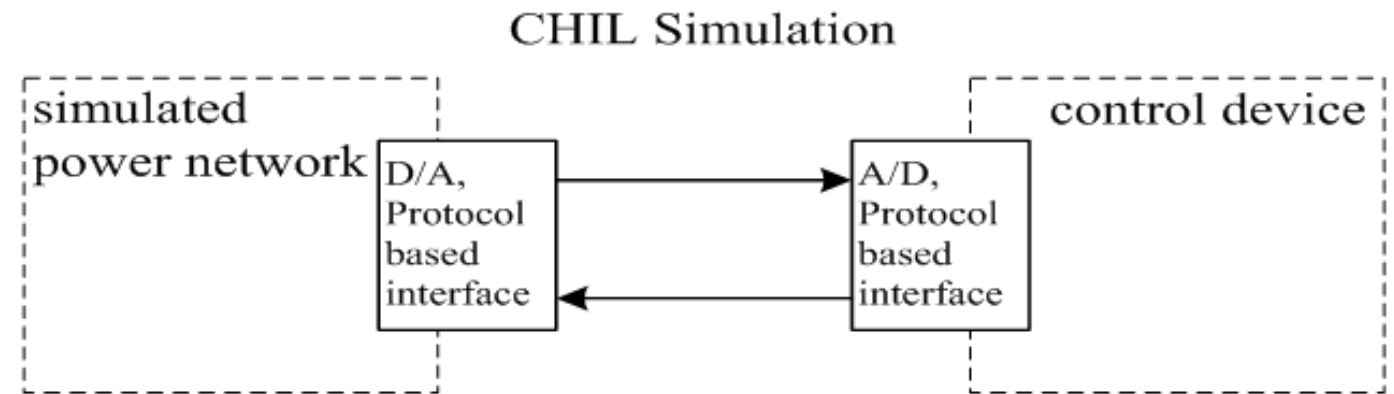
Hardware-in-the-Loop simulation

- Hardware equipment (e.g. relay, controller, motor, PV inverter) is incorporated into a simulated system
- Device under test works in real-time → the simulated system must be computed in real-time
- Digital Real-Time Simulator (DRTS):
 - computes the simulation model in real-time (e.g. power system: 50 us, power electronics 1-3 us)
 - offers Input / Output capabilities (Digital/Analog, Analog/Digital converters, etc)
- The benefits of simulation (e.g. flexibility) and experimental testing (e.g. use of the actual equipment) are combined
- Equipment can be tested repeatedly and economically under conditions as close as possible to the real operating conditions.



Controller Hardware in the Loop simulation (CHIL)

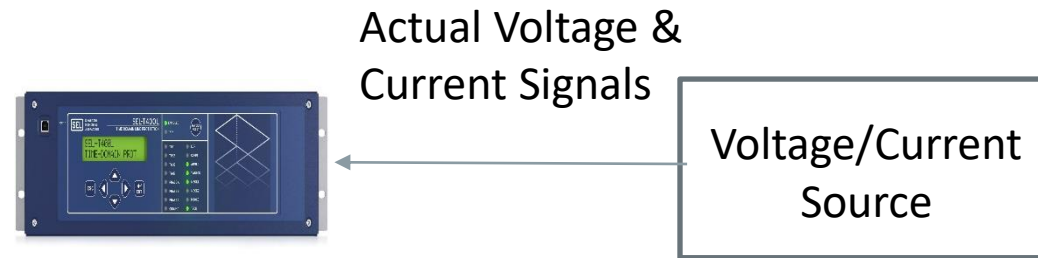
- Hardware control unit (e.g. inverter controller, digital relay, energy management system) is connected to a simulated system
- Communication:
 - Analog Inputs/Outputs
 - Digital Inputs/Outputs
 - IEC 61850 +...



Amplification of signals might be necessary (e.g. relay testing)

CHIL testing of protection relays

1) Conventional testing of digital relays



2) CHIL testing

- A power network is simulated in the DRTS
- Thousands of short circuits are performed safely and conveniently in simulation
- The relay is tested in real grid conditions: optimizing the relay settings. Identifying and avoiding problems.
- *"Like comparing a photograph to a movie" (SEL)*
- Interfacing:
 - Amplifiers
 - Low-level (direct connection to the control unit)
 - IEC 61850 (recent approach)

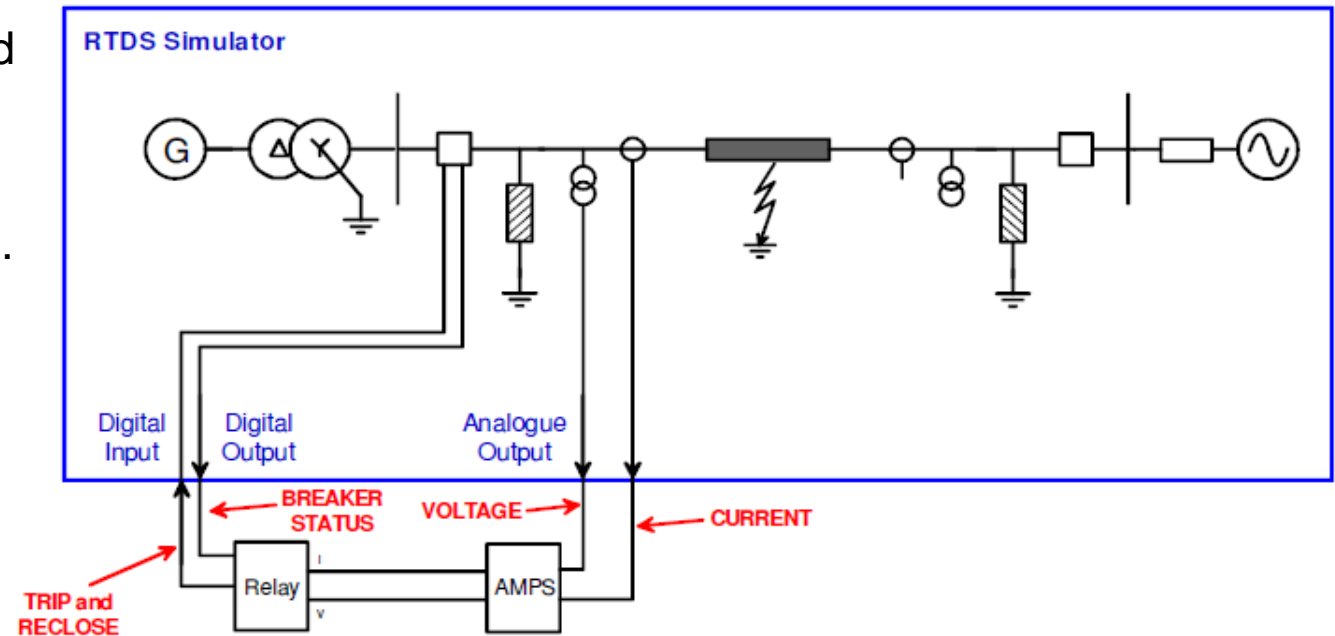


Figure 4: Closed-loop Protective Relay Testing

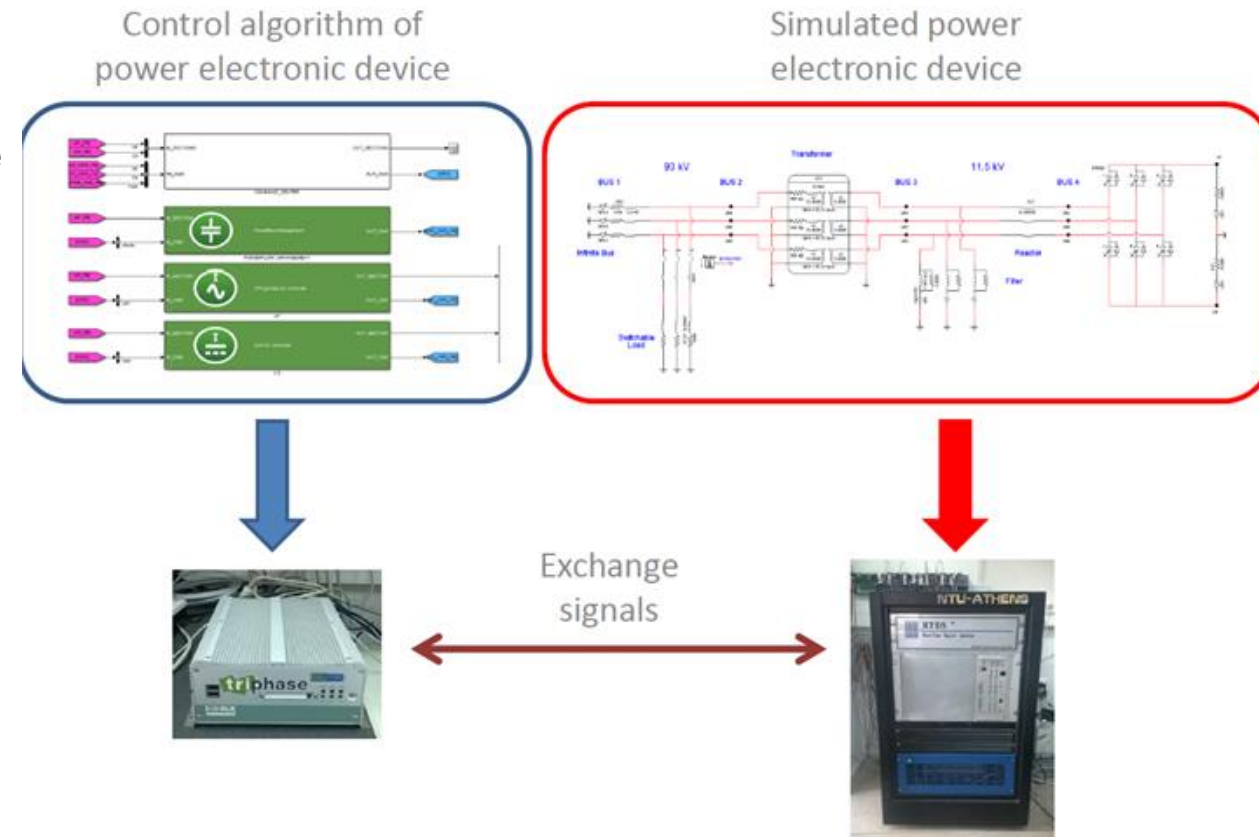
Utility applications of a RTDS Simulator” - Paul Forsyth, Rick Kuffel, RTDS Technologies Inc

CHIL testing of power electronic converter controllers

- Converter and network are simulated in the DRTS
- Control algorithm is running on a hardware controller
- DRTS sends measurements (voltage and current) to the controller
- The controller performs the control and sends the modulating signal of the converter back to the DRTS.

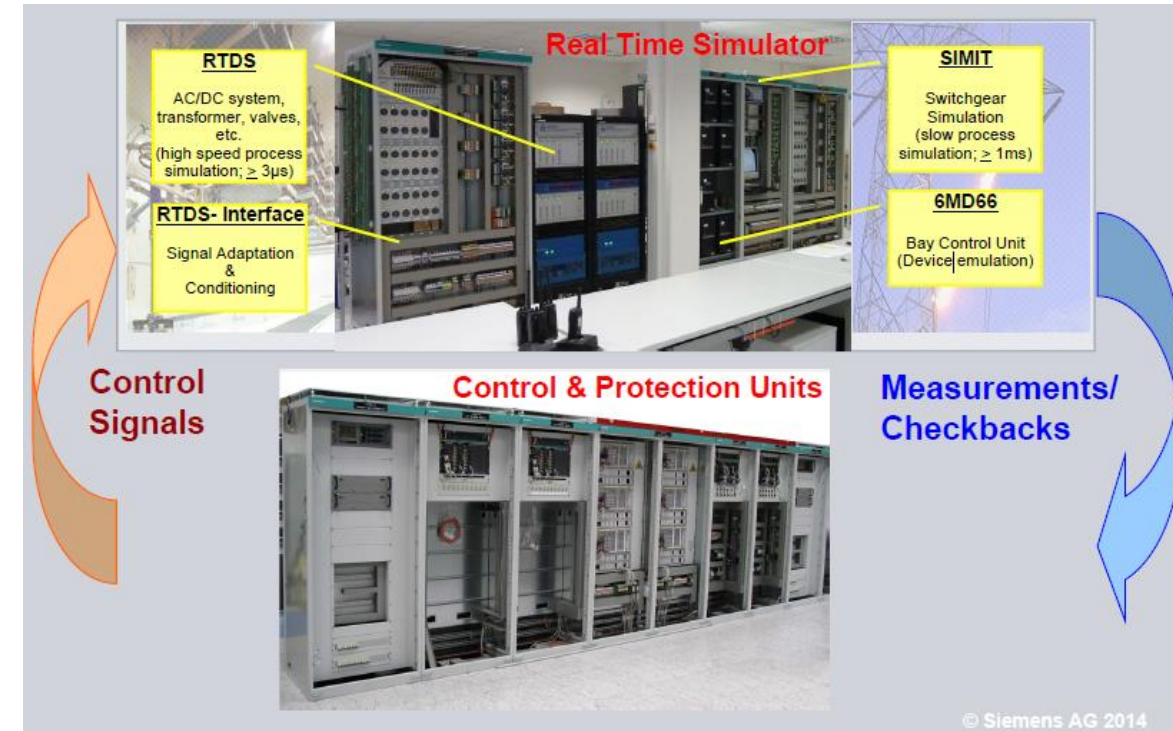
Advantages:

- Pure Simulation can't always model accurately real conditions (exact noise and time delays) properly.
- A stable control in simulation could be unstable in CHIL or hardware setup due to time-delays etc
- Implementation on the hardware controller,
- No risk of damaging the IGBT's, etc



CHIL testing of power electronic converter controllers

- Rapid prototyping (before the full hardware deployment): e.g. tuning of the hardware controller is possible in realistic and safe conditions.
- Reduced development cost
- CHIL has been adopted by industry:
 - CHIL testing of control and protection units of HVDC systems and FACTS
 - Testing of “Replica” HVDC systems
- Standardization efforts: pre-certify inverter's compliance for various international standards (A/T)



T. Timm, H. Schuldt, “Offsite Testing at Siemens AG HVDC”, RTDS European User’s Group Meeting, Lyngby, Denmark, 2014

CHIL testing of Supervisory Controllers (e.g. EMS/DMS)

Conventional Approach:

- Software Simulations: algorithm Validation
- Field-site Implementation –What if something goes wrong?

CHIL simulation:

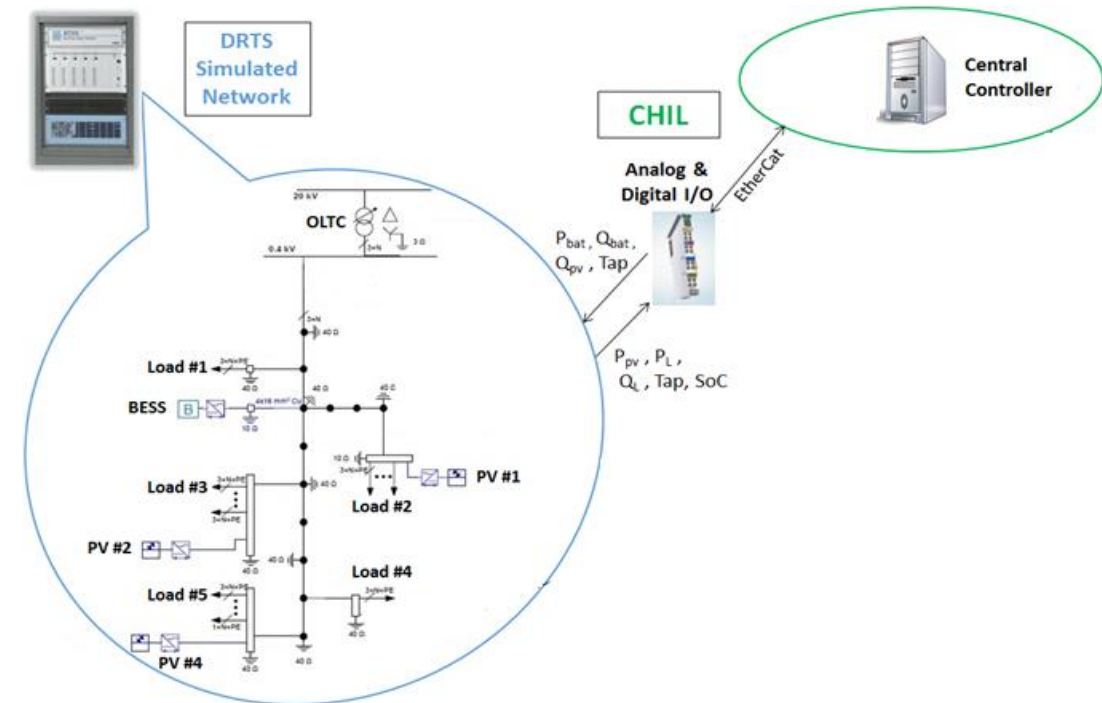
- Real Controller Implementation
- Dealing with communication issues between controller and hardware, implementation in real controller, delays etc

Testing of microgrid controllers:

- Pre-commissioning testing, risk reduction etc
- Compliance with new standards

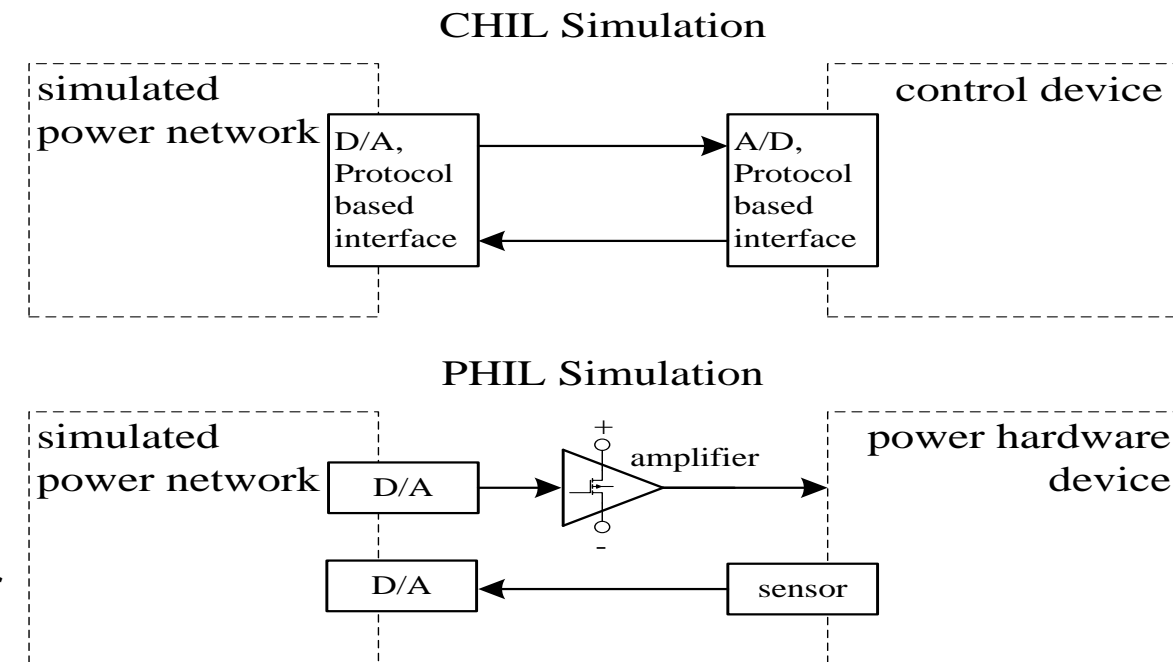
Other HIL applications:

Wide area protection and control, PMU, IEC 61850 device testing

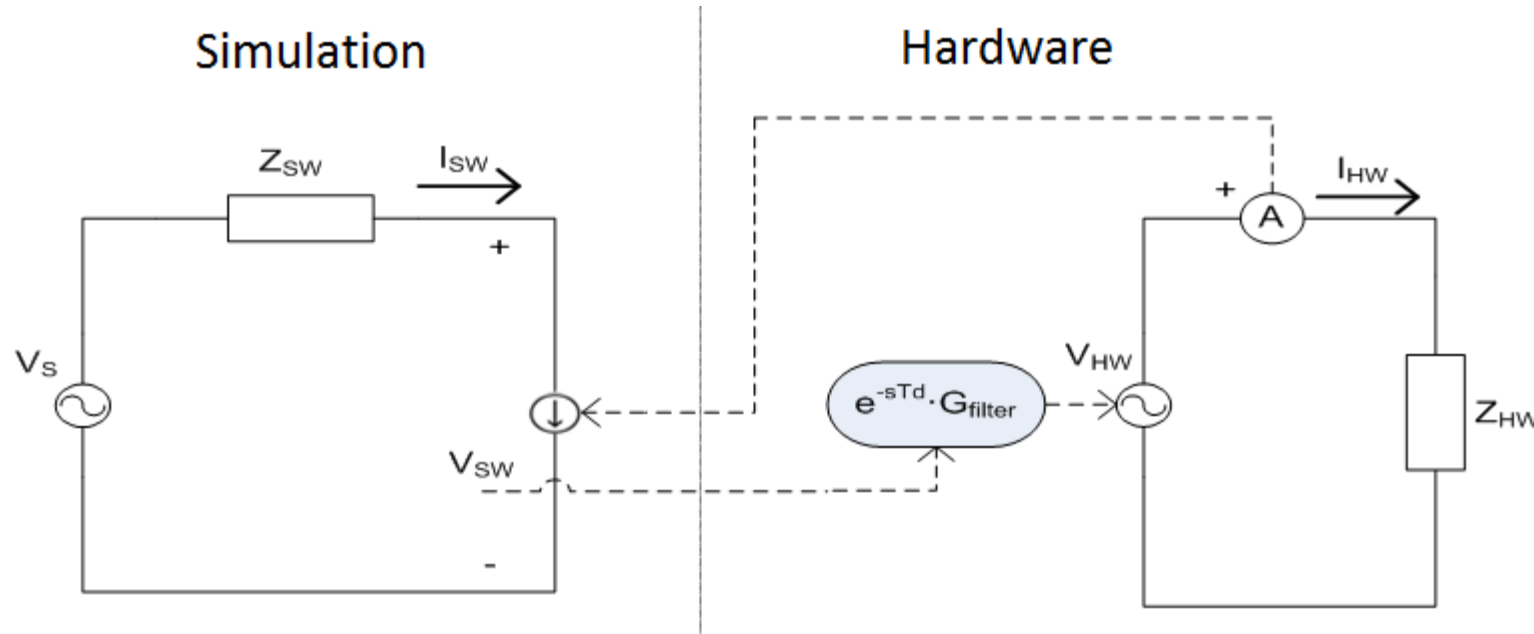


Power Hardware in the Loop (PHIL) simulation

- Hardware Power equipment is tested
 - A device that is hard to be modeled can be introduced as real hardware
 - Extreme Conditions can be studied with low risk
 - The device can be connected to the system where it is destined to operate
- DRTS handles low level signals (e.g. $\pm 10V$)
- A Power Interface is necessary:
 - **Amplifier:** Amplifies the low-level output signal of the DRTS
 - **Sensor:** measures the response of the Hardware Under Test (HUT) and sends it to the DRTS in-order to close the loop.

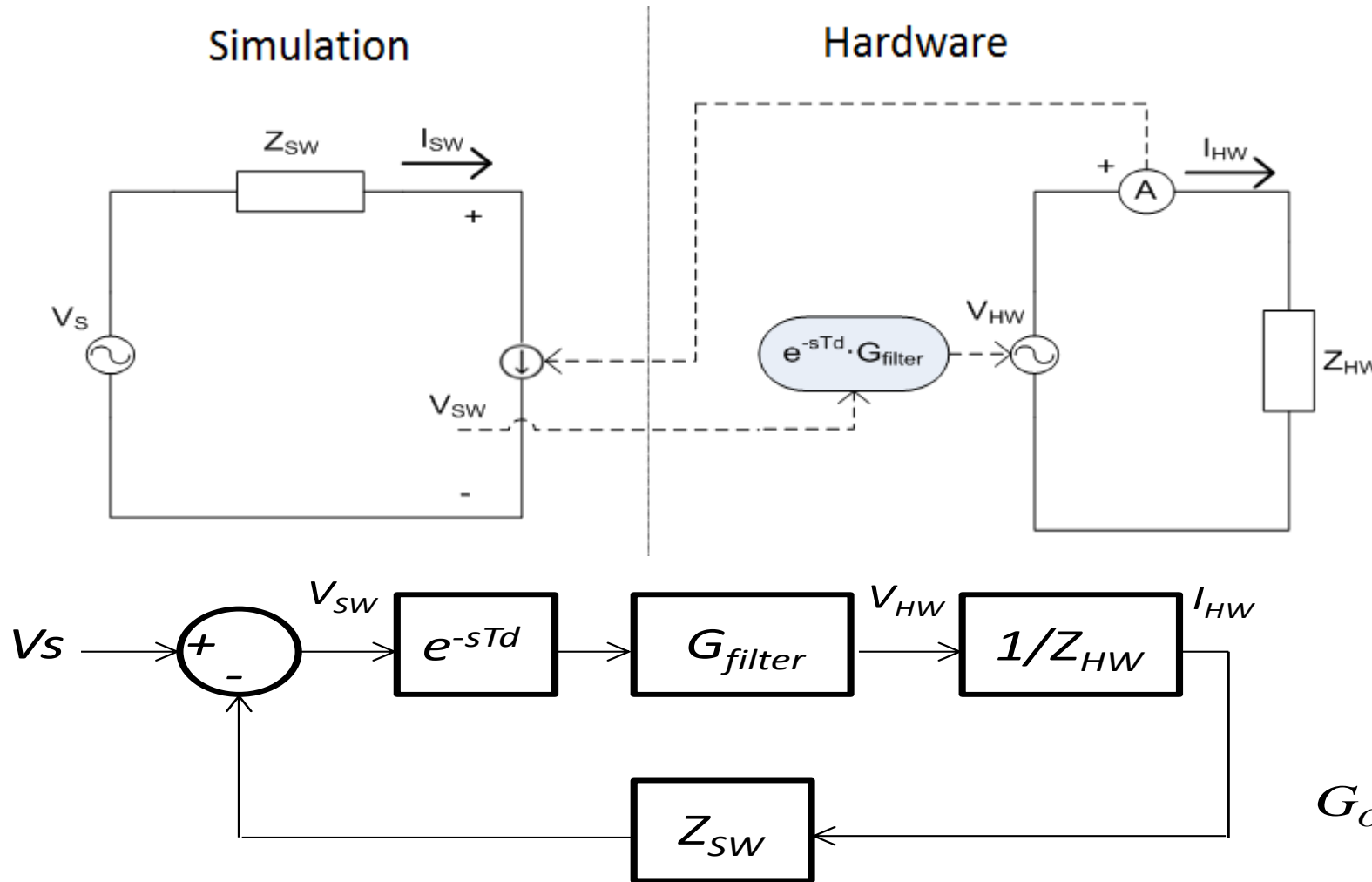


PHIL simulation topology



- The voltage of the common node (point of coupling) in the DRTS (V_{SW}) is the set-point for the Voltage amplifier
- The amplified Voltage $V_{HW} \approx V_{SW}$ is applied on the Hardware Under Test
- The current flowing in the Hardware Under Test (HUT) (i_{HW}) is measured and injected into the DRTS to close the loop.
- **The HUT is represented in the DRTS as a controllable current source**

Stability of PHIL simulation



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

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

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

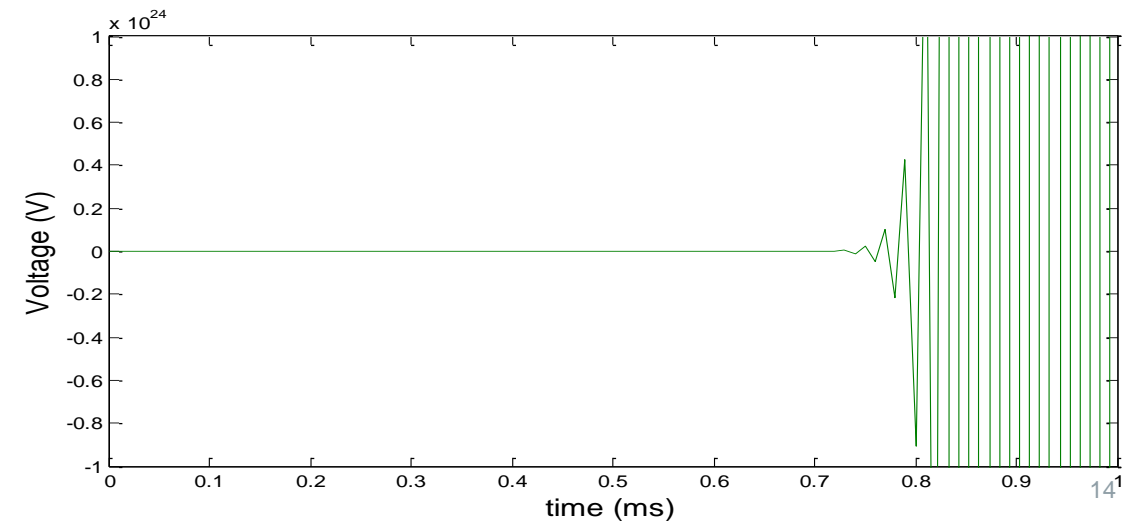
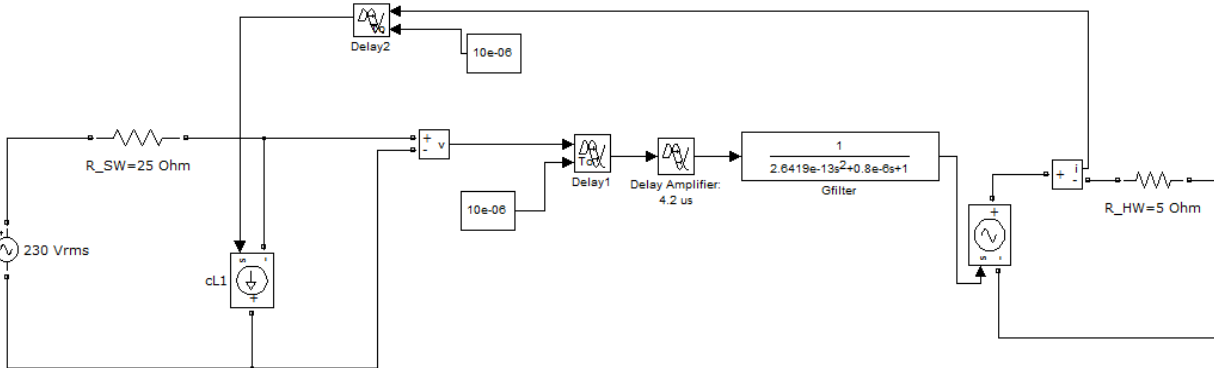
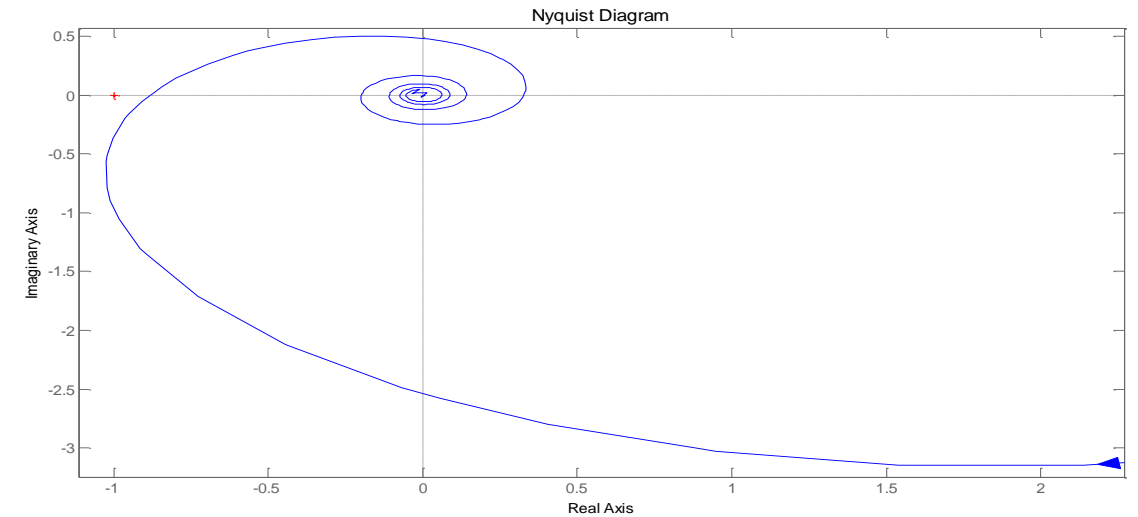
$$V_{SW} = V_s - I_{SW} \cdot Z_{SW}$$

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

- Possibility of instability due to the time-delay
- Instability may damage the Hardware under Test

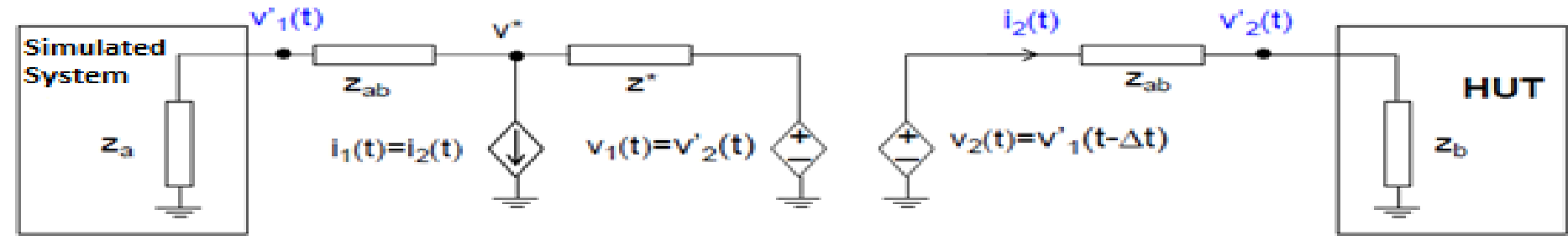
Estimating the stability of PHIL simulation

- Nyquist criterion:
- Routh-Hurwitz criterion : Time-delay approximation
 - Padé 1st order approximation (insufficient)
 - Padé 2nd order approximation
- Root locus (approximation is necessary)
- Virtual dynamic PHIL simulation



Achieving stability of PHIL simulation

- Interface Algorithms: Define the way to realize the interconnection of the Simulated System and the Hardware under test (specifies the topology)
 - Ideal Transformer Model (ITM), Partial Circuit Duplication (PCD), Damping Impedance Method (DIM) and others



- Software solutions
 - Low pass filter on the feedback current (AIT)
 - Time-delay compensation (USRAT)

May improve stability but decrease accuracy
- Multi-rate simulation (AIT)
- *Protection of the PHIL experiment is always necessary (software and hardware)*

Estimating the stability of PHIL simulation: Bode Stability Criterion

Bode Stability Criterion:

If at the phase crossover frequency ω_{pc} (namely, where the phase of $G(s)$ is equal to -180), the corresponding magnitude of $G(i\omega_{pc})$ is less than 0 dB, then the feedback system is stable.

In the simple example of a voltage divider the conditions that should be satisfied are the following:

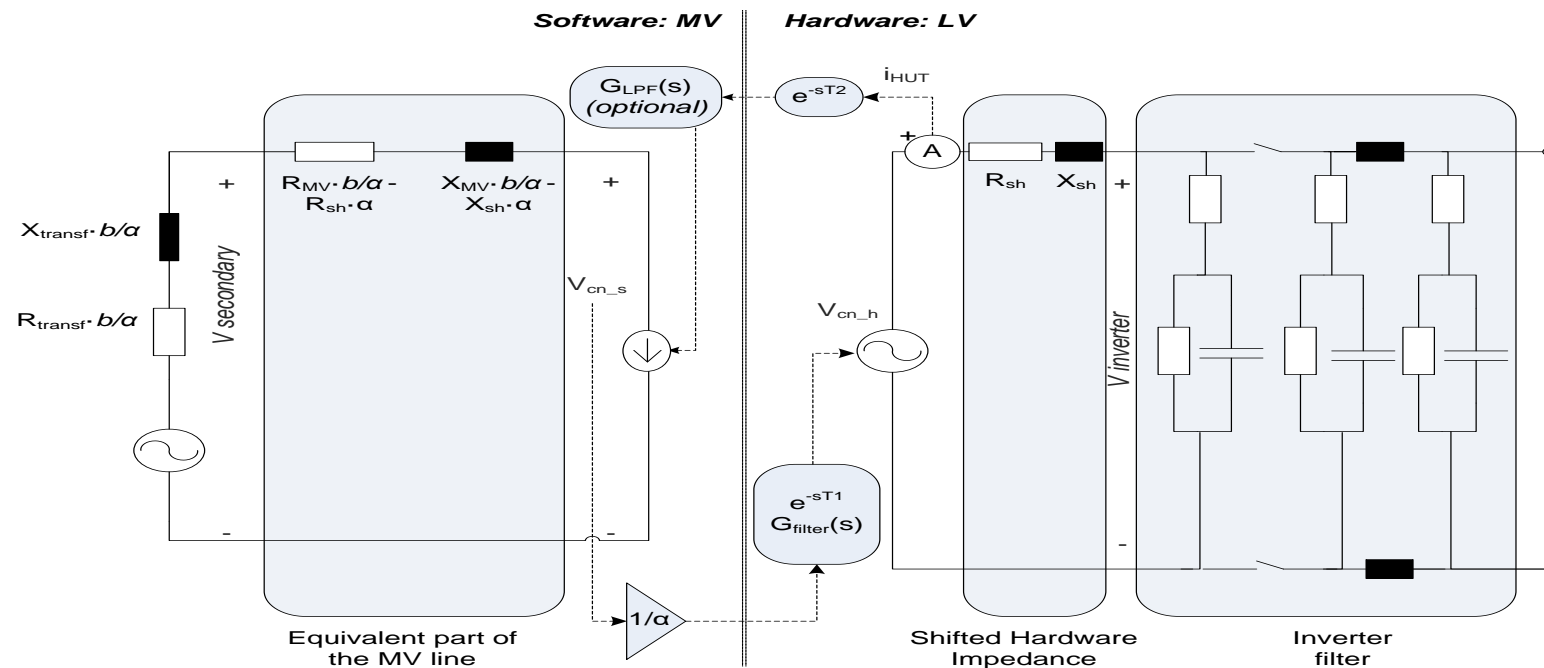
$$\sqrt{\frac{R_s^2 + L_s^2 \omega^2}{R_h^2 + L_h^2 \omega^2}} \leq 1 \quad \arctan\left(\frac{\omega L_s}{R_s}\right) - \arctan\left(\frac{\omega L_h}{R_h}\right) - \omega T_d = \pi$$

- **No approximation for the time delay is needed**
- Calculation of the marginal values of the feedback current filter in order to achieve stability
- The method was validated experimentally
- More complex cases have been analyzed

A. Markou, V. Kleftakis, P. Kotsampopoulos, N. Hatziaargyriou, "Improving existing methods for stable and more accurate Power Hardware-in-the-Loop experiments", IEEE ISIE 2017 conference, Edinburgh, June 2017

Shifting Impedance Method: achieving stability, while maintaining accuracy

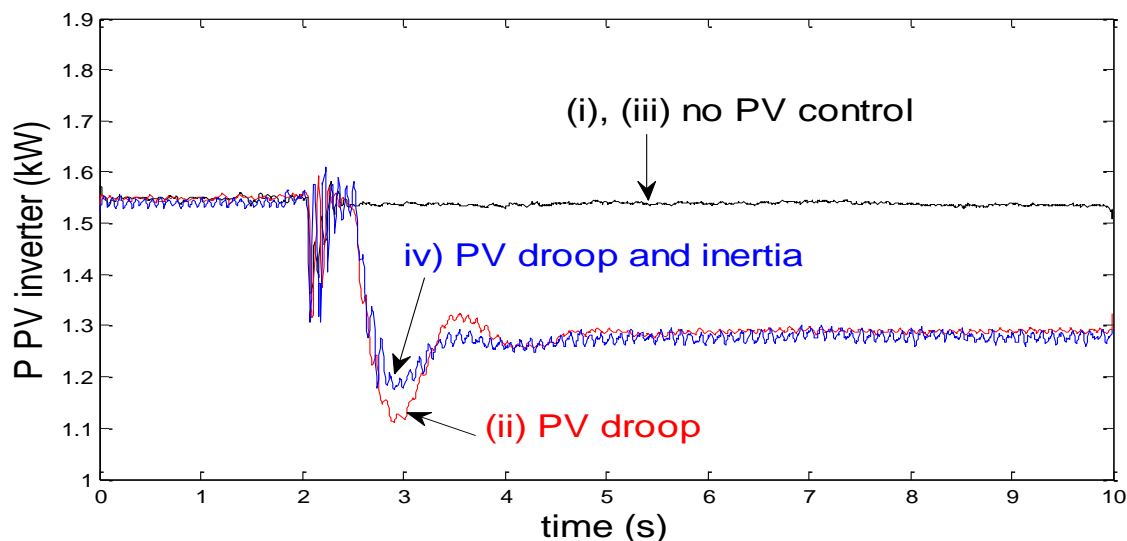
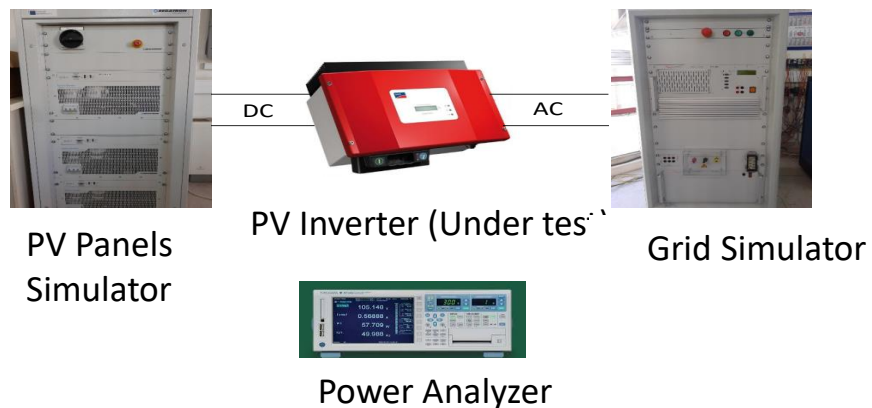
- Shifting part of the software impedance on the hardware side. Stability can be achieved without compromising accuracy (if necessary a “smaller” feedback filter can be used)
- PHIL allows scaling of the software and hardware. A small LV PV inverter is used to evaluate the integration of a large PV park connected to the MV. The grid voltage control algorithm of the full and reduced-scale DGs are exactly the same.



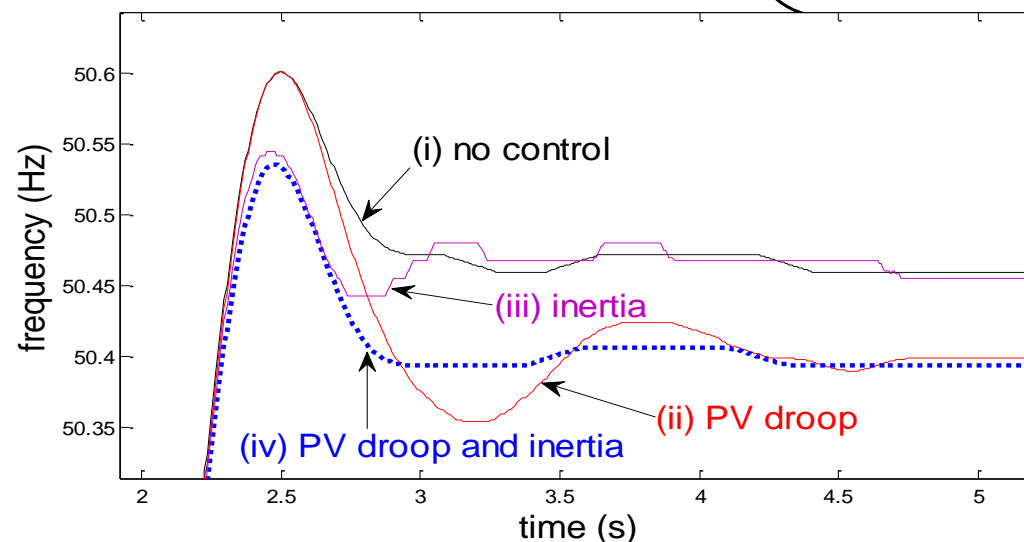
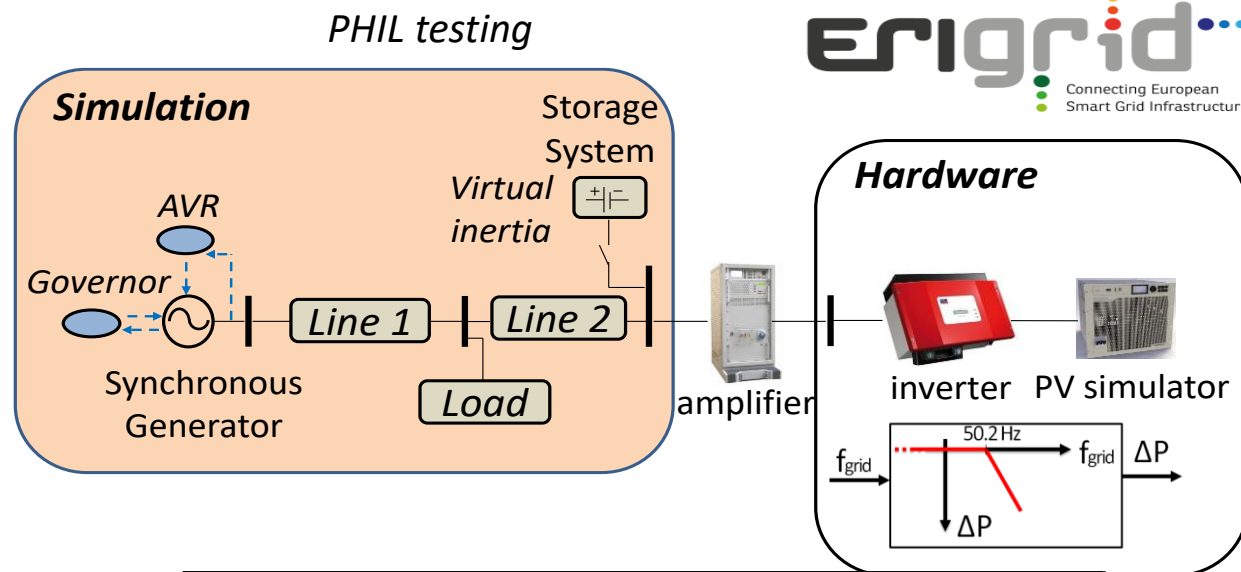
P. Kotsampopoulos, F. Lehfuss, G. Lauss, B. Bletterie, N. Hatziargyriou, “The limitations of digital simulation and the advantages of PHIL testing in studying Distributed Generation provision of ancillary services”, IEEE Transactions on Industrial Electronics, 2015

PHIL testing example

Conventional testing: Open-loop, no feedback from the device



- PHIL testing: **System level testing** (not only the inverter is tested but also its impact on the system).
- The full hardware implementation would be challenging. Additional devices can be simulated



PHIL simulation for Laboratory Education

- Laboratory education in the power systems domain is usually performed with software simulations and more rarely with small hardware setups with limited capabilities (contrary to other domains e.g. electric machines)
- The students have limited familiarity with real hardware power systems
- PHIL simulation can provide to students hands-on experience with real hardware, while maintaining the advantages of the digital simulation (flexibility etc)
 - Real Time system in front of the students: monitor and control
 - Connection of real hardware: actual measurements and equipment control
 - Implementation of demanding tests, such as faults. The students can change the position/type of the fault etc.
- CHIL simulation has already been used in the education of engineers
- The use of the PHIL method for education hadn't been investigated yet in a systematic way

Hands-on Laboratory education using PHIL

- Experiential education: educators engage their students directly to the object of knowledge and later on to a focused reflection relative to that experience
- Kolb's four-stage learning cycle (1984)

- Example:

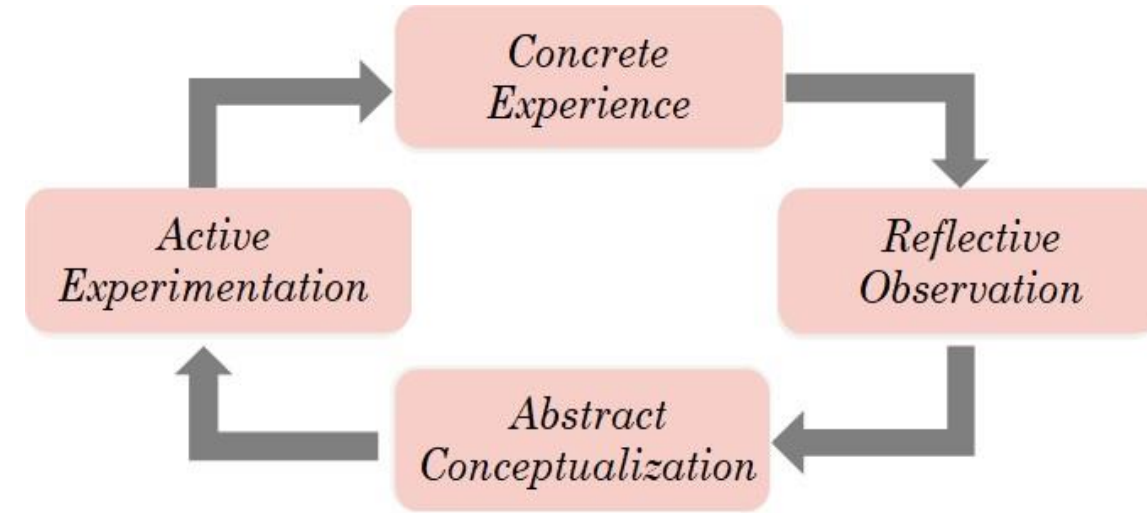
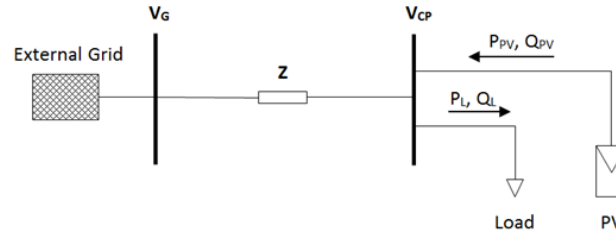
i) Observe voltage rise

(**concrete experience**)

ii) Understand the problem (**reflective observation**)

iii) Solution: reactive power absorption (**abstract conceptualization**)

iv) Send reactive power set-points (**active experimentation**)



Aims to bring the students to the hardware lab

Double PHIL configuration (small groups). Equipment that was not available was simulated

IEEE WG P2004: Recommended Practice for Hardware-in-the-Loop (HIL) Simulation Based Testing of Electric Power Apparatus and Controls

- No standard exists that provides guidance and recommends best practices for the application of HIL simulation

IEEE WG P2004:

- Brings together all the relevant stakeholders
- Serves as a platform to further promote HIL
- Will establish practices for real-time simulation model development
- Will provide guidance on requirements for power amplifiers, DRTS, HIL interface algorithms for classes of HIL testing needs
- etc

Chair: Mischa Steurer (CAPS-FSU)

Co-chair: Georg Lauss (AIT)

Secretary: Blake Lundstrom (NREL)

Get involved

Conclusions

- Active distribution networks require advanced testing and simulation methods
- Advanced control algorithms should be validated at a power system context
- CHIL simulation is an advanced tool for testing digital relays, converters and supervisory controllers
 - Tests the controller in realistic conditions (time delays, noise, real hardware controller implementation) and validates its operation almost risk-free
 - Already adopted by industry
- PHIL simulation is a newer and more complex method:
 - Stability and accuracy issues
 - It assesses the hardware-under-test behavior in more complex conditions, e.g. with other equipment, under faults, etc. **System level testing**
 - *At cases, PHIL simulation can reveal interactions not visible at pure simulation*
 - Beneficial for education/training purposes
- HIL simulation is/must/will be considered for future standardized testing



Thank you for your attention!

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