# WEBINAR | P-HIL Simulation

## for Power Systems and Power Electronics Applications

OPAL-RT TECHNOLOGIES

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# WEBINAR OUTLINE

1. Introduction
2. **Dr. Sudipta Chakraborty**
   What is Power Hardware-in-the-Loop (PHIL)
3. **Jay Jonhson and Adam Summers**
   Hardware-in-the-Loop Simulations of PV Inverter Distribution Voltage Regulation
4. **François Tempez**
   Focus on European PHIL projects from OPAL-RT users
5. **Mathieu Haineault**
   OPAL-RT Product Announcement
6. Question Period

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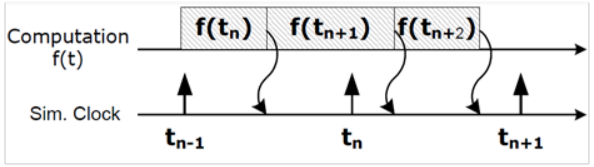
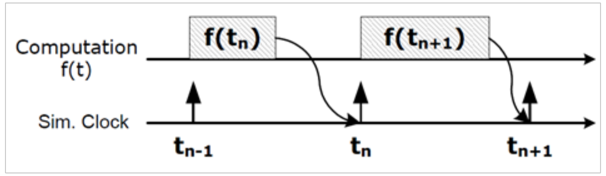
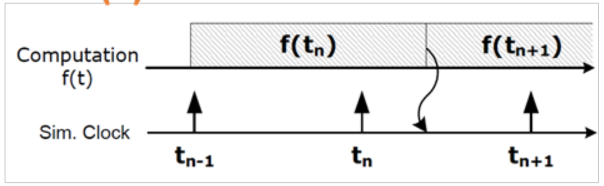
# REAL-TIME SIMULATION

| (*A*) Faster-than-Real-Time   | (*B*) Real-Time   | (*C*) Slower-than-Real-Time   |
|---|---|---|
| Can be achieved with ***desktop/offline simulations*** (simpler models only) | Strictly requires an ***RTS***. Studies with or without HIL can be performed. | Usually the case of ***desktop/offline simulations*** |
| Can be achieved with an ***RTS*** (***Accelerated*** mode, where model allows for clock acceleration) | Hardware-in-the-Loop (***HIL***) is the general term for test applications of an ***RTS*** | Best achieved with an ***RTS*** with complex models (***Accelerated*** mode, where model is too complex for running in RT, but the RTS allows for faster simulation than desktop simulation) |
| | Controller HIL (***CHIL***) | |
| | Rapid Control Prototyping (***RCP***) | |
| | Power HIL (***PHIL***) | |
| ← | Software-in-the-Loop (***SIL***) | → |

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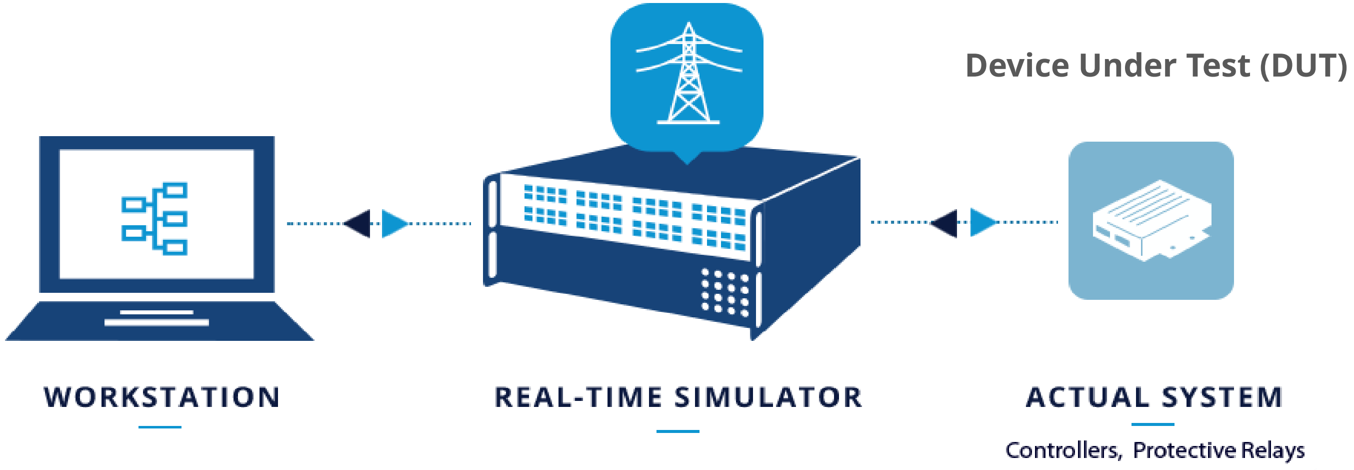
# HARDWARE-IN-THE-LOOP (HIL)

- Hardware-in-the-loop (HIL) testing utilizes real-time simulation to connect and test actual hardware devices with simulation of the rest of the systems and test environments
- This allows users to perform realistic closed-loop tests without the need for testing on a real system
- While HIL typically refers to setups with low-voltage level signal connections, power hardware-in-the-loop (PHIL) can be employed for higher power testing




DUT Examples

- Controllers
  - SCADA, EMS, DMS, Microgrid controllers
  - Power electronics controllers
  - Vehicle ECU
- Intelligent Electronic Devices
  - Protection devices
  - "Smart" sensors

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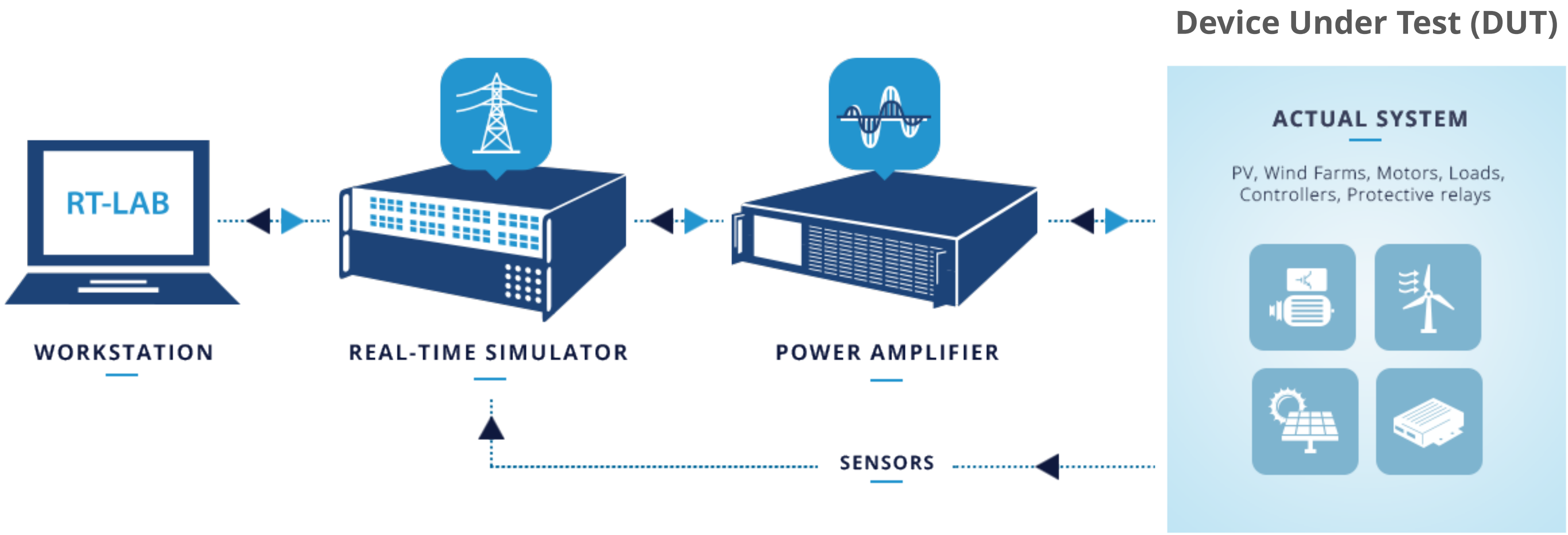
# POWER HARDWARE-IN-THE-LOOP (PHIL)

- Power hardware-in-the-loop (PHIL) involves in creating a virtual power interface between the digital simulation and devices under test
- Typically, the power interface involves power amplifiers (voltage and/or current), which must be selected carefully depending on the application
- PHIL setup is more complex and typically much costlier due to cost of amplifier and sensing hardware




DUT Examples

- Power converters (inverters, rectifiers, power supplies)
- Electric machines and drives
- Microgrid switch and PCC
- Batteries including BMS
- Electrical drivetrain for EV
- Vehicle charger

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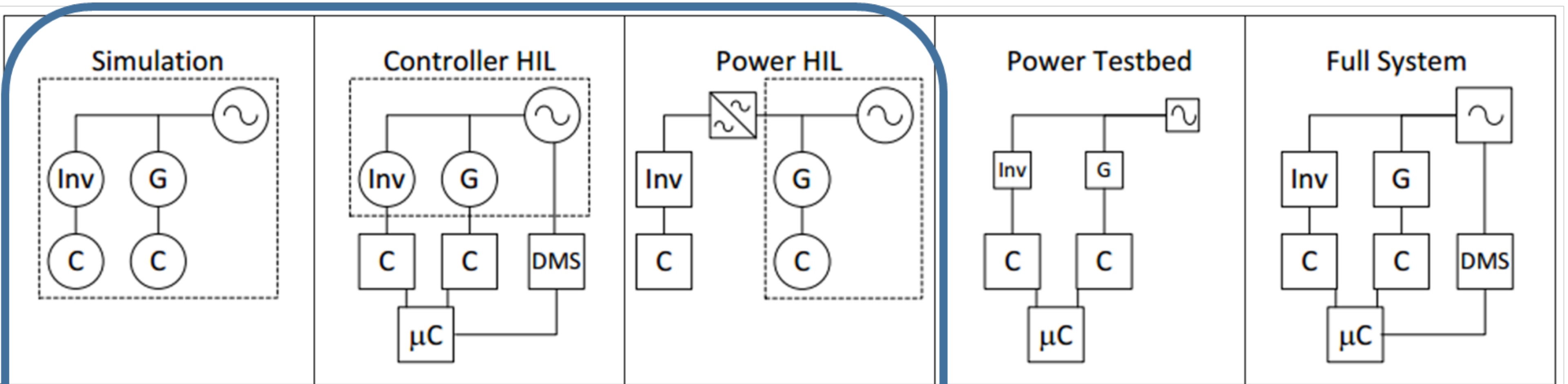
# TRADEOFFS BETWEEN TESTBEDS

## Applications of a Real-Time Simulator (RTS)

*Figure modified from the concept originally proposed by MIT-LL [1]*




| | Simulation | Controller HIL | Power HIL | Power Testbed | Full System |
|---|---|---|---|---|---|
| Testbed cost | - | +/- | + | ++ | +++ |
| Test Fidelity | - | + | ++ | +/- | +++ |
| Test Coverage | + | +++ | ++ | +/- | - |

- **Test fidelity** depends on purpose of testing, model validity and test setup. For Power Testbed, fidelity depends on equipment used and similarities between that and the real installation.
- **Test coverage** depends on purpose of testing and flexibility of running various 'what-if' scenarios. Pure simulation does not allow testing of real devices; but with good models, it is a powerful tool for design studies. CHIL provides the best coverage for testing control systems, such as micorgrid controller, allowing fault scenarios, transitions and dispatch scenario functional testing.
- **PHIL** can provide good balance between test fidelity and test coverage at a cost that is lower than full-system testing.

[1] R.O. Salcedo, J.K. Nowocin, C.L. Smith, R.P. Rekha, E.G. Corbett, E.R. Limpaecher, J.M. LaPenta, TR-1203: Development of a Real-Time Hardware-in-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers, MIT Lincoln Laboratory, Lexington, MA, Feb. 2016.

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# BENEFITS OF PHIL



- PHIL allows developers to test a wider range of device characteristics than analog benches or dynos with less maintenance and setup time
  - Allowing robustness of the hardware under test over a wider variation of parameters, test conditions and faults

- In addition to interacting with the hardware, PHIL testing allows incorporation of real-world communication networks (Modbus, DNP3, 61850, etc.)
  - Allowing incorporation of real-world delays, latencies, cyber-events into the system-level validation

- PHIL creates a robust, flexible and reliable test platform
  - Allowing validation of complex, system-level, dynamic interactions between multiple devices, at-power, without costly field demonstration or detailed device models
  - Enabling tests that are not feasible or too risky to do with the real system (e.g. fault on feeder, over-speed on motors etc.)

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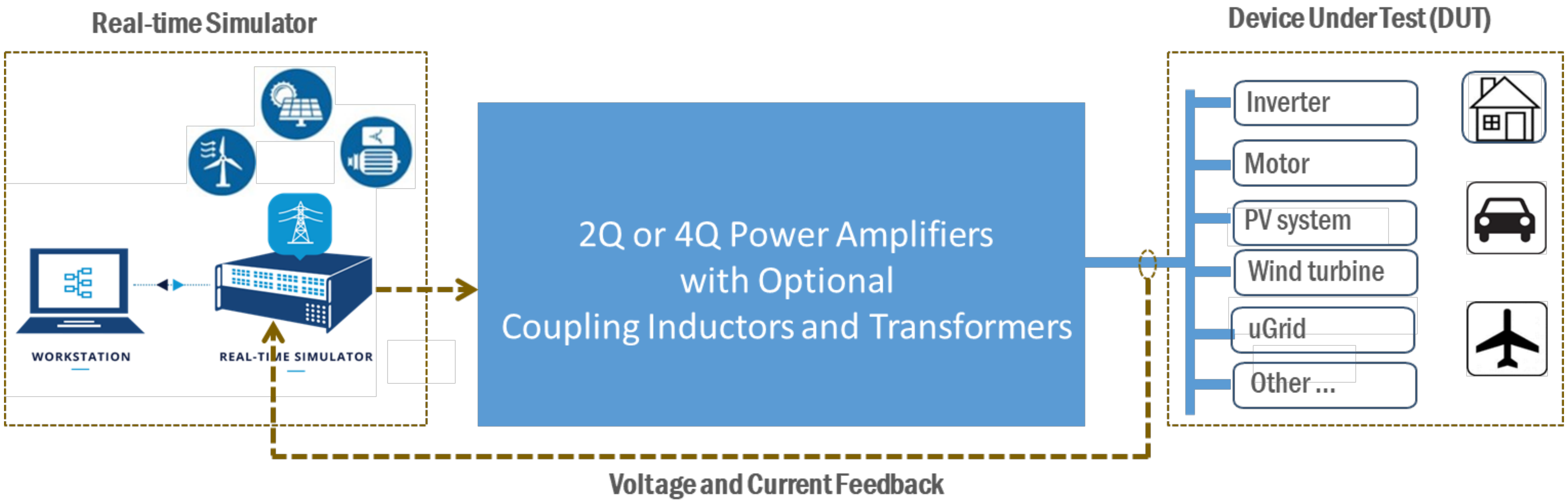
# TYPICAL PHIL SETUP



- Amplifier
- Real-time simulator with inputs and outputs
- Sensors for feedback to simulator
- Real-time models along with interface algorithms, filtering, compensation, protection, etc.



# AMPLIFIERS

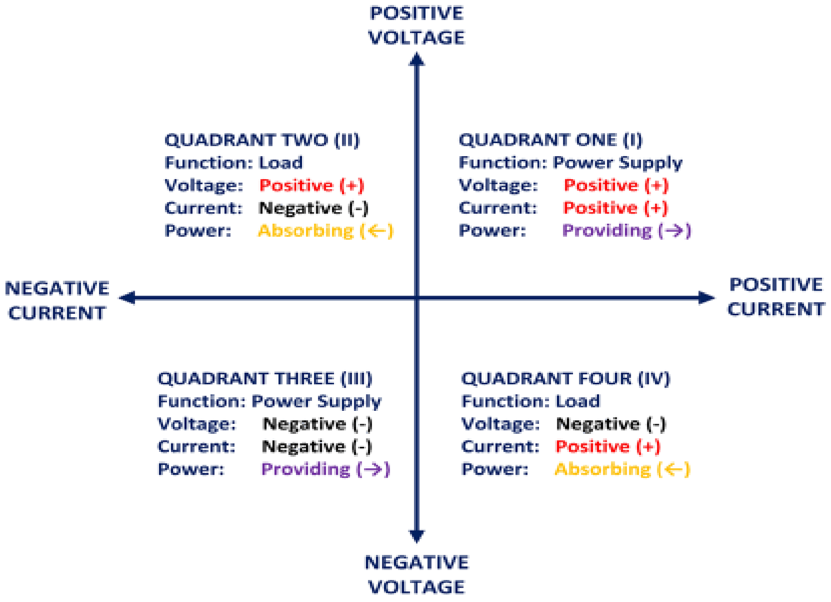


- Amplifier selection is technical and is extremely sensitive to the application

## Sample Specifications

- Application : Motor / Grid / Inverter
- Power rating
- Number of phases
- Capabilities : AC / DC / AC-DC
- Type : 2Q / 4Q and Linear / Switching
- Nominal voltage, current and peak current
- Nominal frequency
- Frequency range
- Frequency resolution
- Output Impedance
- Harmonic distortion
- Amplifier slew rate
- Amplifier control type : Analog Out / SFP
- Feedback Measurement : Internal / External
- Parallel or series connection capabilities
- Amplifier size and weight
- Price range

## 2Q vs. 4Q Amplifiers




- 2Q amplifiers only generate power – requires additional sink (loads) for some applications
- 4Q amplifiers generates and absorbs power – more flexible and common now-a-days
- Not all amplifier can absorb 100% power

## Linear vs. Non-linear

| Linear | Non-Linear |
|---|---|
| • Voltage/Current amplifier<br>• Higher bandwidth<br>• Faster response<br>• Lower flexibility<br>• Bulky<br>• Costly | • Switched mode<br>• Lower bandwidth<br>• Slower response<br>• Higher flexibility<br>• Smaller<br>• Less costly<br>• Higher power |

## Example of Amplifier

AMETEK | EGSTON POWER | SPHEREA PUISSANCE PLUS | triphase | Chroma Systems Solutions | SPITZENBERGER SPIES

**And a newest one!!**
**You will hear about it later**

# OTHER CONSIDERATIONS FOR PHIL TESTING

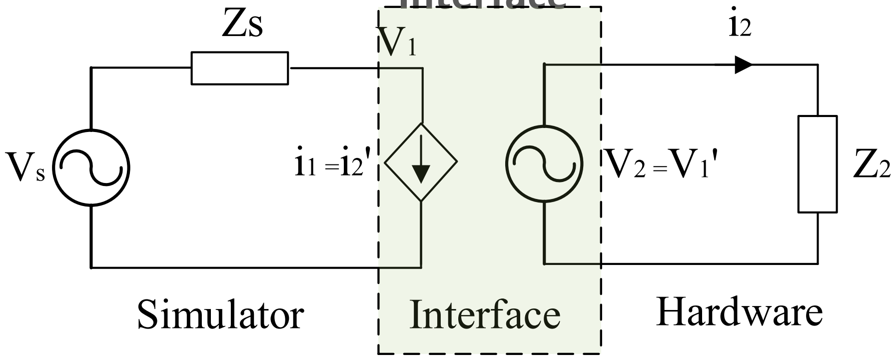


- Interface algorithms

  Ideal Transformer Model (ITM), Damping Impedance Method (DIM), Transmission Line Model (TLM), Partial Circuit Duplication (PCD), Time-variant First-order Approximation (TFA) [2]

- Filtering and compensation
  - Noise due to sensors, EMI/EMC can create issues in interfacing – introducing filters create unwanted delay and attenuation
  - Compensation algorithms often required to mitigate filtering effects

**Example of ITM Interface**




- Stability analysis
  - Closed loop PHIL system, including simulation, amplifier, sensors, can become unstable for certain operating conditions
  - Instability may damage equipment or result is loss of simulation fidelity

[2] W. Ren, M. Steurer, T. L. Baldwin, Improve the Stability and the Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms, IEEE/IAS Industrial & Commercial Power Systems Technical Conference, 2007.

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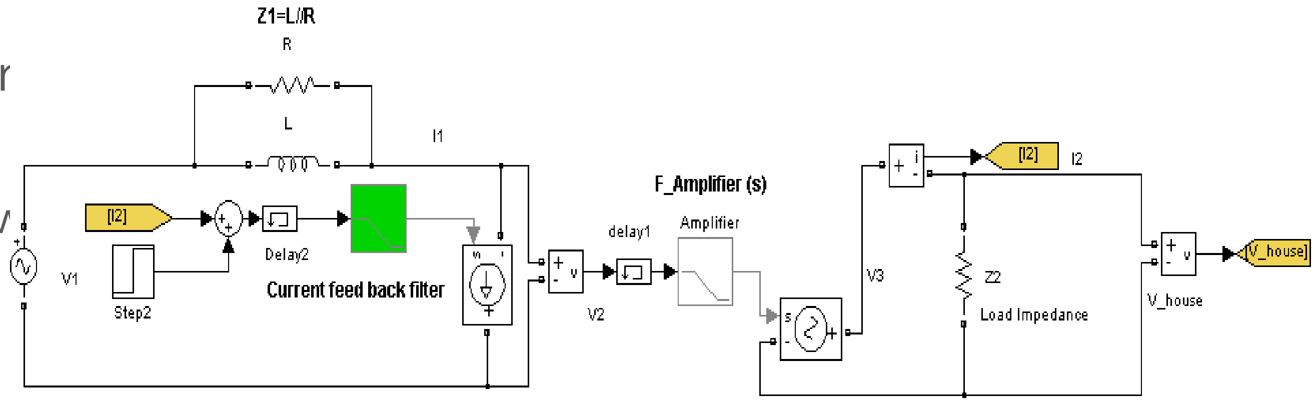
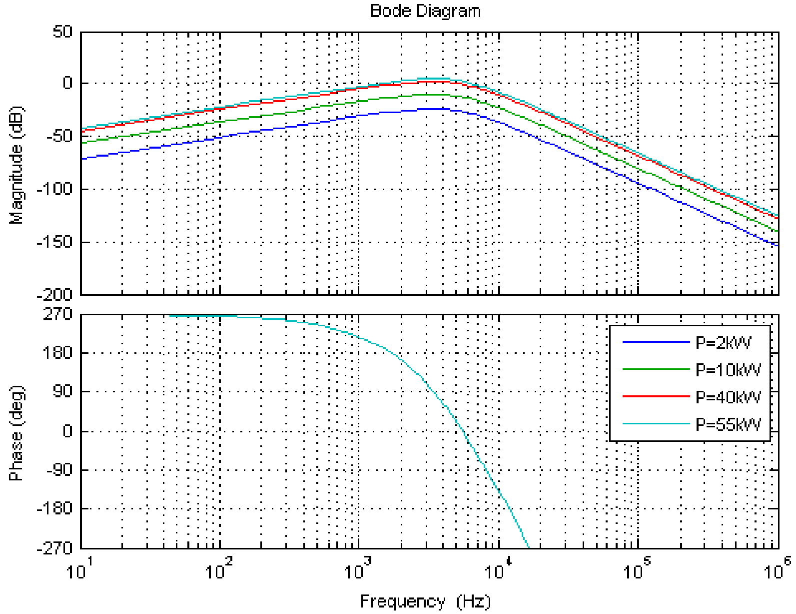
# PHIL STABILITY ANALYSIS

- Example shown here is based on ITM inter
- Stability depends on :
  - Ratio of load power to short-circuit pov
  - Type of load
  - Damping of source impedance
  - Power amplifier bandwidth
  - Simulator's sampling frequency
  - Use of current feedback filter
- Various methods for stabilization for ITM can be found in [3]




Determining the best interface and stabilization methods to ensure system stability and maximum accuracy must be done on a case-by-case basis

[3] A. Viehweider, G. Lauss, L. Felix, Stabilization of Power Hardware-in-the-Loop simulations of electric energy systems, Elsevier Simulation Modelling Practice and Theory, August 2011.

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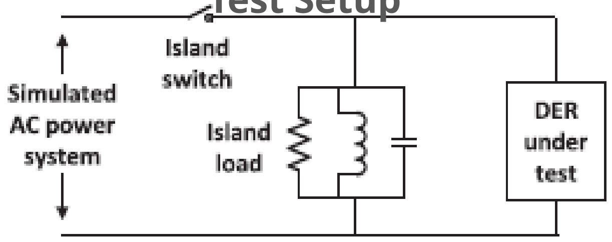
# PHIL EXAMPLE – INVERTER TESTING

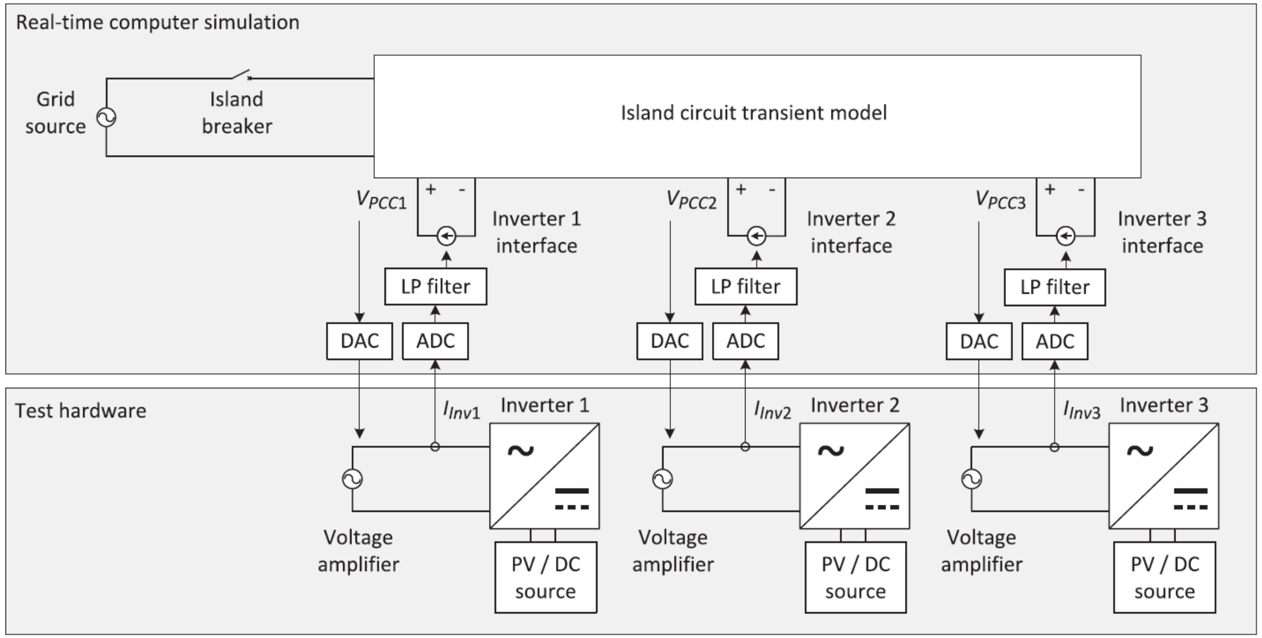


- Multi-inverter islanding detection test platform [4]:
  - Efficient testing of a large number of island configurations simply by changing the distribution circuit model in the real-time simulator
  - Detailed models for the smart inverters are no longer required ("black box" approach)
  - Validation of islanding detection capability of the inverters with advanced grid support functions (VVAR, FWATT etc.)

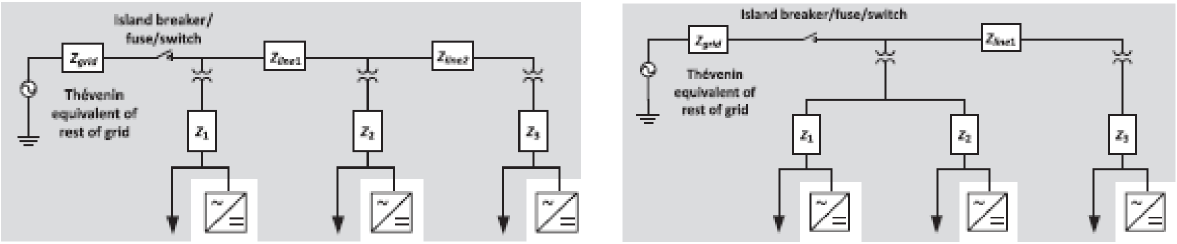
**Conventional Islanding Detection Test Setup**




**PHIL Test Setup for Multi-inverter Islanding Detection Test**




**Example Test Cases**




[4] A. F. Hoke, A. Nelson, S. Chakraborty, F. Bell, M. McCarty , An Islanding Detection Test Platform for Multi-Inverter Islands Using Power HIL, IEEE Transactions on Industrial Electronics, Oct. 2018.

# PHIL EXAMPLE – ADMS TESTBED

- Flexible testbed for Advanced Distribution Management System (ADMS):
  - Model large scale distribution systems for evaluating ADMS applications
  - Integration of real-time phasor-domain and electromagnetic transient simulations along with communication protocols
  - Integration of distribution system hardware and distributed energy resources for CHIL and PHIL experimentation
  - Multi-time scale, multi-platform test setup involving actual power and control hardware

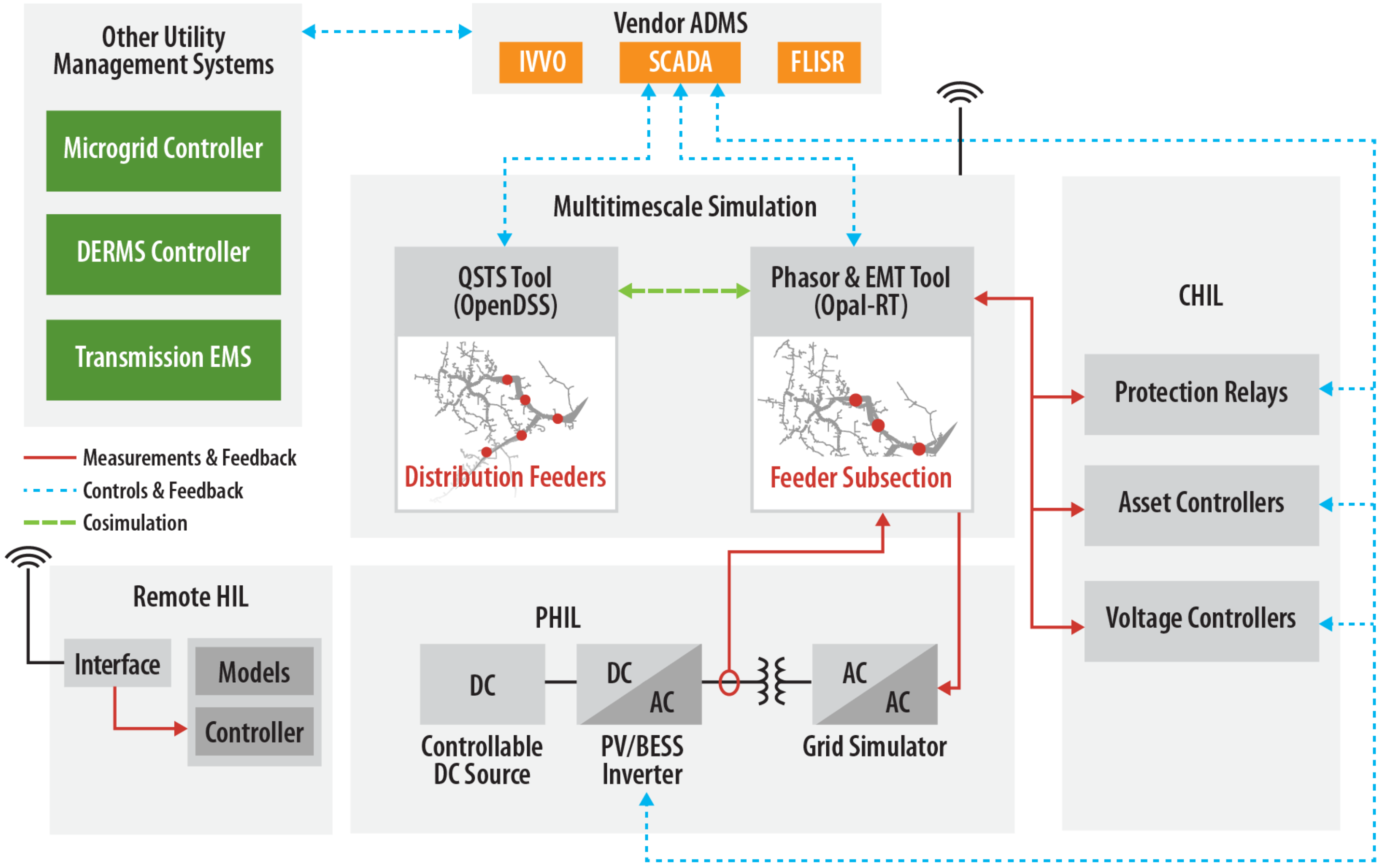



Figure source: NREL (from 2018 ISGT presentation)

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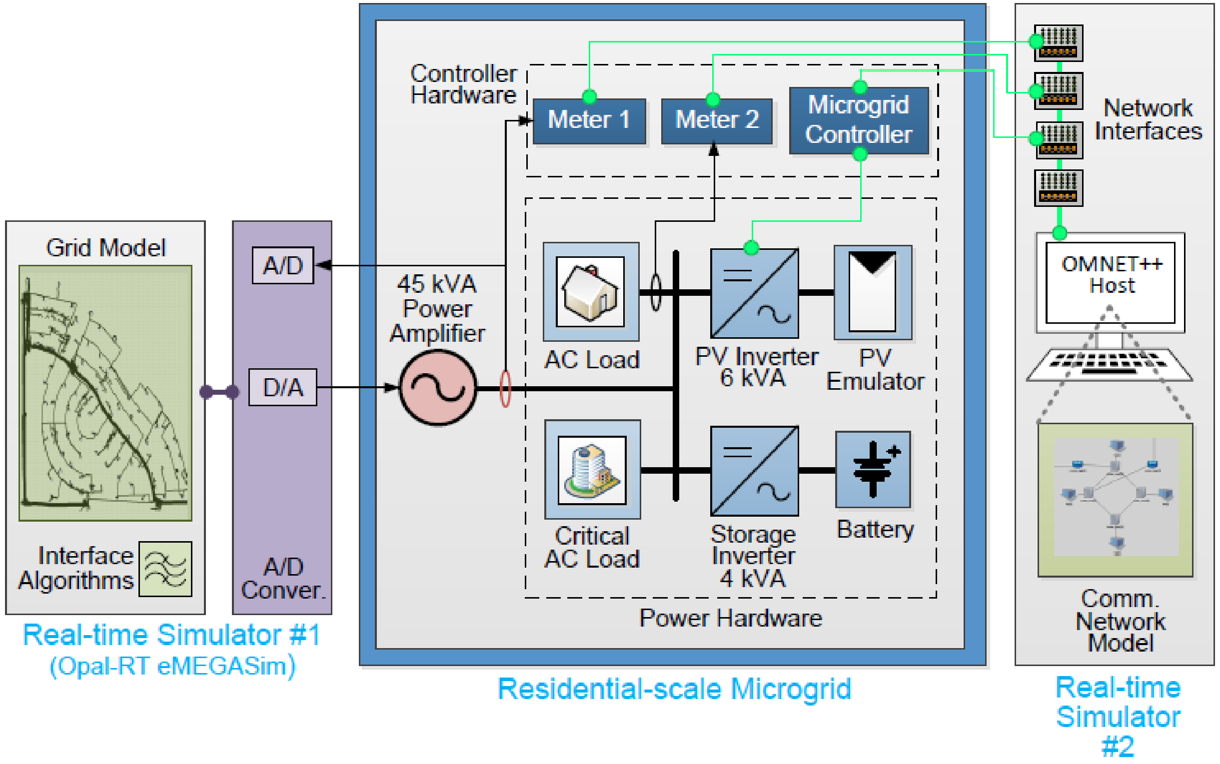
# PHIL EXAMPLE – MICROGRID TESTBED



- Cyber-physical testbed for microgrid [5]:
  - Real-time models of an electrical distribution network in OPAL-RT platform
  - Real-time network-simulator-in-the-loop (NSIL) models in OMNET++
  - Physical power hardware, including a simplified microgrid controller, power meters, a smart PV inverter, and a battery storage inverter, interconnected using PHIL techniques
- Sample case studies demonstrated how communication delays could impact microgrid controller performance and the operation of the power grid




[5] B. Lundstrom, S. Chakraborty, G. Lauss, R. Bründlinger, R. Conklin, Evaluation of system-integrated smart grid devices using software- and hardware-in-the-loop, IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2016.

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# THANK YOU!



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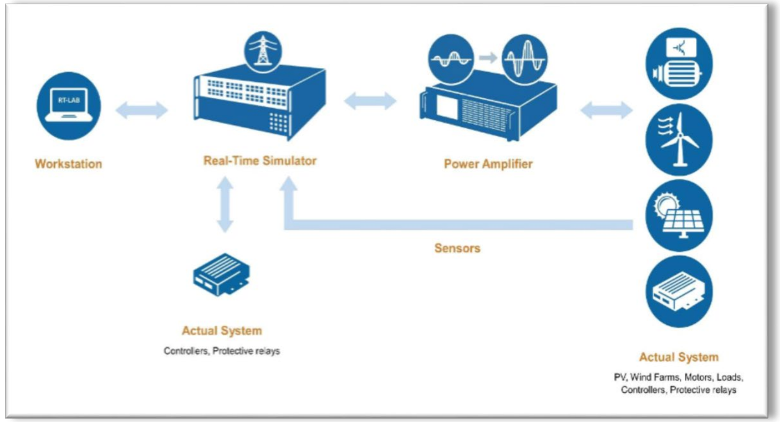


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