Power HIL (P-HIL): A Revolution in the Industry

OPAL-RT

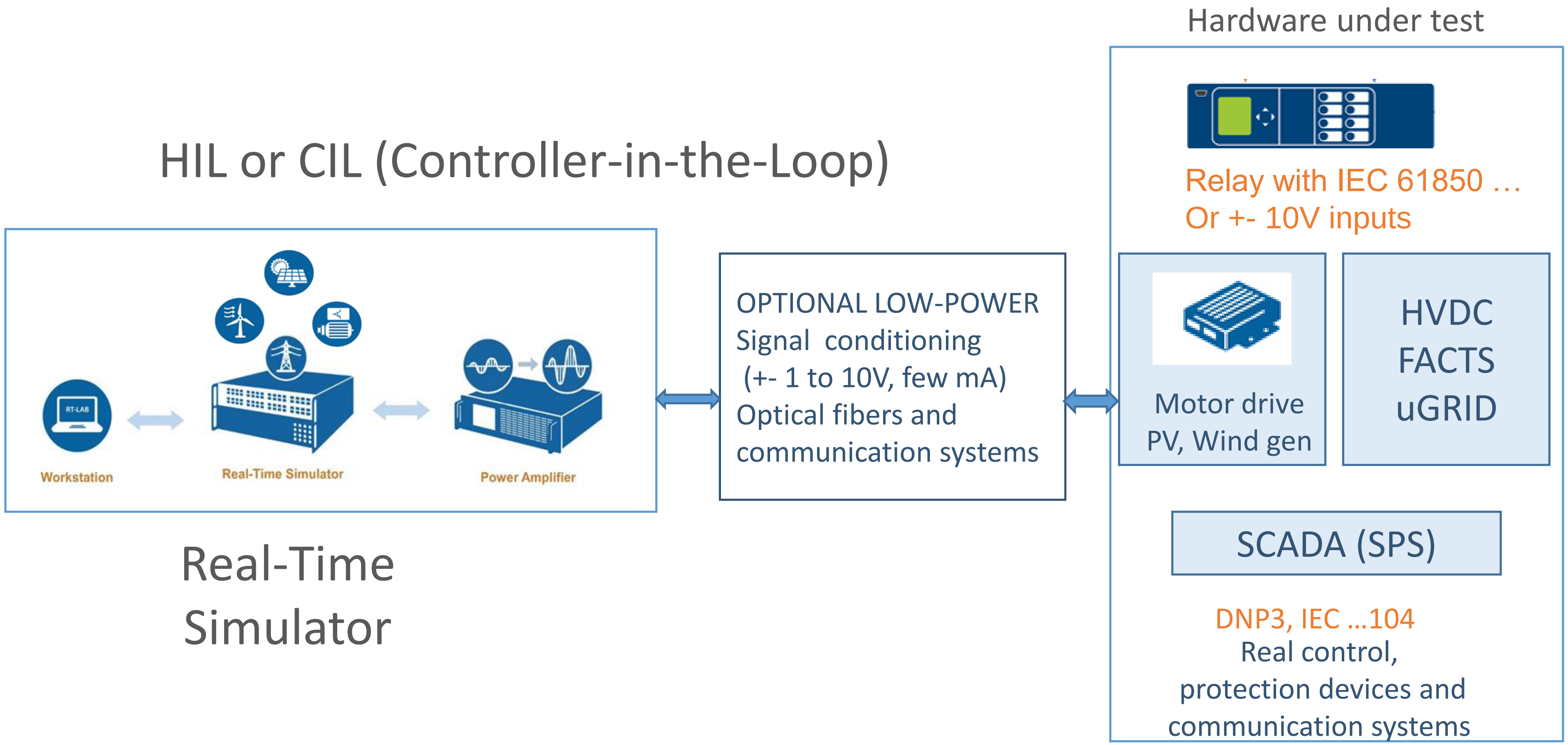
PRESENTATION OUTLINE

1. P-HIL INTRODUCTION & BENEFITS
2. P-HIL APPLICATIONS & AMPLIFIERS TYPES
3. P-HIL CASE STUDIES
4. P-HIL STABILITY ANALYSIS
5. PARTNERS & OPAL-RT SOLUTIONS
6. CONCLUSION

PRESENTATION OUTLINE

HARDWARE-IN-THE-LOOP (LOW POWER INTERFACE CASES)

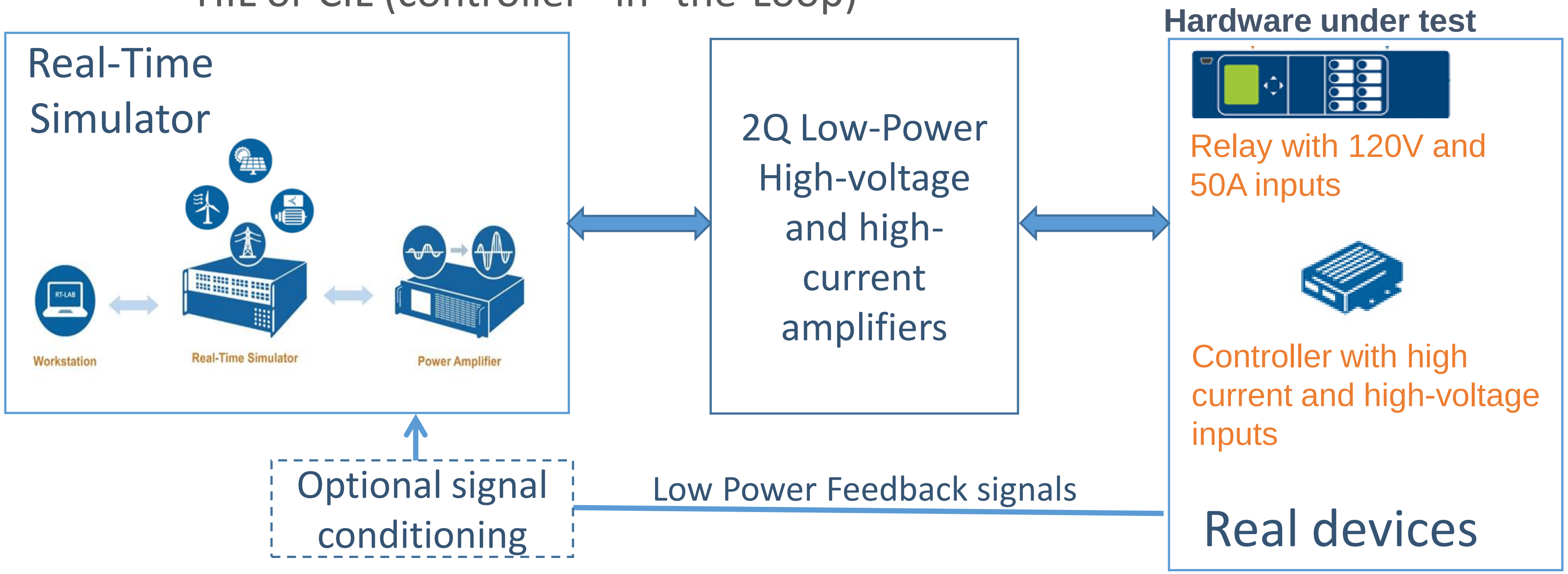
HIL or CIL (Controller-in-the-Loop) simulation is a real-time plant model (grid …) interfaced to a piece of hardware under test **usually with low-power signal interfaces**



HARDWARE-IN-THE-LOOP (HIGH-POWER INTERFACE CASES)

In some cases, high-voltage and high curent interfaces are required.

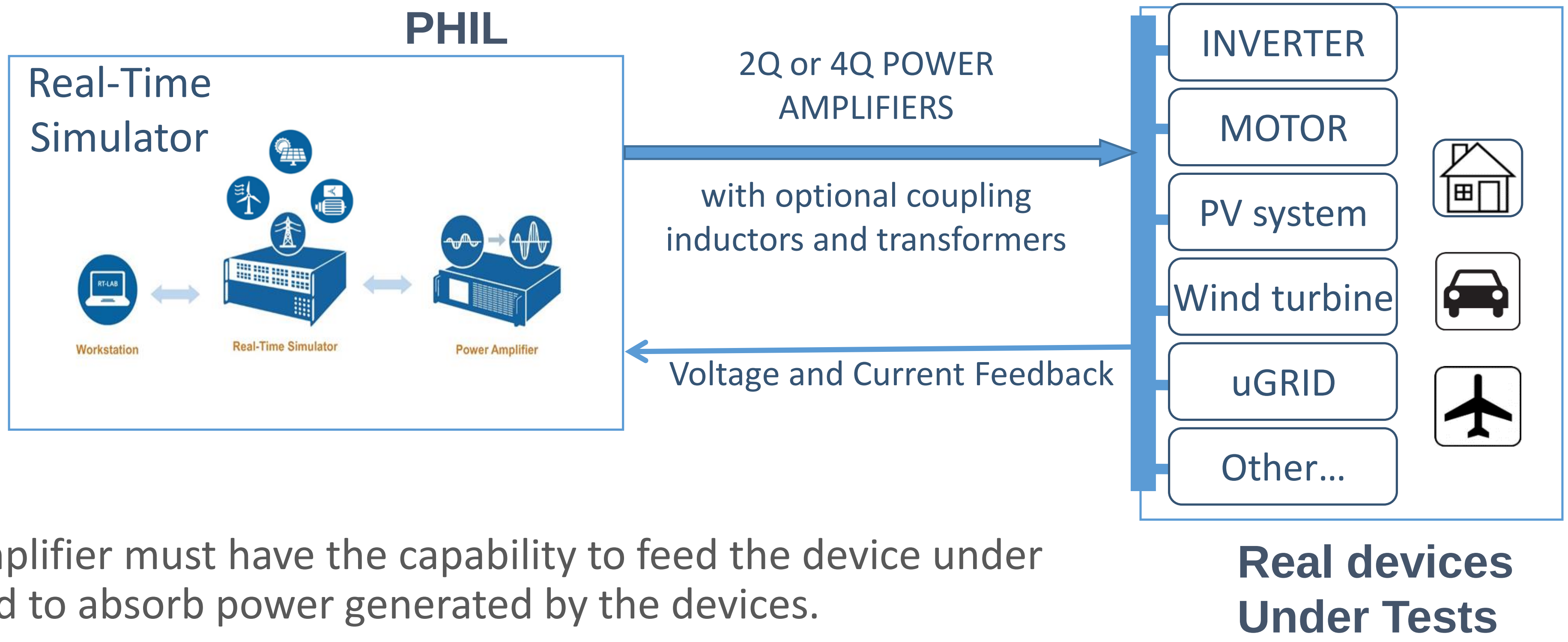
HIL or CIL (controller –in- the-Loop)



High-voltage (60 to 200V) and high-current (5A to 100A) high-frequency and high accuracy amplifiers are required to interface with some controllers and protection systems. The **power rating is relatively low** and **the amplifier load does not influence the simulation**.

POWER HARDWARE-IN-THE-LOOP

PHIL simulation is the **integrated simulation of a complete system** with **one part simulated numerically** and the **other part using real devices.**



The amplifier must have the capability to feed the device under test and to absorb power generated by the devices.

The amplifier loads will influence the global simulation.

POWER HARDWARE-IN-THE-LOOP: BENEFITS

High-fidelity real-time power electronics and power system plant models combined with a quality amplifier can match the performance of a dynamometer or analog bench to achieve a 90% confidence-level that the system will perform as expected.*

- **PHIL allows developers to test a wider range of 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, characteristics and faults.

- **In addition to interacting with the hardware, PHIL simulators are often used to simulate communication networks (CAN,DNP3, ARINC, 61850, others)**

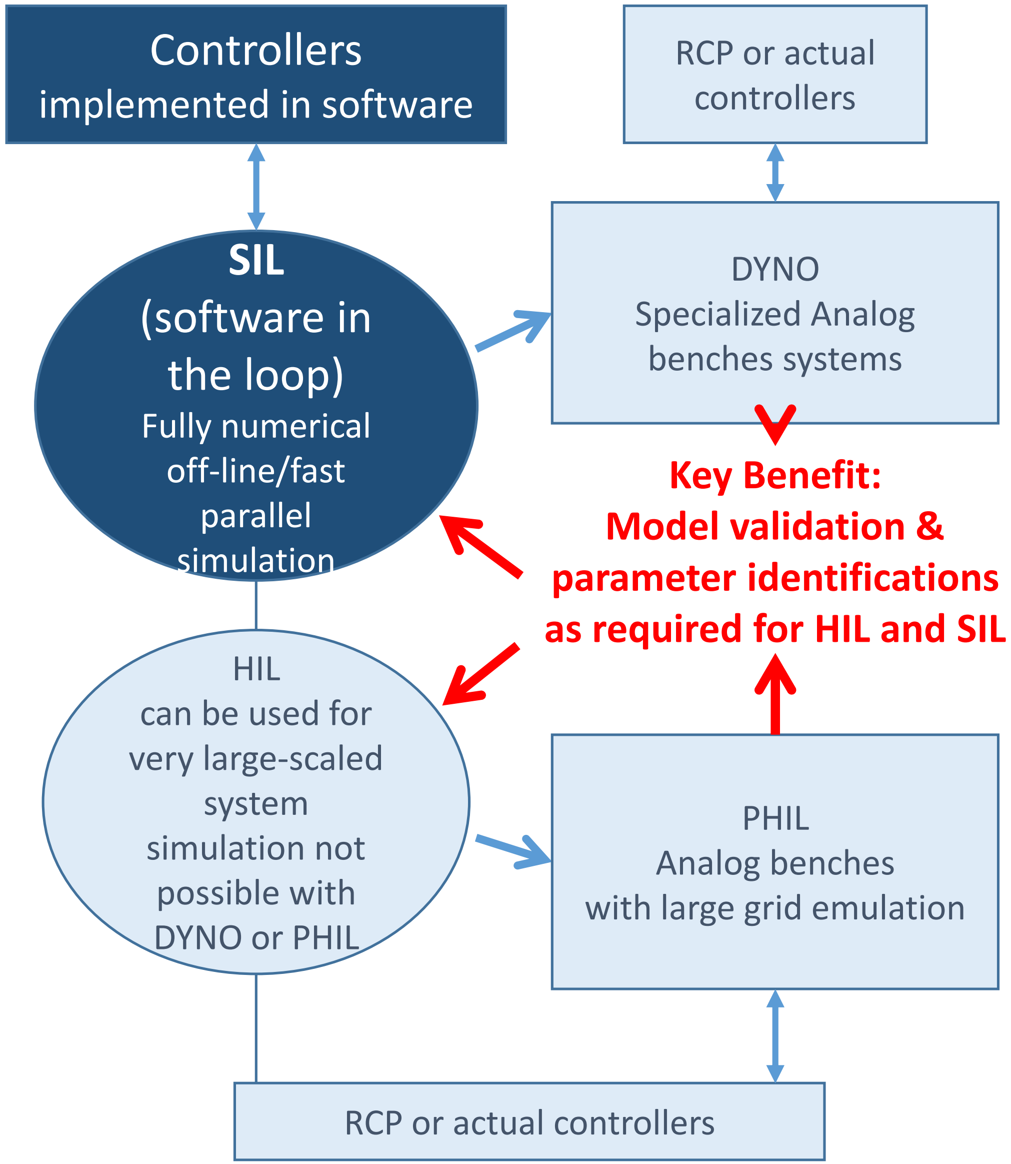
  Allowing Integration of multiple protocols/systems into a single system.

- **A PHIL simulator creates a robust, flexible, versatile, and reliable system**

  Allowing multiple experiments for multiple programs or research.

**Source: Delphi*

POWER HARDWARE-IN-THE-LOOP: BENEFITS: COMPLEMENTARY TOOLS TO SIL, HIL AND DYNO TESTING



- **RCP+ DYNO: component testing**
  - Emulated mechanical system using the dyno and the simulated torque
  - Use of actual motors and inverters for maximum accuracy
  - Final testing but with limited functionalities
- **RCP+PHIL: system aspects**
  - Emulated Power Grid/microGrids or on-board generation systems and loads (ship, aircrafts, automobiles) to analyze interactions between several subsystems
  - Each subsystem
    - Can be the **actual systems** operating under normal voltages and power rating
    - Or **scaled-down analog models**
    - Or **emulated PHIL models**
  - Enable to make power tests without detail models (black box)
  - Enable to make tests impracticable or too risky to do with the dyno (faults, over-speed …)
  - Enable inverter thermal testing without actual motors or complex systems

OPAL-RT TECHNOLOGIES

PRESENTATION OUTLINE

PHIL Applications

Grid Applications

- Grid Emulator (50, 60, 400 Hz)
- Grid Load
- PV-Inverter Emulation
- Wind-Generator Emulation
- Grid Inverter Emulation

Microgrid Applications

- Motor Applications
- Motor / Generator Emulator
- Drive Inverter Emulator
- Frequency Inverter Emulator

Aerospace / Military

- 400 Hz Supply Grid Emulator
- DC-Supply Emulation
- 400 Hz Aerospace Device Emulator
- AC-DC Coupling Emulator

Automotive Applications

- **Electrical Drive Train Emulation**
  - Battery Emulator
  - Drive Inverter Emulator
  - Motor Emulator
- **eVehicle Applications**
  - eVehicle Charging Station Emulator
  - Test Bench for Charging

Transportation

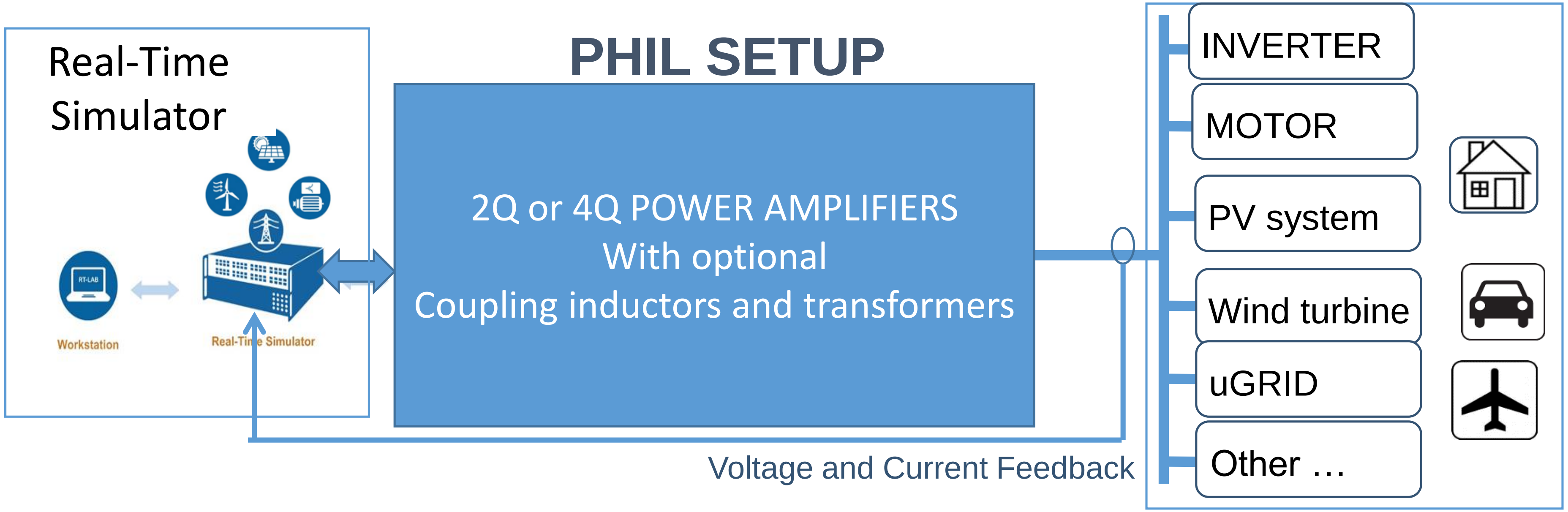
- Supply Grid Emulator
- Machine Emulator
- Inverter Emulator
- Electrical Drive-Train Emulation

Model validation & parameter identifications as required for HIL and SIL

POWER HARDWARE-IN-THE-LOOP: AMPLIFIERS

For PHIL applications, OPAL-RT's simulators can be delivered with standard or custom amplifiers that meet the most demanding requirements with

- **Scalability: few hundred watts to Megawatt**
- **2Q (power generation) and 4Q mode (generation and absorption)**
- **High accuracy, low distortion and low phase lag**
- **Low or high bandwidth depending on the applications**



APPLICATIONS VS AMPLIFIER TYPES

2Q Amplifier Generates Power :

- When simulating PV cells
- When simulating fuel-cells
- When output is connected to passive resistive loads (power factor close to 1)
- When output is connected to relays or controller with high-current inputs (HIL mode)

4Q Amplifier Generates and Absorbs Power:

- When driving active loads (ex. : motor/generator)
- When emulating a grid
- When emulating a load
- When emulating a battery (energy supply and charging mode)
- When connected to capacitive or inductive loads (low power factor)

Amplifier design depends a lot on the type of loads and the capability to absorb active and reactive power and to return the energy to the grid.

APPLICATIONS VS AMPLIFIER TYPES

AC AMPLIFIER: (monophase or triphase)

- When emulating a grid(4Q)
- When emulating AC motors(4Q)
- When connected to AC motors(4Q)
- When connected to AC/DC converters(4Q)
- When simulating a DC/AC controller(4Q)

DC AMPLIFIER:

- When simulating PV-cells(2Q)
- When simulating fuel-cells(2Q)
- When connected to DC/AC controllers(4Q)
- When simulating an AC/DC controllers(4Q)
- When simulating and/or connected to a battery(4Q)

In most cases amplifiers with DC and AC capability up to the maximum specified bandwidth will be used to reproduce DC current transients during faults simultaneously with electromagnetic transients that will be applied on equipment under tests and to increase overall system fidelity, bandwidth and stability. Case-by-case analysis must be performed.

PRESENTATION OUTLINE

CASE STUDY: NITHECH SMART GRID PROJECT (JAPAN)

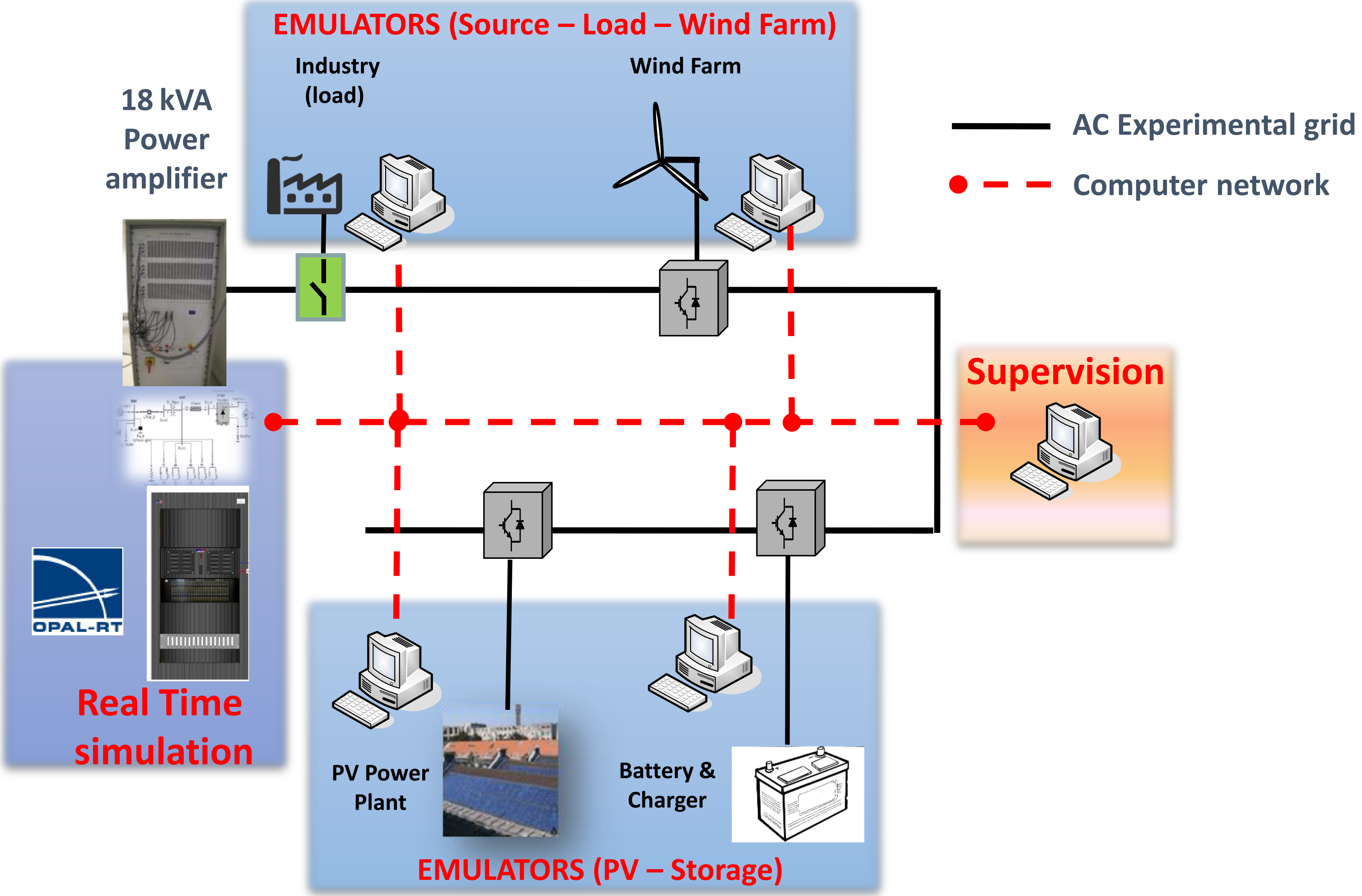
Needs :

Modern distribution systems with several active loads and storage systems require advance voltage controllers

The goal is of PHIL experiment are:

- to test several Volt & Var controller logic using real equipment (PV, FC, micro wind turbines, storage equipment)
- To develop controllers
- To analyse various steady-state and fault conditions

CASE STUDY: NITECH PHIL SETUP



CASE STUDY: NITECH – AMPLIFIER CONNECTION

VOLTAGE CONTROL

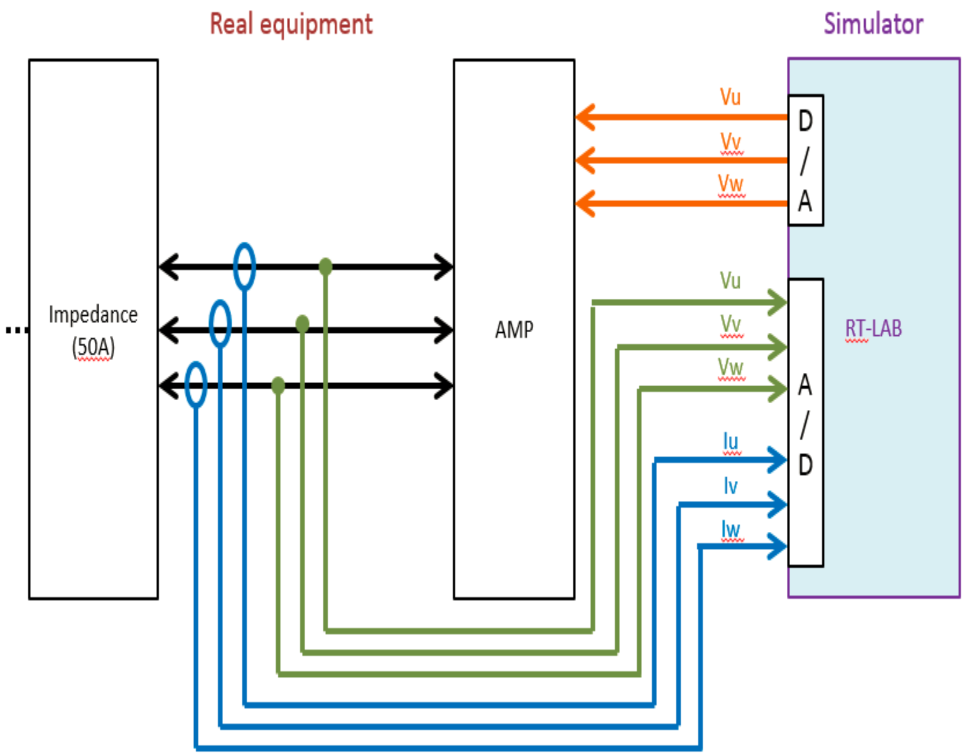
- Vu, Vv, Vw
- 1 step delay

CURRENT RESPONSE

- Iu, Iv, Iw
- 1 step delay

AMPLIFIER RESPONSE

AMPLIFIER CONNECTION



CASE STUDY: JAPANESE SMART HOUSE PROJECT

Needs :

In a Smart House, the energy generation, energy consumption control and energy storage are all integrated, with individual components.

The goal is of PHIL experiment are:

- to ensure control logics for an adequate energy supply at all times and also minimize the number of storage units needed, because rechargeable batteries are still a high cost factor
- To analyse the effect of power grid transients on house electronic
- To analyse interactions between houses

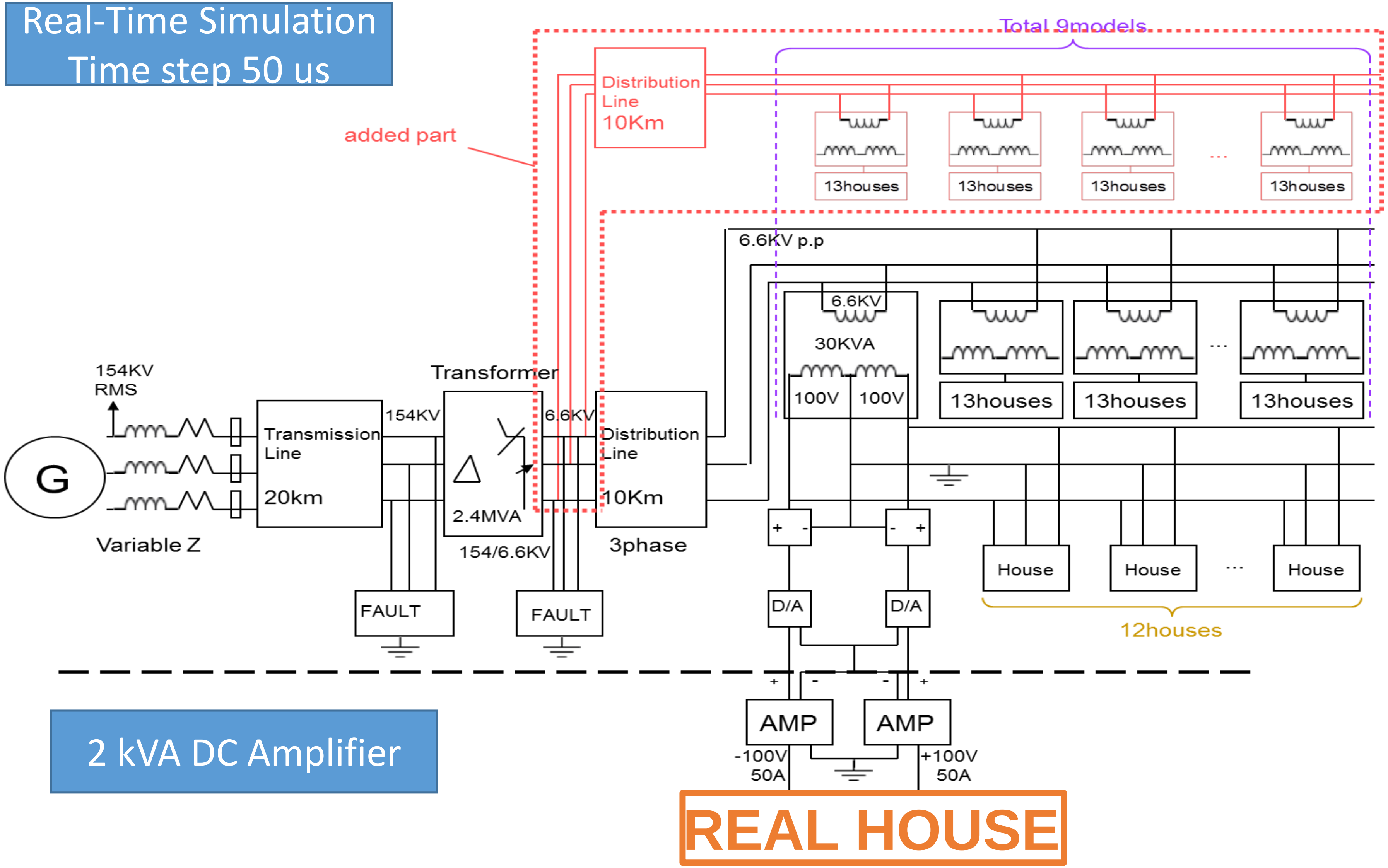
CASE STUDY: JAPANESE SMART HOUSE PROJECT

Smart house has regenerative energy installations such as photovoltaics, solar thermal devices, wind power and energy storage.

The interaction between houses and the distribution network must be carefully analysed.

CASE STUDY: JAPANESE SMART HOUSE PROJECT

Real-Time Simulation
Time step 50 us



2 kVA DC Amplifier

CASE STUDY: PLASTIC OMNIUM - FRANCE
3-PHASE ELECTRICAL MOTOR PHIL – 1200 W SETUP

Needs :

- To test a 3-Phase BLDC motor sensorless controller with trapezoidal back EMF at power levels lower than 100W in steady state.
- The PHIL bench needs to generate and absorb power like a real DC motor.
- Open-Circuit and Short Circuit faults required.
- Possibility to reuse the hardware in future application (versatility and upgradability).

CASE STUDY: PLASTIC OMNIUM
3-PHASE ELECTRICAL MOTOR PHIL – ACTUAL CIRCUIT

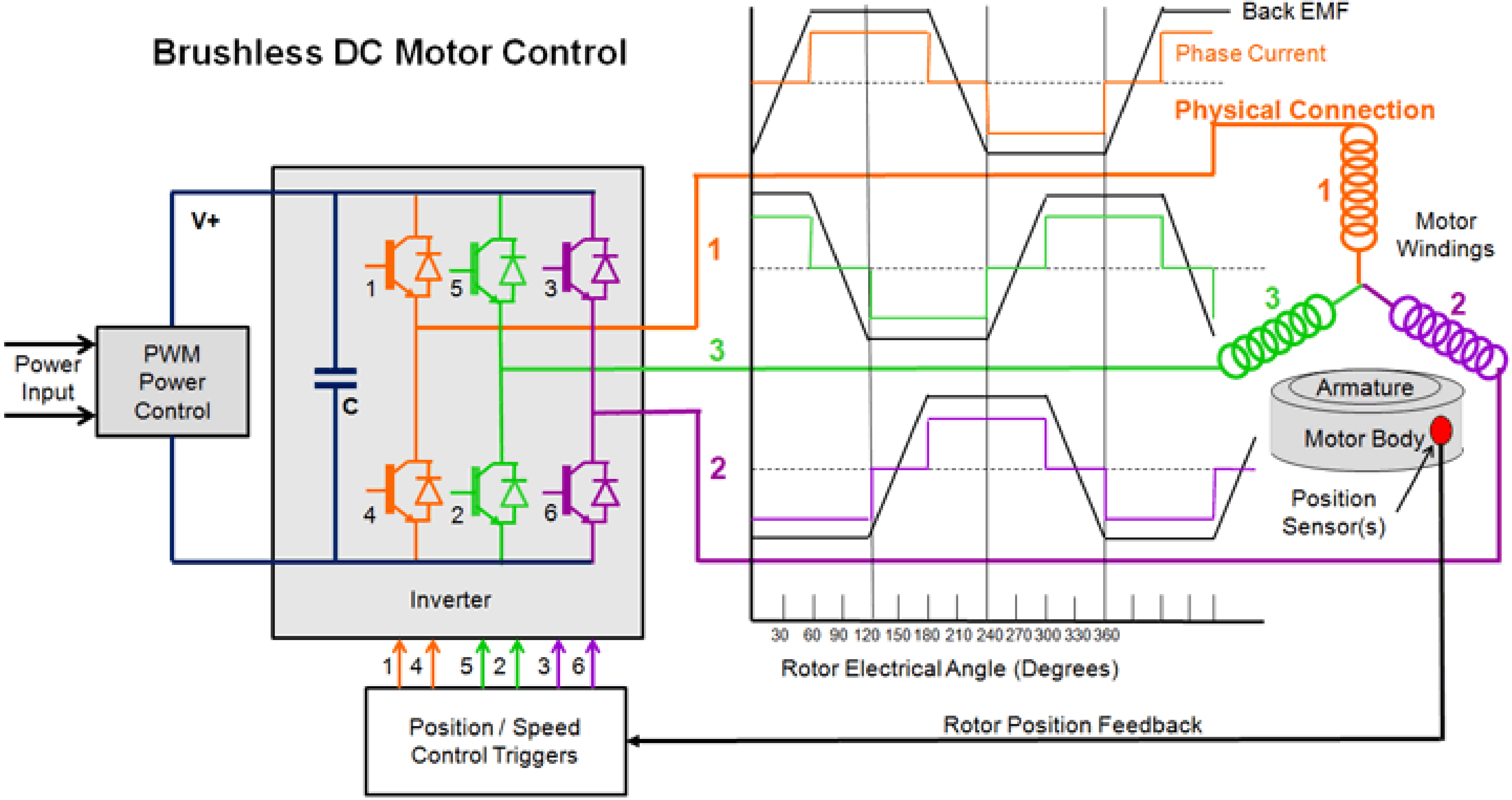
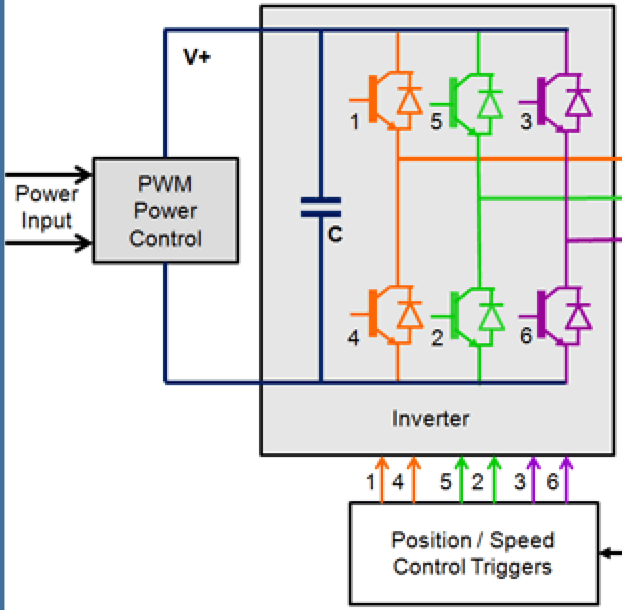


Image source: http://www.mpoweruk.com/motorsbrushless.htm
Consulted 01/19/2015

CASE STUDY: PLASTIC OMNIUM
3-PHASE ELECTRICAL MOTOR PHIL

Brushless DC Motor Control

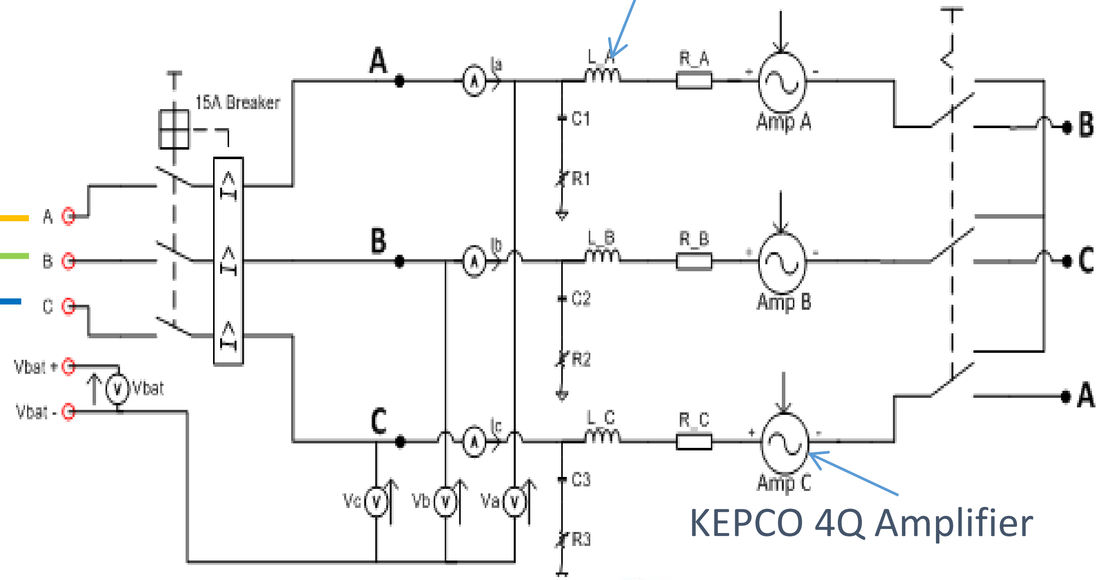


Actual Controller inverter under test

Image source: http://www.mpoweruk.com/motorsbrushless.htm
Consulted 01/19/2015

Motor Emulator

Real RL impedance for each branch of the motor to simulate motor inductance



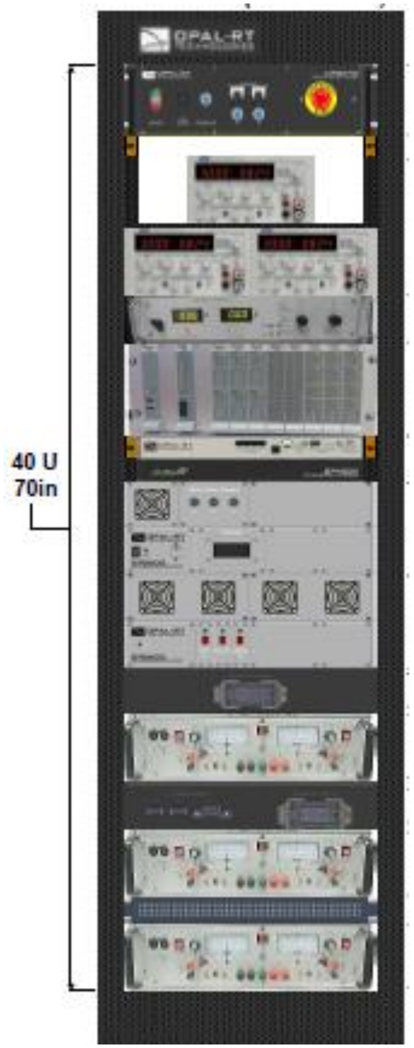
KEPCO 4Q Amplifier

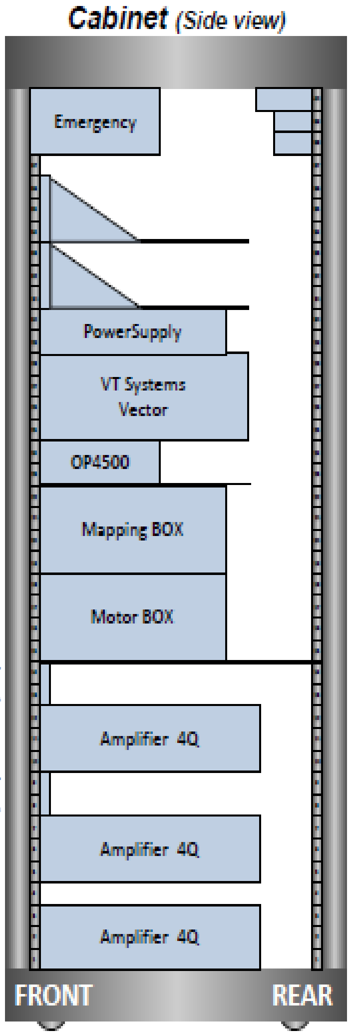
OP4500 HIL simulator

The FPGA motor models of the OP4500 simulator will control the amplifier to have an accurate simulation of the motor back EMF and impedance. FEA based motor model can be used

OPAL-RT TECHNOLOGIES

CASE STUDY: PLASTIC OMNIUM
3-PHASE ELECTRICAL MOTOR PHIL – 1200 W SETUP





- BLDC Motor 3 Phases motor of 100W
- Real-Time simulation of the Motor on FPGA
  - Max PWM Frequency: 20Khz
  - Time-Step: 500 ns
  - Model vs theoretical precision within 1%
- Amplifier 20V-20A Kepco (BOP 20-20ML)
  - Nominal Power 400 Watts (4Q)
  - Loads connected in Delta or Star
- Possibility to perform multiple faults:
  - Short-Circuit (Phase-Phase)
  - Open-Circuit per phase
  - Short Circuit (Phase-Battery)
- Programmable Loads

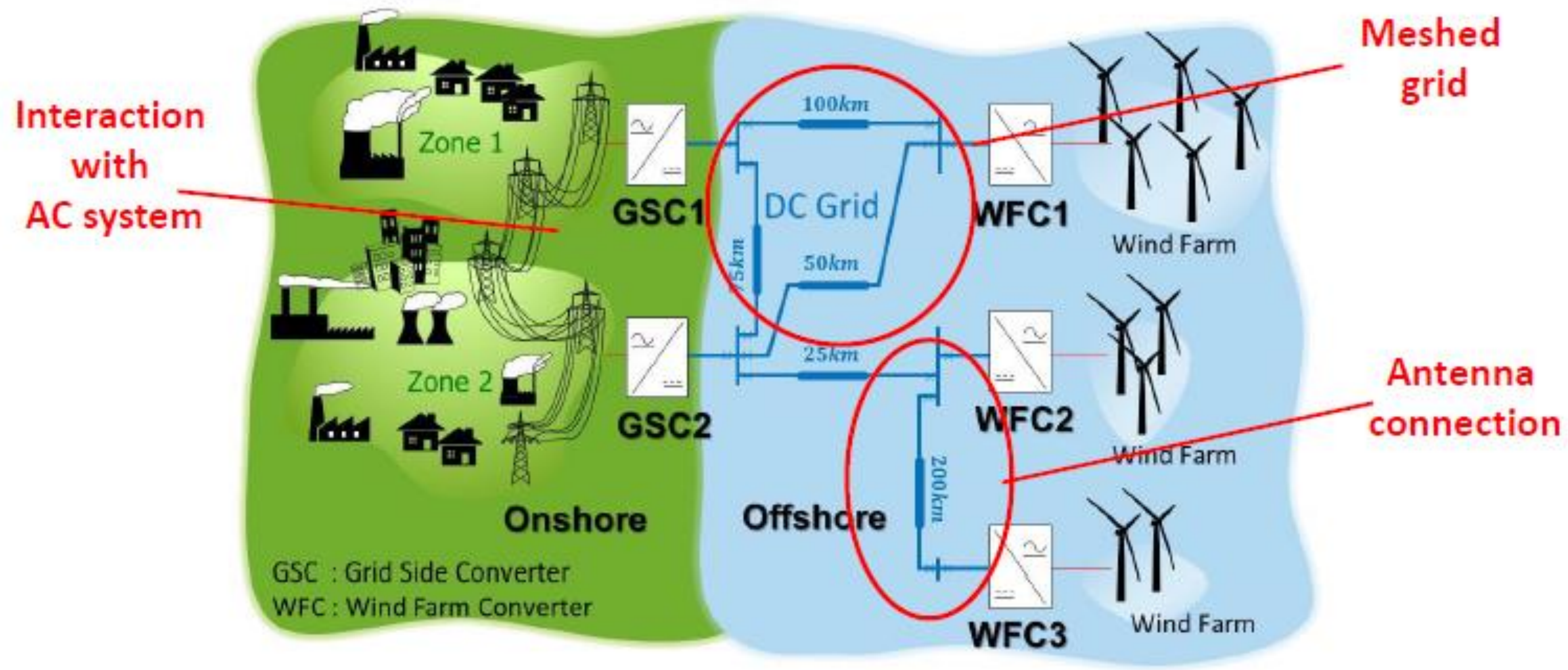
CASE STUDY: L2EP – U. LILLE, FRANCE

Electrical Engineering Laboratory of Université des Sciences et Technologies de Lille, Arts et Métiers ParisTech, Ecole Centrale de Lille, Hautes Etudes d'Ingénieur

- Studies on impact of energy storage systems, in terms of efficiency, quality and services on the network
- Studies of new architectures : microgrid, island networks
- Production sources & storage systems coordination, in order to optimize quality and stability of embedded networks

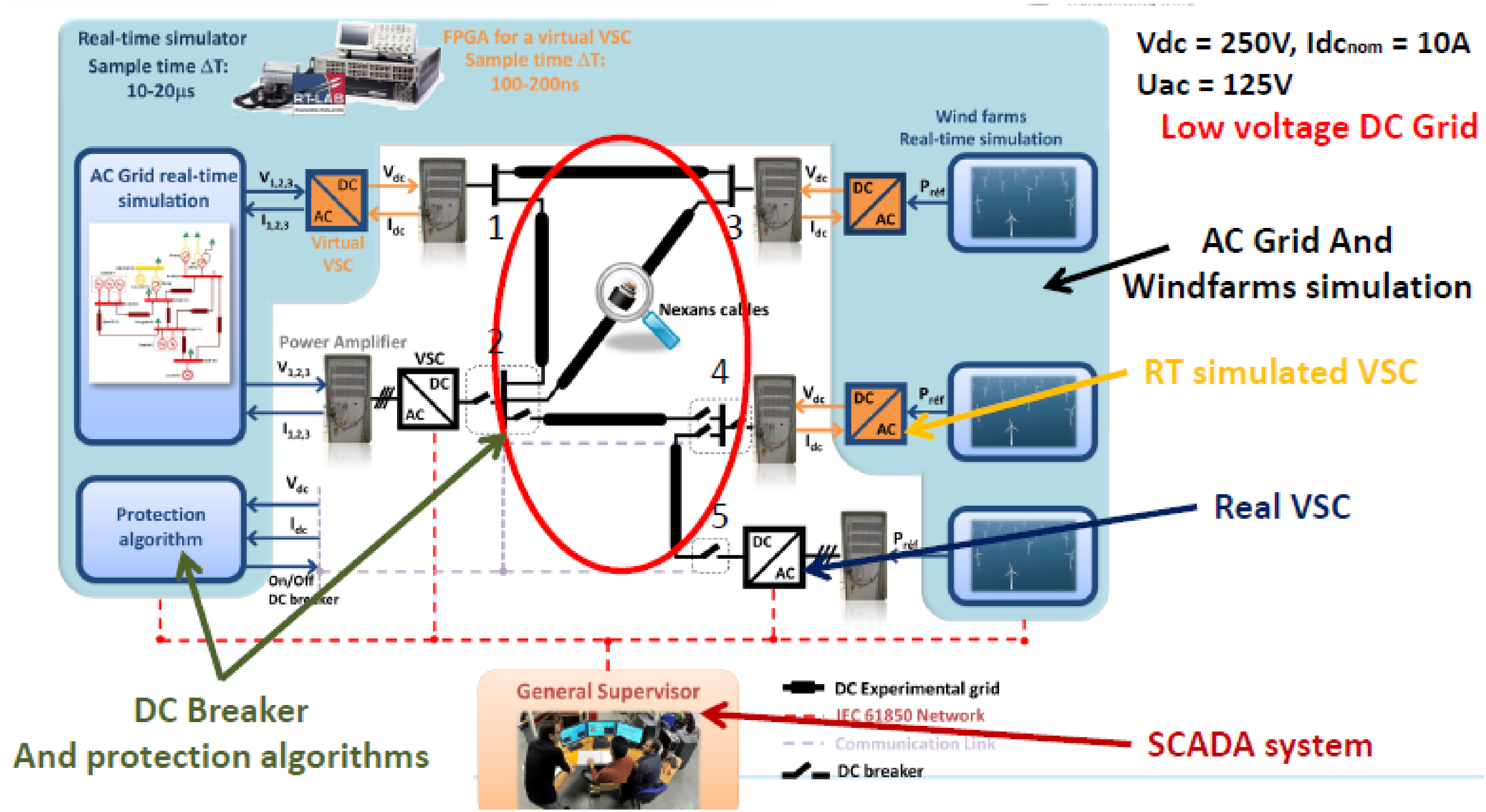
CIRCUIT UNDER ANALYSIS

Multi Terminal High Voltage DC grid



http://l2ep.univ-lille1.fr/plateforme/

CASE STUDY: L2EP PHIL SETUP



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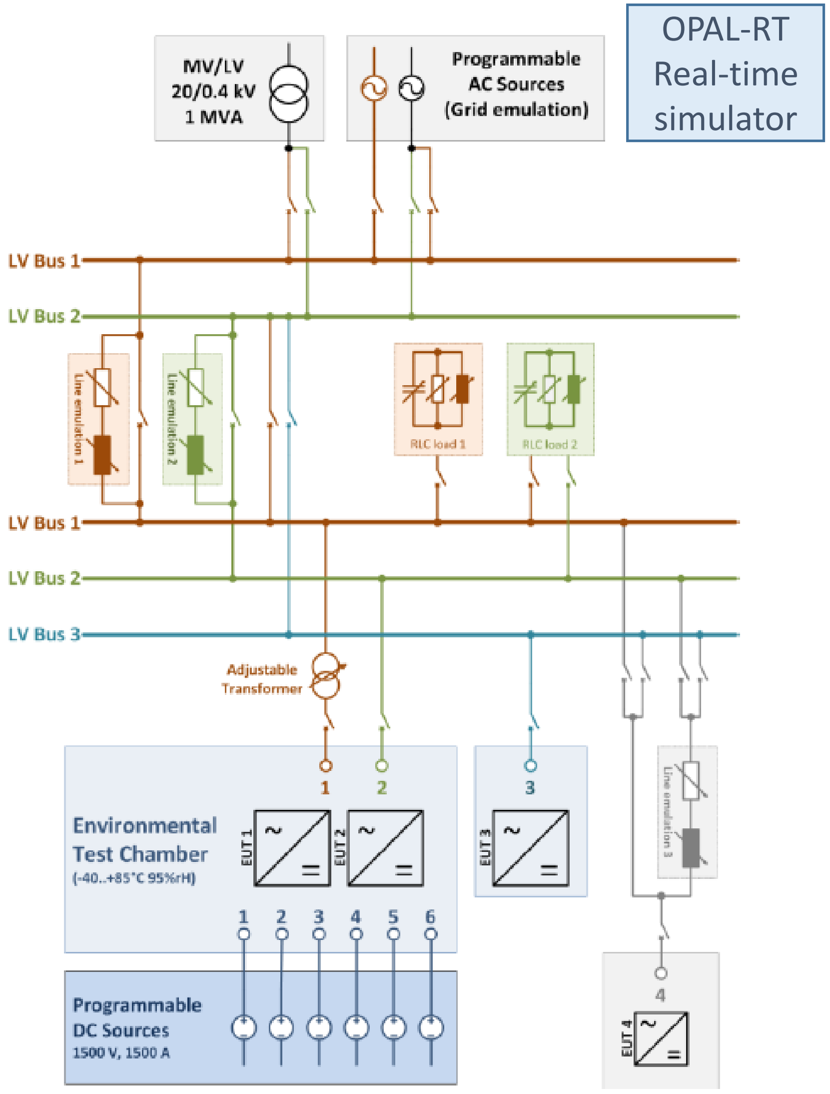
CASE STUDY: AIT SMARTEST LABORATORY - AUSTRIA

- Developing and testing PV controller.
- Testing overall performance of PV systems as per standard.
- Analyzing interactions between systems and with the distribution system under steady-state and fault conditions.

For development and research, AIT offers unique opportunities for customers and project partners to optimize their products and control strategies directly at this advanced facility, accompanied by qualified experts in order to shorten the time-to-market of new products.

CASE STUDY: AIT SMARTEST LABORATORY



GRID SIMULATION

- 2 independent high bandwidth Grid Simulation Units: 0 to 480 V 3-phase, 800 kVA
- 3 independent laboratory grids, which can be operated in grounded/isolated mode
- 3-phase balanced or unbalanced operation
- Capabilities to perform LVRT (Low Voltage Ride Through) and FRT (Fault Ride Through) testing

DC SOURCES

- 5 independent dynamic PV-Array Simulators:
- 1500 V, 1500 A, 960 kVA

Adjustable loads for active and reactive power

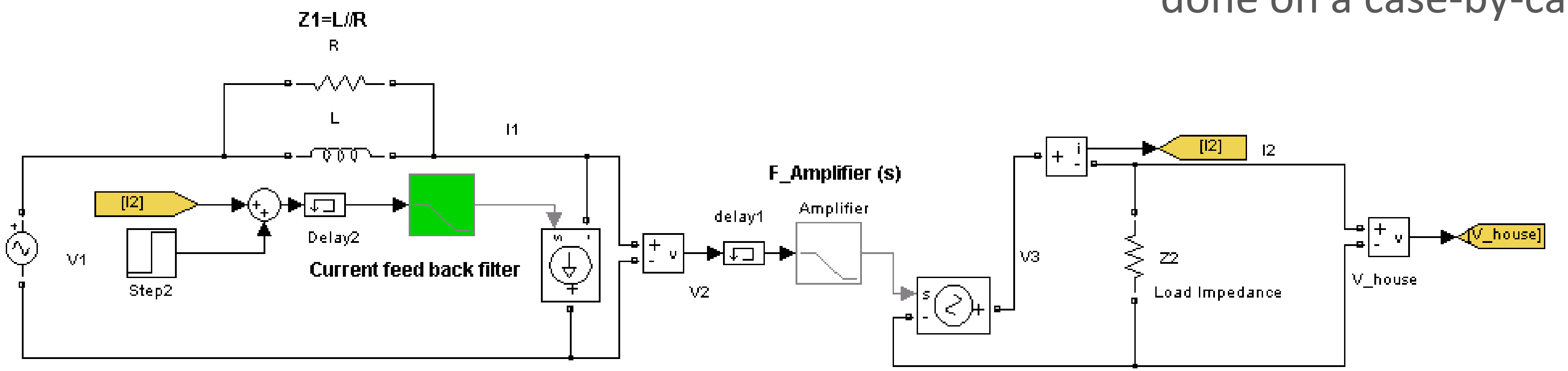
Line impedance emulation

PRESENTATION OUTLINE

PHIL STABILITY ANALYSIS

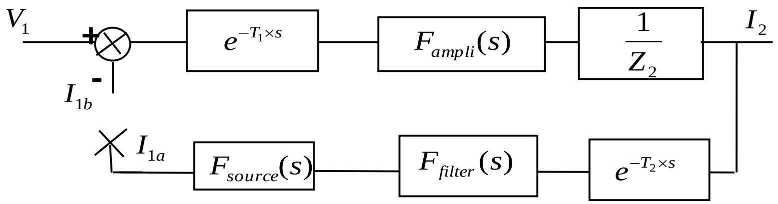
- Closed-loop system may become unstable under certain conditions
- Instability caused by delays may damage equipment or reduce simulation accuracy
- Stability depends on:
    - Ratio of load power over short-circuit power of the feeder
    - Type of load
    - Damping of source impedance
    - Power amplifier bandwidth
    - Simulator’s sampling frequency
    - Use of current feedback filter

Determining the best method to ensure system stability and maximum accuracy must be done on a case-by-case basis.



PHIL simulation equivalent circuit

PHIL STABILITY ANALYSIS



$$F(s) = \frac{I_{1a}(s)}{I_{1b}(s)} = \frac{1}{Z_2} \times \left[-F_{source}(s) \times F_{ampli}(s) \times F_{Filter}(s) \times e^{-T.s} \right]$$

$$F(s) = \frac{1}{Z_2} \times \left[-L.s \times \frac{1}{1+\tau_{LR} \times s} \times \frac{-s+1}{s+1} \times \frac{1}{1+\tau_{ampli} \times s} \times \frac{1}{1+\tau_{filter} \times s} \right]$$

$$Z_2 = R_2 \qquad Z_2 = L_2 wj \qquad Z_2 = \frac{1}{Cwj}$$

Instability caused by the interaction of:

- Lsource (linear gain with a phase of $(-\pi)/2$)
- L//R filter and voltage amplifier (Limit gain, add phase lag)

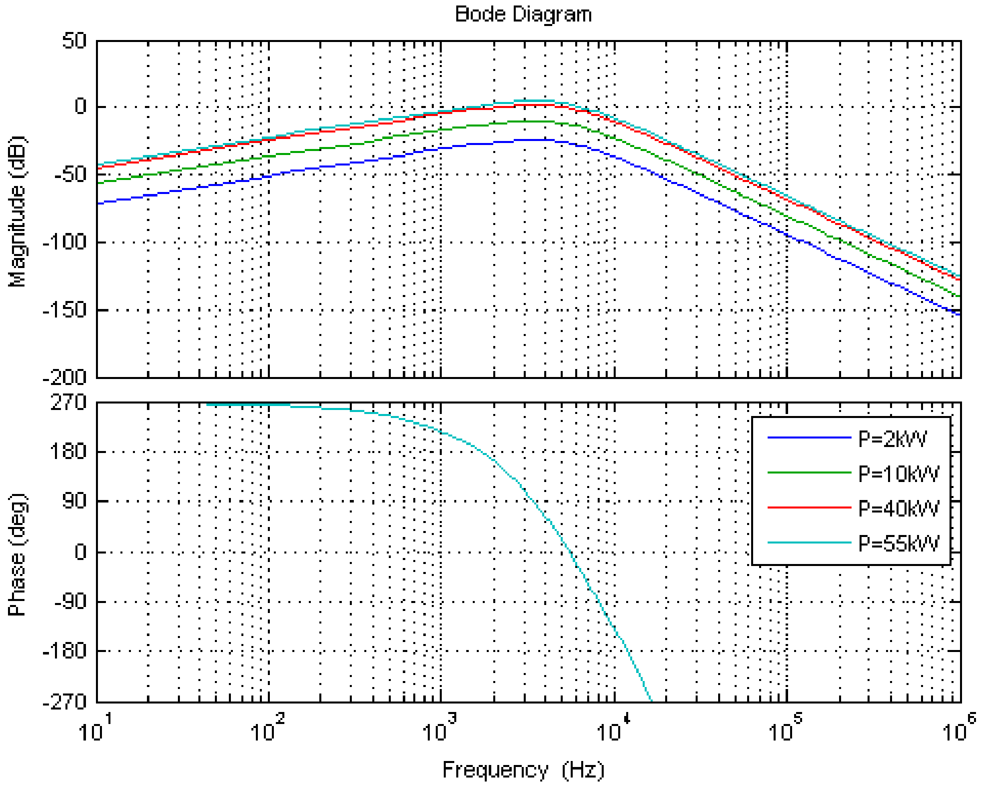
IO time delay (adds linear phase lag)

Type of load (higher power, higher gain)

- Resistive (No phase effect)
- Inductive (Reduce Lsource phase & gain)
- Capacitive (Increase Lsource phase & gain)

Current feedback filter (Limit gain at fc)

PHIL STABILITY ANALYSIS CONCLUSIONS



Bode Diagram

- Stability becomes gain dependent when phase reaches 0
- Maximum stable load (gain ≤ 1), determines max load power
- Lower sample time increases the simulation stability and accuracy

DETAILED INFORMATION ON PHIL STABILITY ANALYSIS

Simulation Modelling Practice and Theory 19 (2011) 1699–1708

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Stabilization of Power Hardware-in-the-Loop simulations of electric energy systems

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http://www.sciencedirect.com/science/article/pii/S1569190X11000566

OPAL-RT TECHNOLOGIES

PRESENTATION OUTLINE

OPAL-RT TECHNOLOGIES

POWER AMPLIFIER PARTNERS

AMETEK®

This high power AC and DC test system covers a wide spectrum of AC and DC power applications at an affordable cost.

Using state-of-the-art Pulse Width Modulation (PWM) switching techniques, the RS series combines robustness and functionality in a compact, floor-standing chassis.

http://www.ametek.com/

POWER AMPLIFIER PARTNERS

EGSTON provides a new compact Digital Amplifier Series (EGSTON COMPISO) with high bandwidth output signals. The COMPISO (Ultra Compact Bidirectional Multi-Purpose Inverter with Sinusoidal Output) is a compact high efficient digital amplifier family.

The modular series is optimally suited for building up DC-DC, DC-AC, AC-DC as well as AC-AC converter systems in the power range of 120kW up to 1 MW. The COMPISO can be used in many different applications.

http://www.egston.com/en/index.php


COMPISO Digital Amplifier Inside


COMPISO Digital Amplifier (CDA)

POWER AMPLIFIER PARTNERS

Puissance + proposes innovative, high-range, reliable and accurate programmable power solutions in AC, DC, AC+DC. They can be standard or made according to specifications.

Puissance + experience in the generation, absorption and measures in low and high power allows us to test or simulate all types of generators, power sources and charges for laboratory, production and embedded applications.

www.puissanceplus.com/en

POWER AMPLIFIER PARTNERS

triphase

Programmable, Reconfigurable Units for the swift realization of Research, Development and Test setups for Power Applications.

The Modules are modular and can combine units for AC/DC, DC/DC and motor drives in 5, 15 and 90 kW power ranges.

http://www.triphase.be/

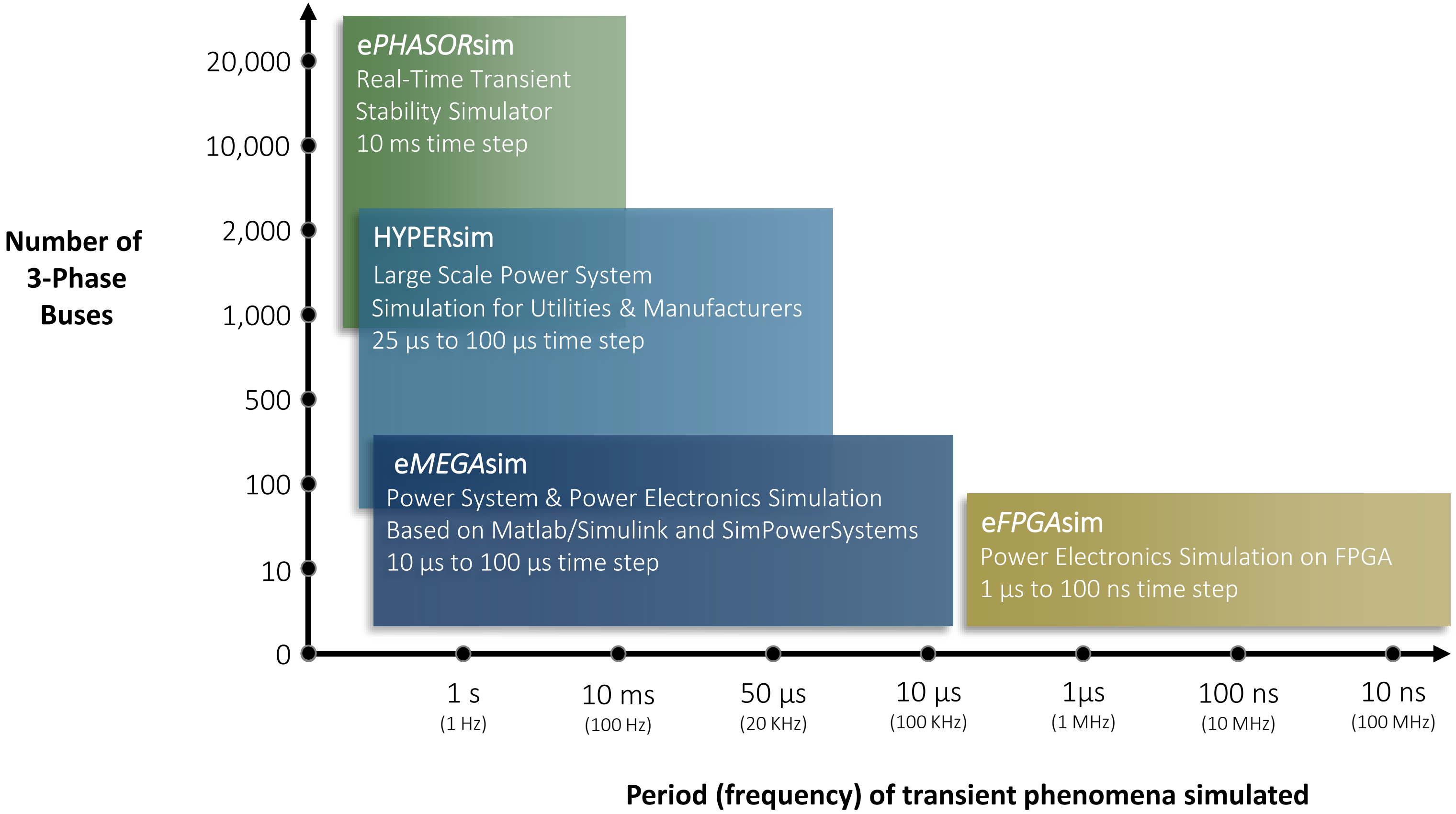
OPAL-RT SOLUTIONS

- **OP5600 (12 CPU cores, 1 VIRTEX 6)**
  - IO and EtherCAT
- **OP4500 (4 cores, 1 KINTEX 7)**
  - IO, EtherCAT and ORION
- **OP5607 (12/32 CPU cores *, 1 VIRTEX 7)**
  - IO, FPGA motor modeling and cascading of units
- **OP7000 (12/32 CPU cores*, 1 to 4VIRTEX 6**
  - IO, Multi-FPGA and FPGA motor modeling

**Using external PC*

OPAL-RT TECHNOLOGIES

Our solutions cover the complete spectrum of power system analysis and studies



PHIL APPLICATIONS

- Power rating
- Output voltage/current limit
- Ripple, THD, DC offset,…
- Bandwidth
- Latency
- AC application
  - Monophase
  - Three-phase

- DC application
- 2Q or 4Q
- Communication (EtherCAT, Optic Fiber, AIO, …)
- Emulators
  - Motor/Generator module
  - PV, wind turbine …

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CONCLUSION

CONCLUSION

Power Hardware-in-the-Loop should be considered as a complementary tool to SIL, HIL and DYNO testing and not as a replacement of these tools and method.

OPAL-RT has the expertise to help you find the right tools for your PHIL application.

Our Integration Experts can help you achieve your goal by designing your PHIL testing bench and our Field Application Engineers can bring their experience to the field to ensure your PHIL application runs like a charm.

UPCOMING EVENTS

Visit our event page to learn where to meet

OPAL-RT TECHNOLOGIES

http://opal-rt.com/events

Thank you

OPAL-RT