CHIL and PHIL Simulation for Active Distribution Networks

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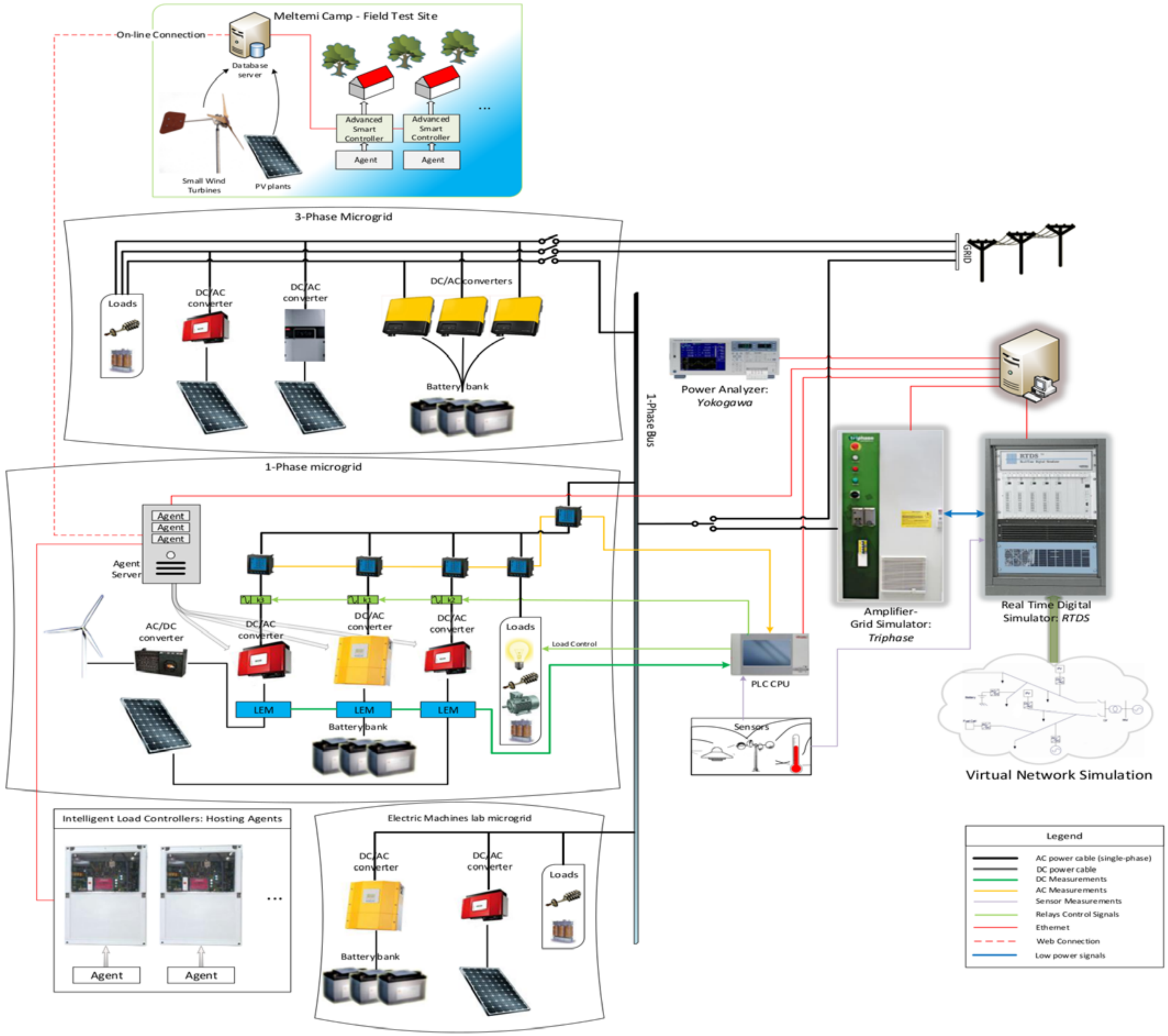
Overview

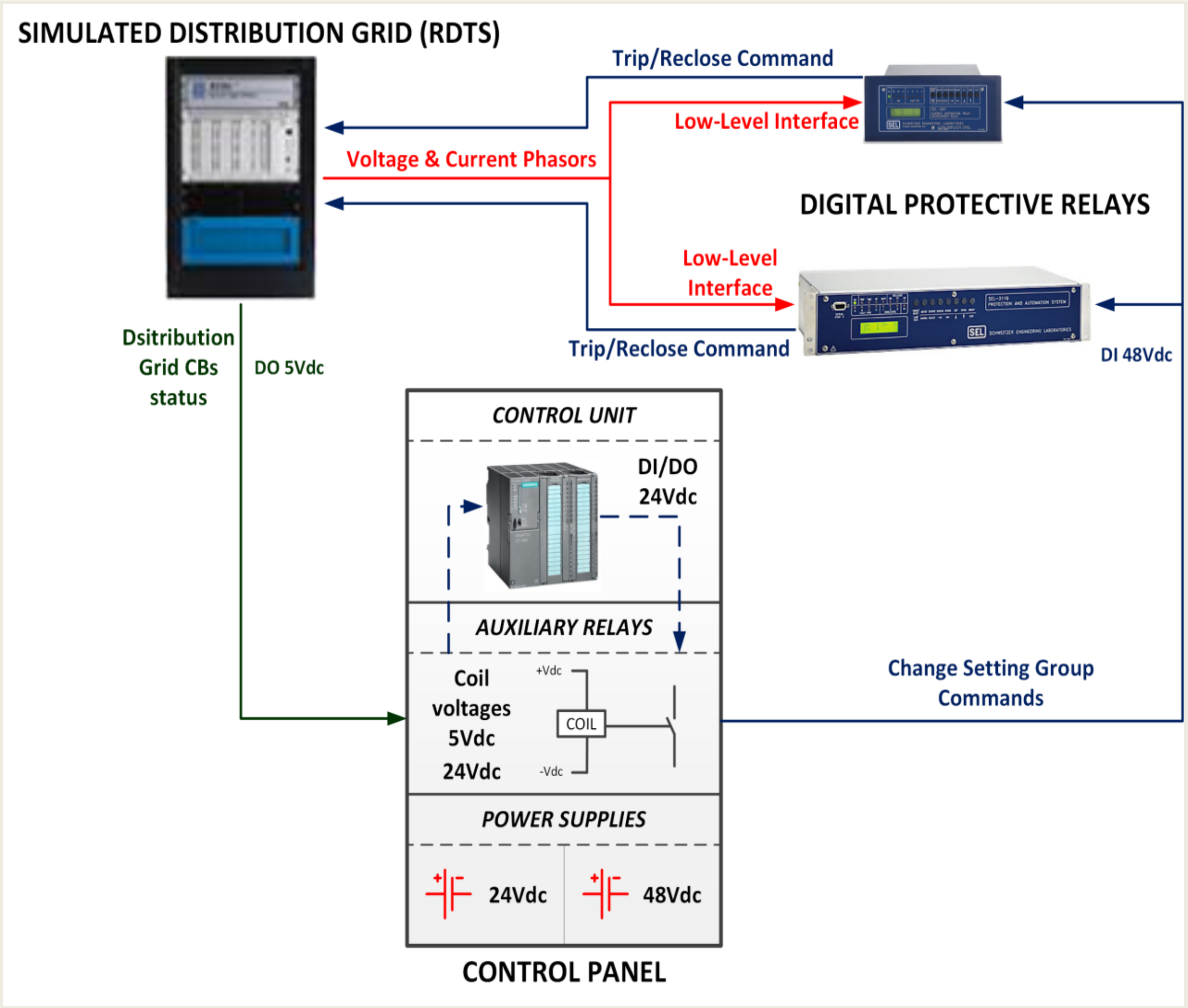
- **Adaptive protection scheme testing:** *CHIL simulation*
- **DER Inverter controls testing:** *CHIL simulation*
- **Coordinated voltage controller testing:** *Combined Controller HIL (CHIL) and Power HIL (HIL) simulation*

NTUA lab

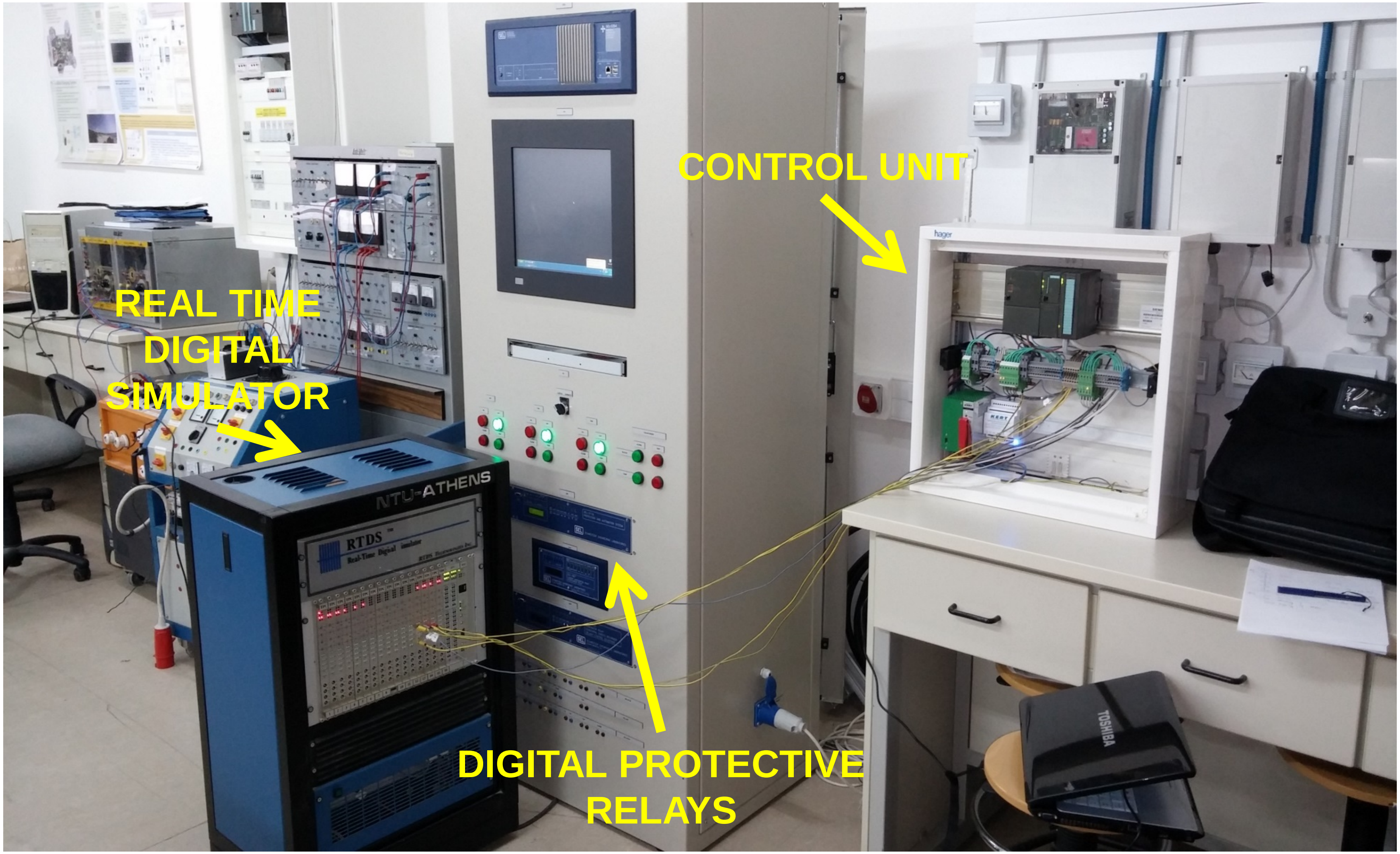

Meltemi Camp - Field Test Site
On-line Connection
Database server
Advanced Smart Controller
Agent
Small Wind Turbines
PV plants
3-Phase Microgrid
GRID
Loads
DC/AC converter
DC/AC converters
Battery bank
1-Phase Bus
Power Analyzer: Yokogawa
1-Phase microgrid
Agent
Agent Server
AC/DC converter
LEM
Load Control
PLC CPU
Sensors
Amplifier-Grid Simulator: Triphase
Real Time Digital Simulator: RTDS
Virtual Network Simulation
Intelligent Load Controllers: Hosting Agents
Electric Machines lab microgrid
Legend
AC power cable (single-phase)
DC power cable
DC Measurements
AC Measurements
Sensor Measurements
Relays Control Signals
Ethernet
Web Connection
Low power signals

1) Adaptive protection testing scheme

- ❑ Real Time Digital Simulator (RTDS)
- ❑ 2 multifunctional digital relays
  - •SEL-311B
  - •SEL-587
- ❑ Programmabe Logic Controller (SIMATIC S7-300)

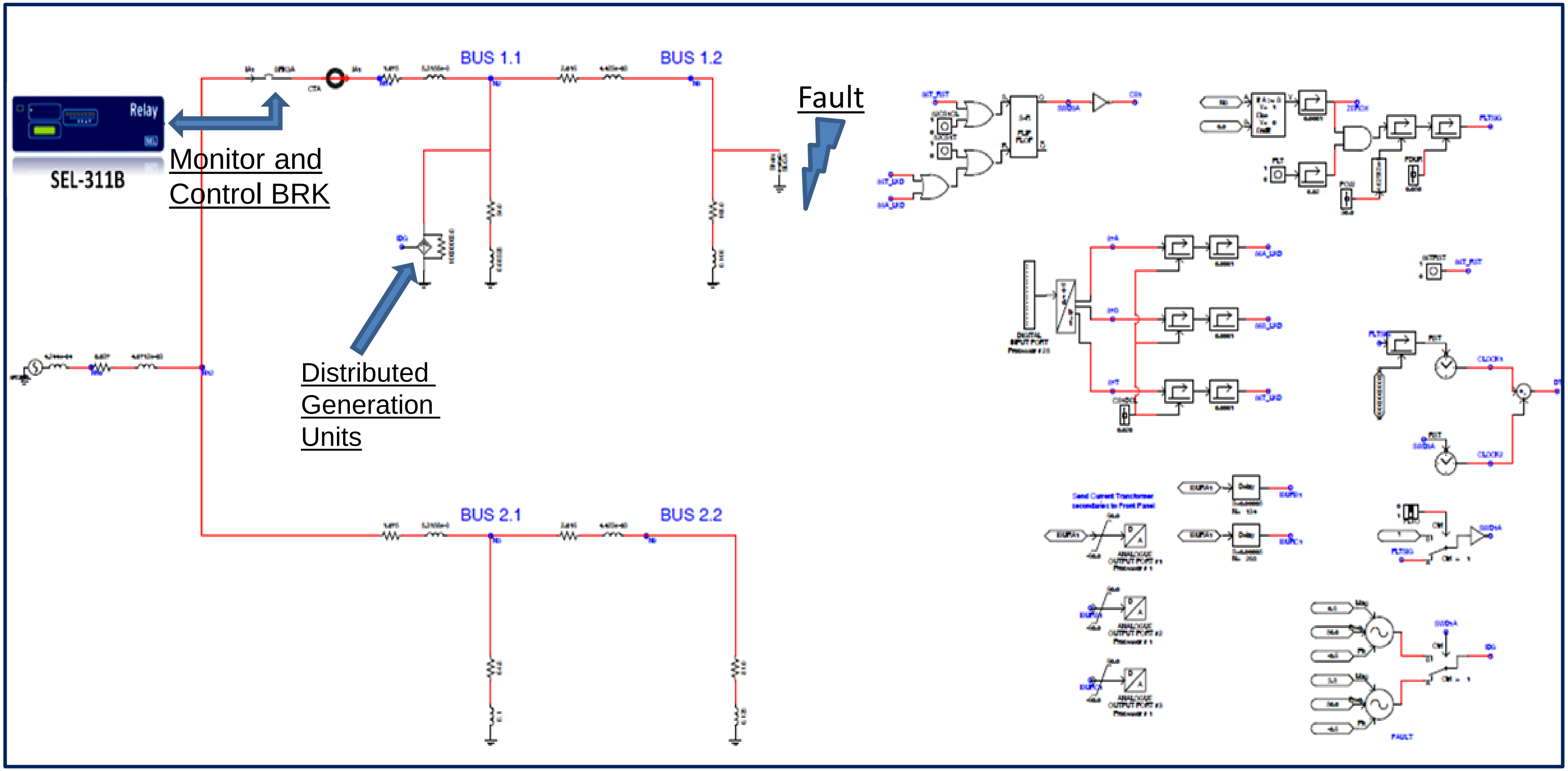


Test setup


CONTROL UNIT
REAL TIME DIGITAL SIMULATOR
DIGITAL PROTECTIVE RELAYS
NTU-ATHENS
RTDS
Real-Time Digital Simulator
hager
TOSHIBA

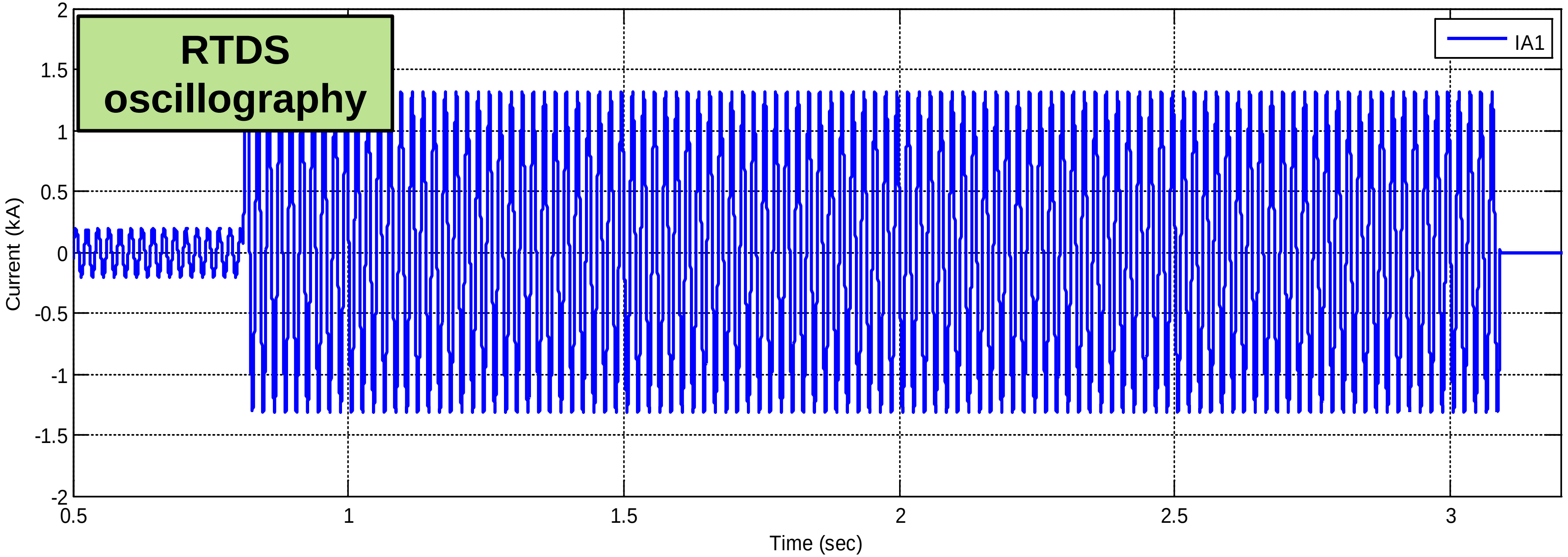
HIL testing-Protection Blinding

➢ simplified configuration of a Rhodes HV/MV Substation with 2 feeders

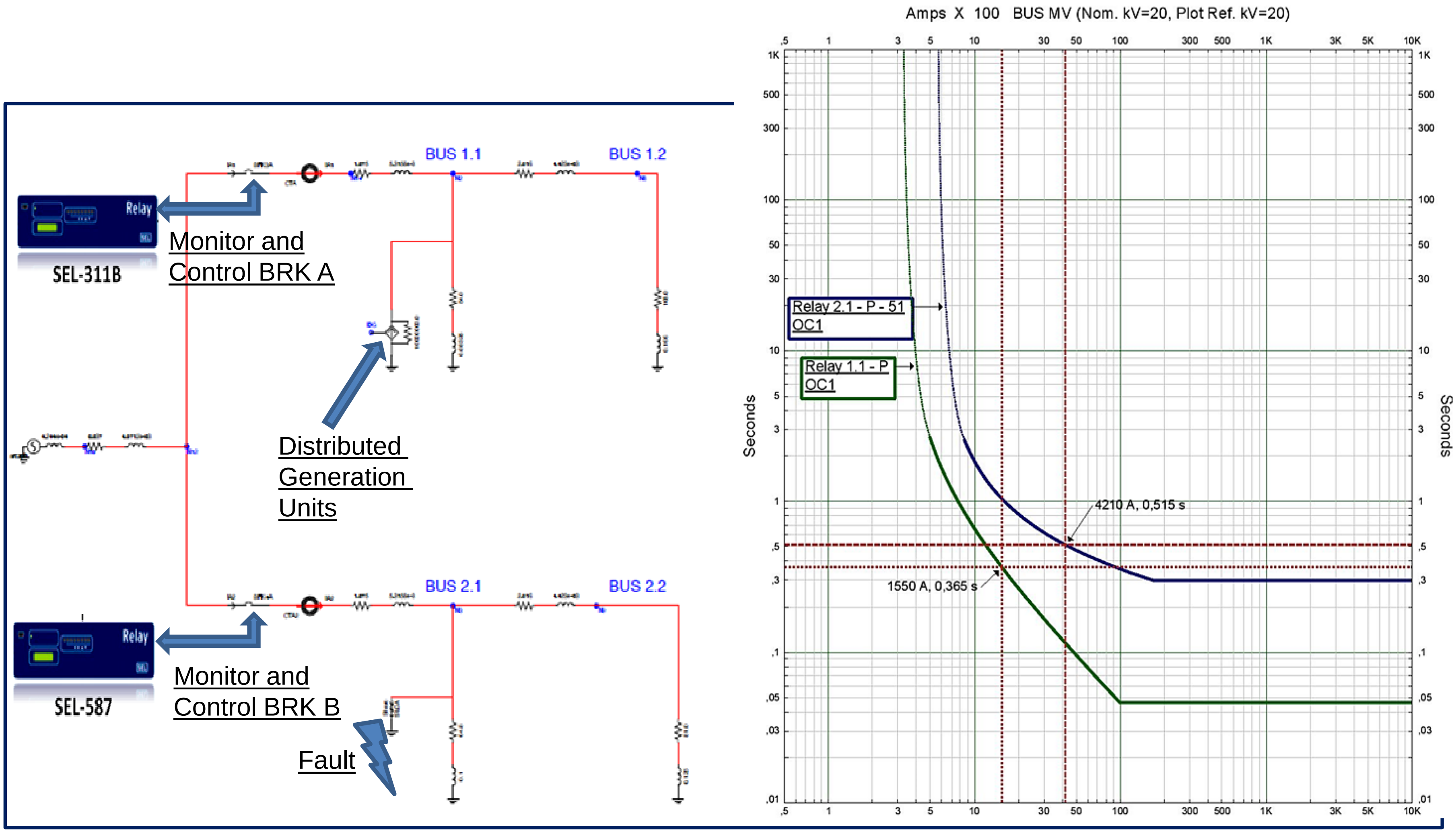


HIL testing-Protection Blinding

- 3-phase fault at Bus 1.2
- Total short-circuit current = 3,43 kA
- Short-circuit current through SEL-311B (grid's contribution) = 0,932 kA (primary)
- Time for fault clearance = 2,28 s

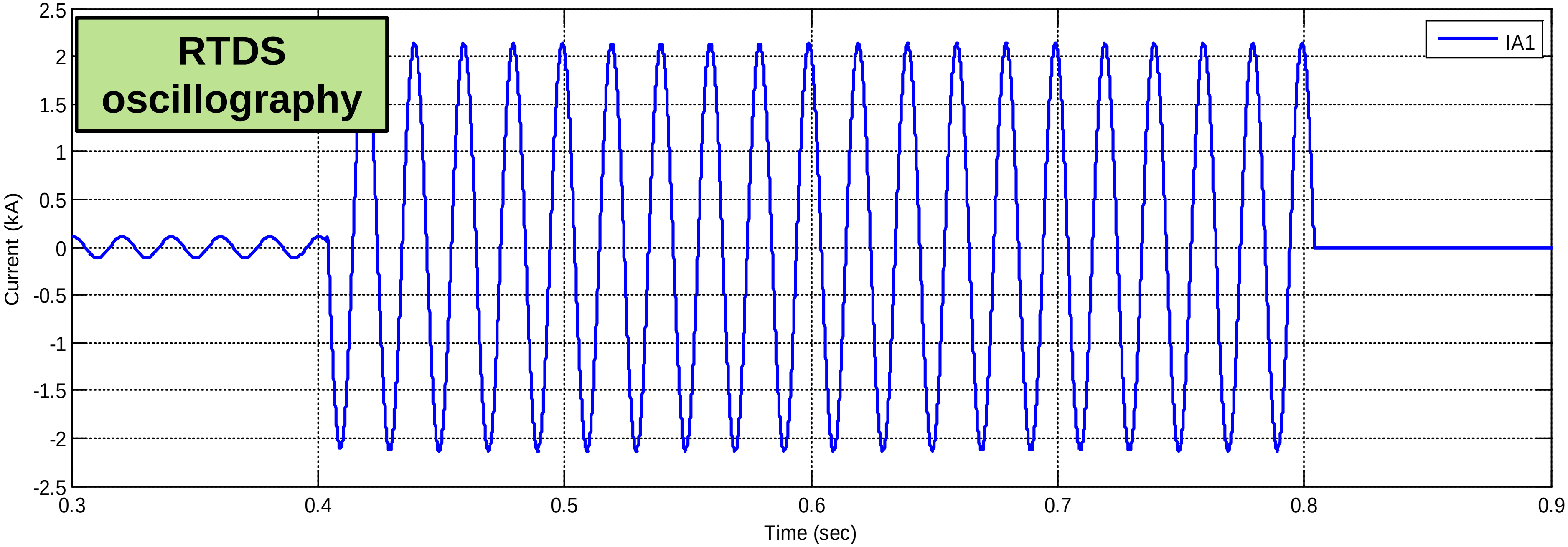


HIL testing-Sympathetic tripping



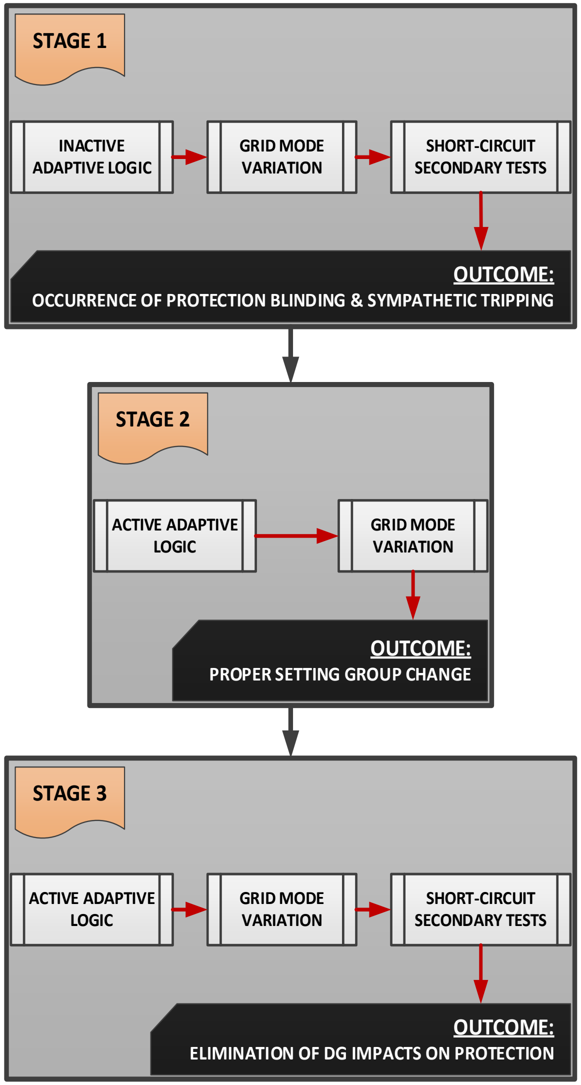
HIL testing-Sympathetic tripping

- 3-phase fault at Bus 2.1
- Short-circuit current through SEL-311B (Feeder 1) = 1,51 kA (primary)
  - Operating time = 400 ms
- Short-circuit current through SEL-587 (Feeder 2) = 3,95 kA (primary)
  - Operating time = 551 ms



Evaluation of the Adaptive Protection System

- *The evaluation procedure is composed of three stages*
- *In the first stage, the adaptive logic is inactive, and the prospect of protection blinding and sympathetic tripping incidents is confirmed, depending on the grid operating mode and the initial protection settings.*
- *Subsequently, the whole adaptive protection logic is put into effect, and the proper adjustment of relay setting groups to grid mode variations is validated.*
- *Finally, in the third stage, the same short-circuit secondary tests as in the first stage are re-conducted, demonstrating that adaptive protection can address the arising DG impacts on distribution protection.*



Evaluation of ICCS Adaptive Protection System (2/2)

Relay log file showing Setting Group transition in the proposed adaptive scheme

10:22:22.798	IN103	Asserted	Signal to activate Setting Group 2
10:22:22.808	IN102	Deasserted	Signal to deactivate Setting Group 1
10:22:22.898	SG2	Asserted	Setting Group 2 activated
10:22:22.898	SG1	Deasserted	Setting Group 1 deactivated
10:22:24.763	Relay settings changed		Successful transition from SG1 to SG2

- *The determination of feeder relay setting groups (SGs) in the proposed adaptive protection system is formulated as a NLP optimization problem.*

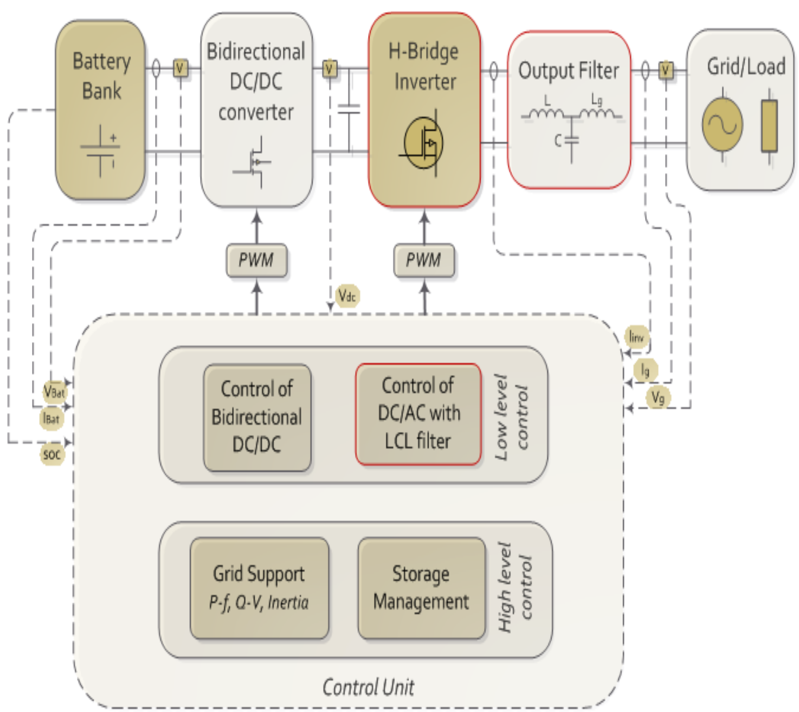
- *For each possible configuration, distribution feeders are considered to be protected by directional overcurrent relays (DOCRs) with the associated SG enabled.*

- *The objective function aims at minimizing the aggregate operating time of both primary and backup DOCRs installed at the distribution network, subject to technical constraints imposed by DSO.*

2) CHIL for Islanded and grid connected operation of VSC

Set Requirements → Design → Testing

- ❑Grid connected Operation
- ❑Islanded Operation
- ❑Bidirectional Power flow
- ❑Grid Support Functions



System Modeling & Control Design

Step 1
Matlab/Simulink Simulations

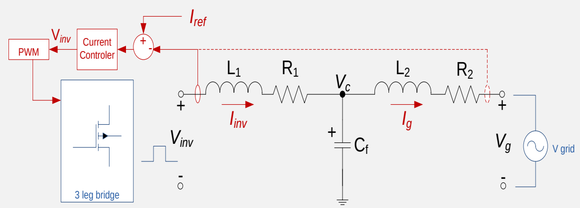
Step 2
Controller-Hardware-in-the Loop Testings (CHIL)

Step 3
Power-Hardware-in-the Loop Testing (PHIL)

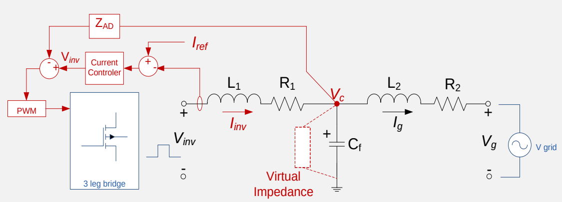
Investigated Control methods for VSC

Grid Connected operation

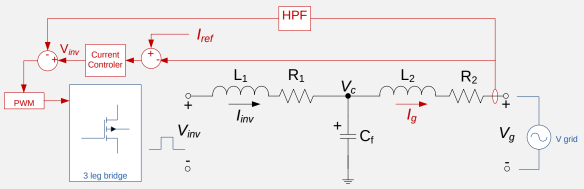
- **PI SF Voltage Control**



- **Virtual Resistance**

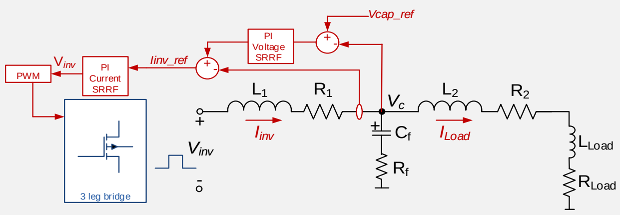


- **2DoF**

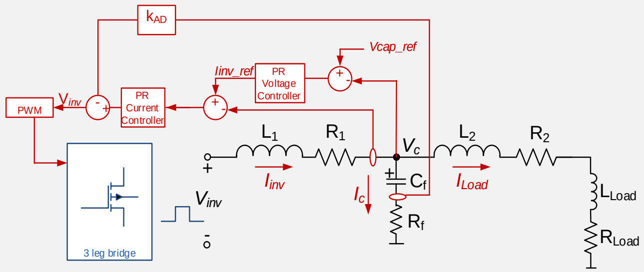


Islanded operation

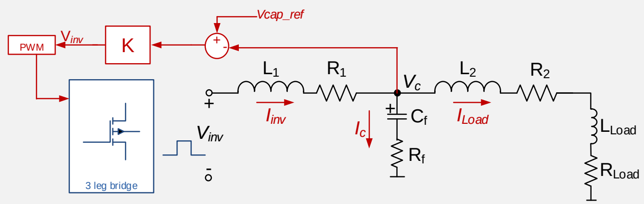
- **PI SRRF Voltage Control**



- **PR Voltage Control**

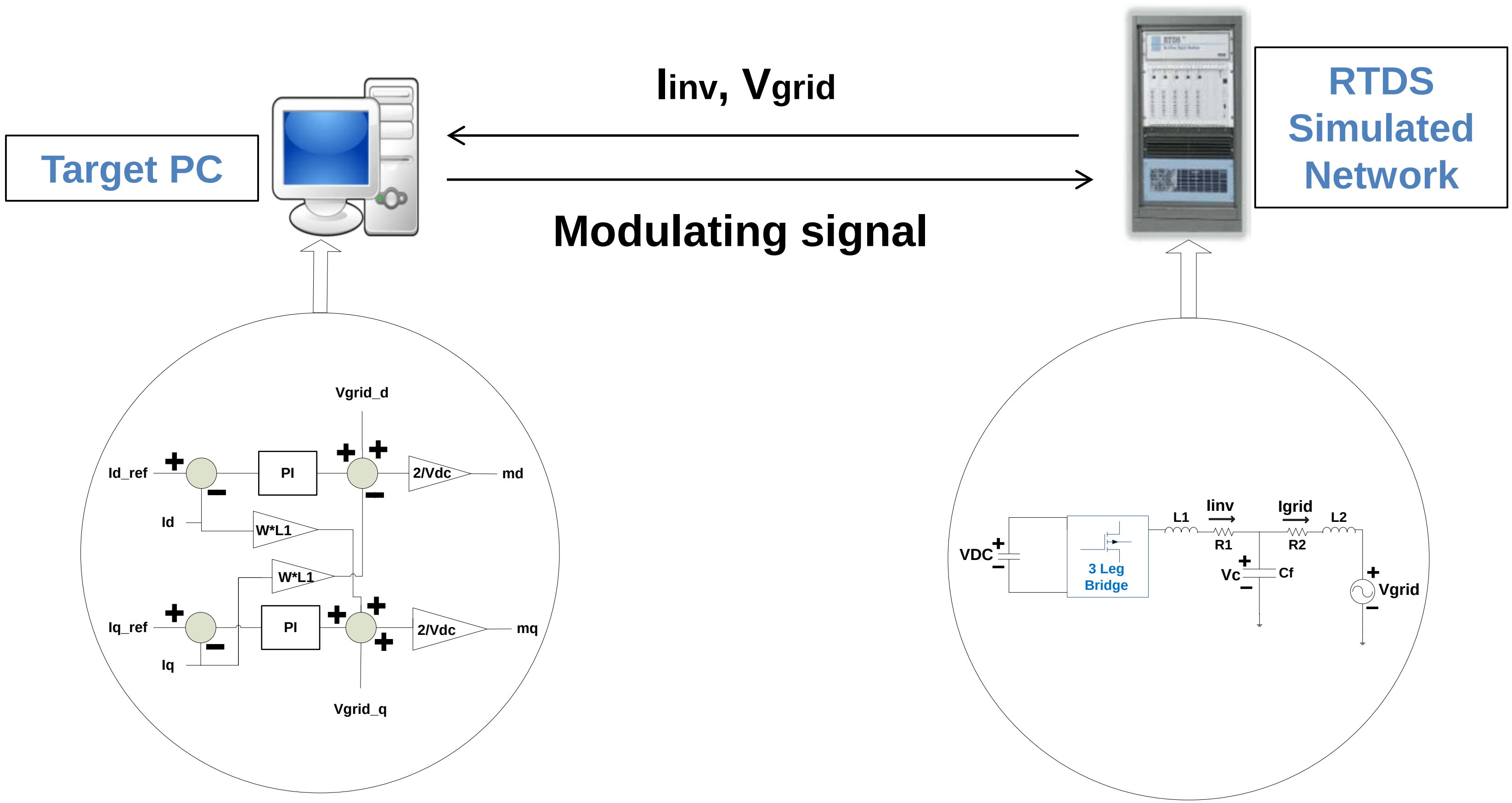


- **H-Infinity Control**



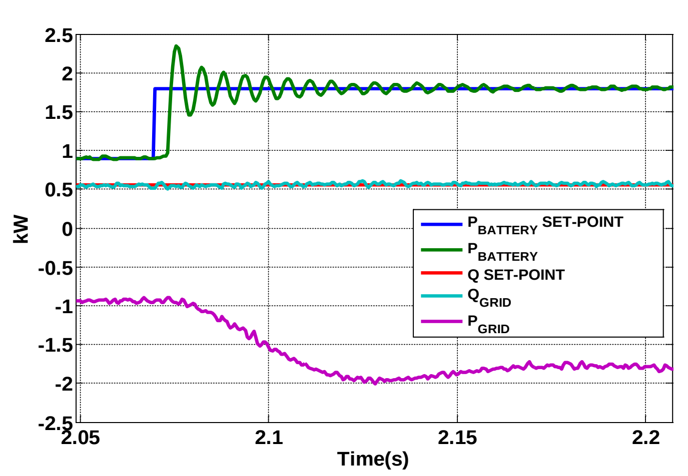
Grid Connected inverter-CHIL

- The measurements from the RTDS are transferred to the target PC (controller)
- The target PC (controller) performs the control and sends the modulating signal back to the RTDS

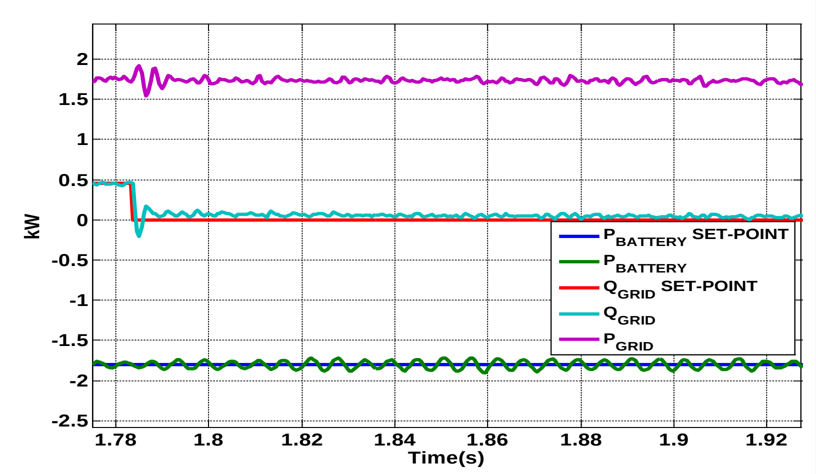


CHIL Test Results-Grid Connected

- **PI SF Voltage Control**



Battery Active Power Tracking

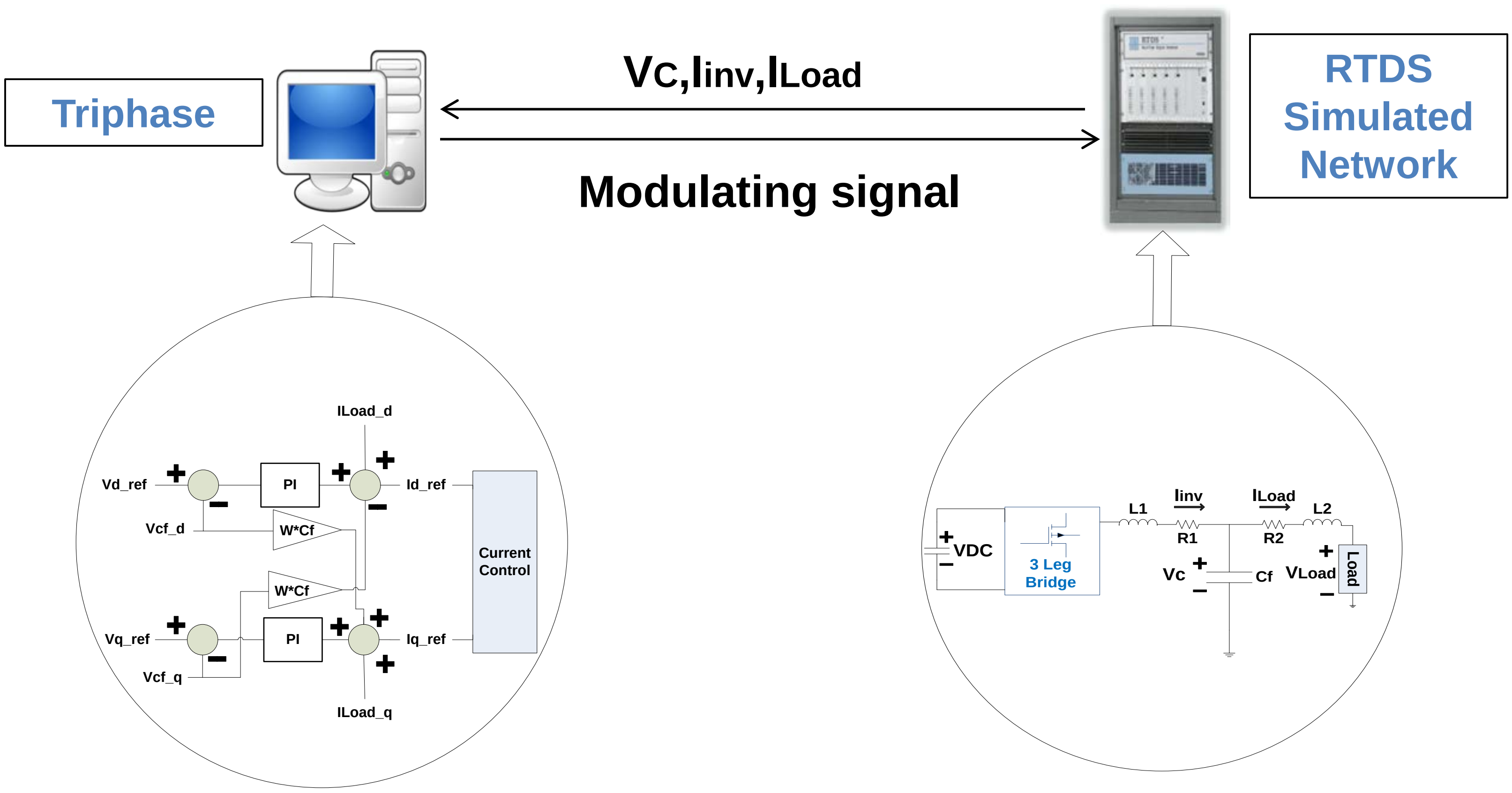


Reactive Power Tracking

- The DC/DC control algorithm regulates the battery power to the new set-point (charge at 1,8kW).
- The DC/AC control algorithm provides that power from the grid by regulating the DC BUS voltage.
- The reactive power set-point is set to zero and the reactive power is regulated at that value.

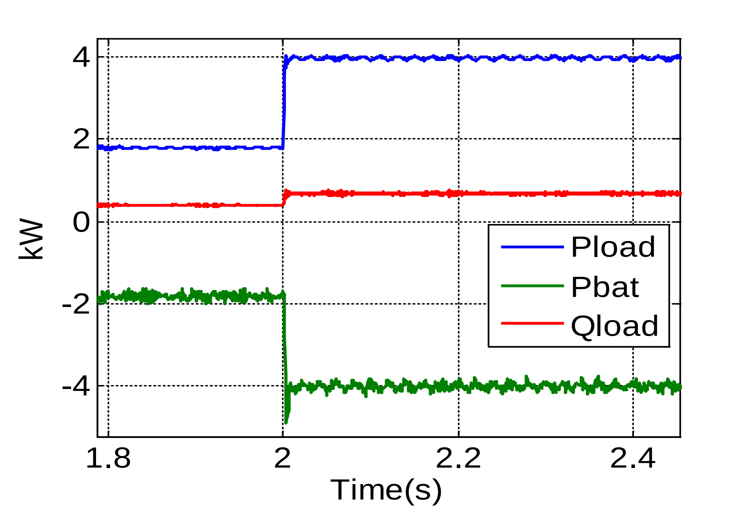
Islanded inverter - CHIL

- The measurements from the RTDS are transferred to the target PC (controller)
- The target PC (controller) performs the control and sends the modulating signal back to the RTDS

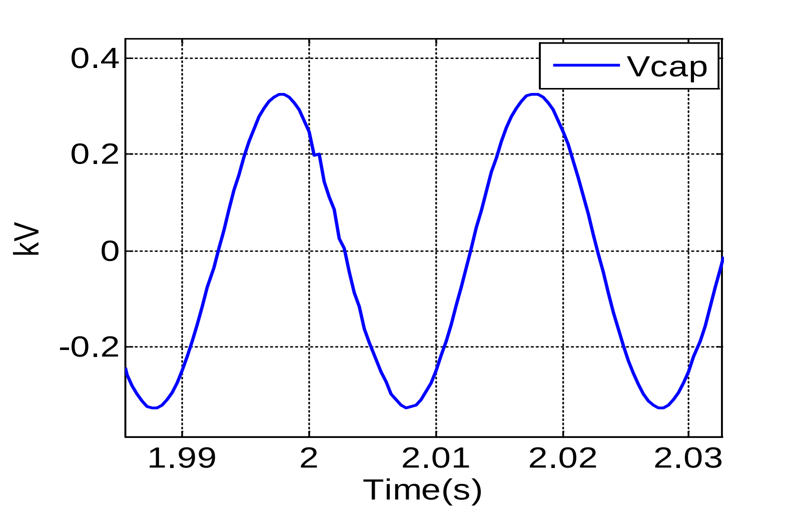


CHIL Test Results-Islanded(1)

- **PR Voltage Control**



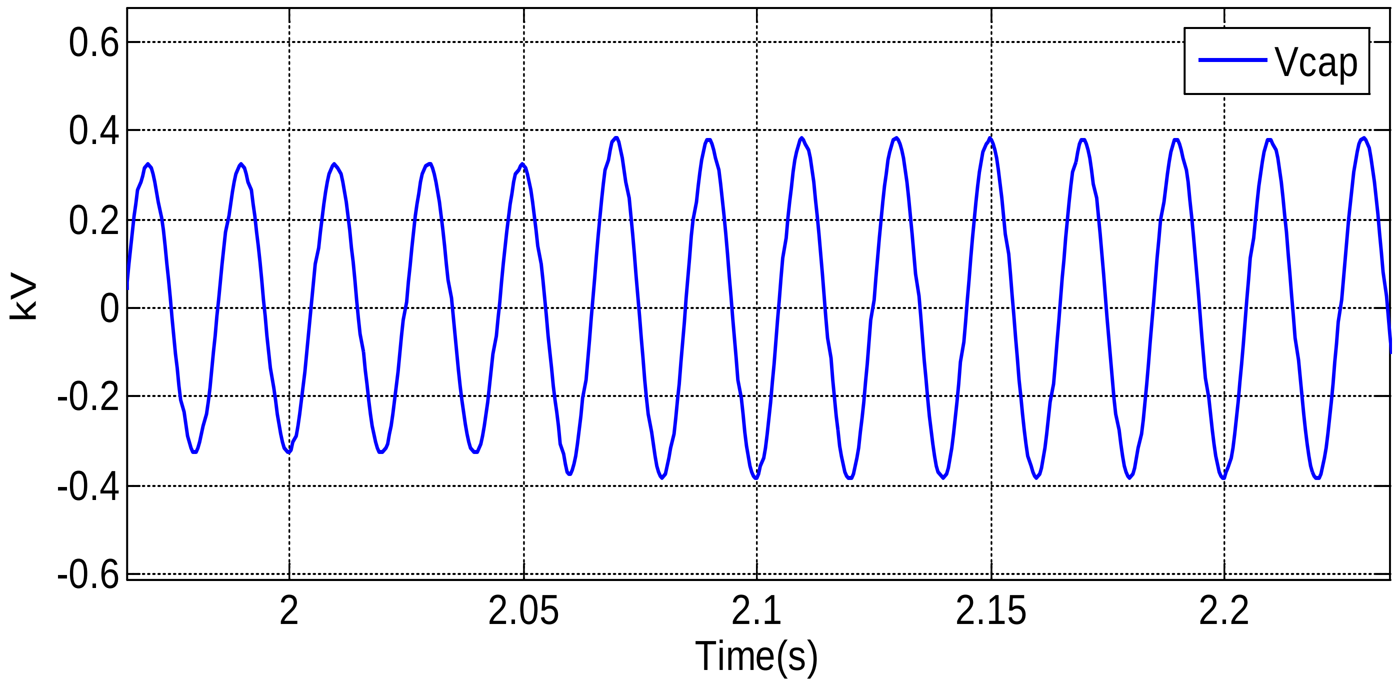
Pload - Qload Change



Capacitor Phase voltage

- At 2s the load is increased from 1.8kW/0.98 to 4kW/0.95 power factor and the DC/AC control algorithm tracks fast the nominal voltage providing the nominal load power.
- The DC/DC control algorithm provides that power from the batteries by regulating the DC BUS voltage.

CHIL Test Results-Islanded(2)

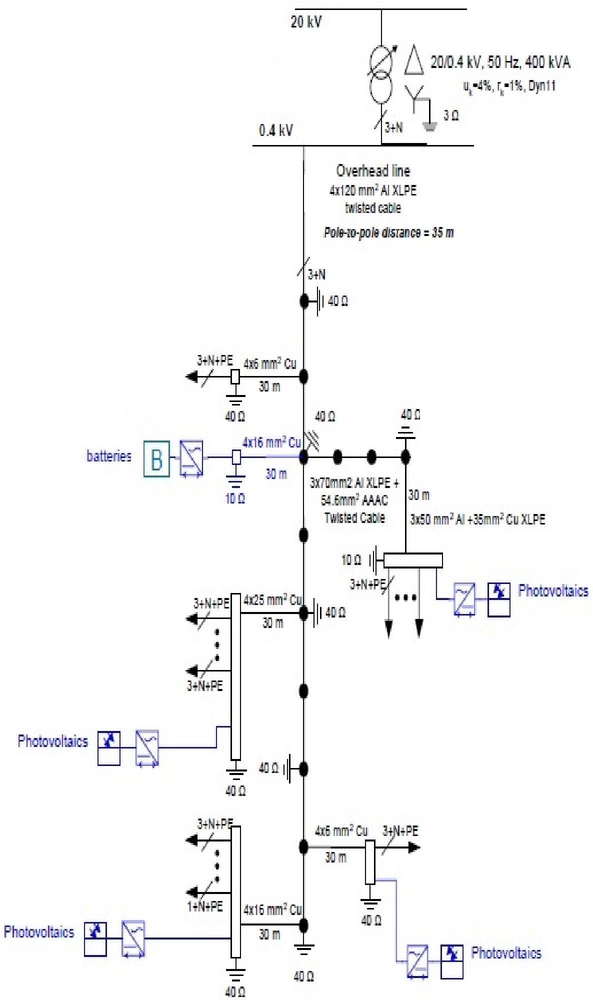


Voltage tracking at voltage reference change

- After a change in the RMS value of the voltage reference signal the load voltage tracks fast the new reference signal.

3) Coordinated Voltage Control - Simulated Network

- Low voltage Benchmark Network (based on CIGRE)
  - 12 buses
  - MV/LV transformer with On-Load Tap Changer - 17 steps - 1.25%$_{pu}$/step
  - **5 residential** consumers - 0.85 lagging , **4 PVs** - 0.9 minimum power factor (leading or lagging), **1 BESS**
- Development of the Coordinated Voltage Control
  - **Coordinated**: *Cooperation among the regulating devices.*
  - **Centralized:** *Central controller is used for the coordination.*
  - **Optimal**: *The algorithm is an optimization problem*
  - **Real-time**: *The algorithm runs in discrete iterations, relying on real-time measurements from Smart Meters and other devices.*



Coordinated Voltage Control – Optimization Problem Formulation

$$\min_{x} f(x) = w_1 * \sum_{i=1}^{12}\sum_{j=1}^{12} P_{losses,ij} + w_2 * \sum_{k=1}^{6}(V_k - 1)^2 + w_3 * |tap_{new} - tap_{current}|$$

$$x = [V_1 \quad \dots \quad V_{12} \quad \delta_1 \quad \dots \quad \delta_{12} \quad P_{bat} \quad Q_{bat} \quad Q_{pv,1} \quad Q_{pv,2} \quad Q_{pv,3} \quad Q_{pv,4} \quad Tap\_changes]$$

$$P_{losses,ij} = -G_{ij}[V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}]$$

$$tap_{new} = Tap\_reference + Tap\_changes$$

w_1, w_2, w_3 = weights for the objective function terms

Constraints:

Bounds:

$$0.9 \le V_i \le 1.1$$

$$0^{\circ} \le \delta_i < 360^{\circ}$$

$$P_{discharge,max} \le P_{bat} \le P_{charge,max}$$

$$-S_{bat} \le Q_{bat} \le S_{bat}$$

$$|Q_{pv,i}| \le P_{pv,i} * \tan(\cos^{-1}(0.8))$$

$$-8 \le Tap\_changes \le 8$$

Inequalities:

$$P_{pv,i}^2 + Q_{pv,i}^2 \le S_{pv,i}^2$$

$$P_{bat}^2 + Q_{bat}^2 \le S_{bat}^2$$

$$Y_{ij} * (\tilde{V}_i - \tilde{V}_j) \le I_{ij,limit}$$

Equalities:

$$V_1 = 1$$

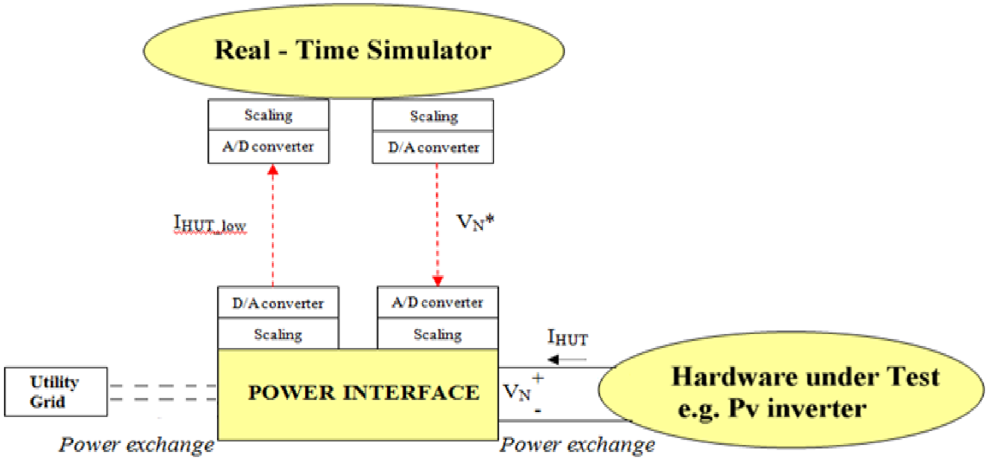
$$\delta_1 = 0$$

$$P_{pv,i} - P_{load,i} = V_i \sum_{j=1}^{n} V_j[G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}]$$

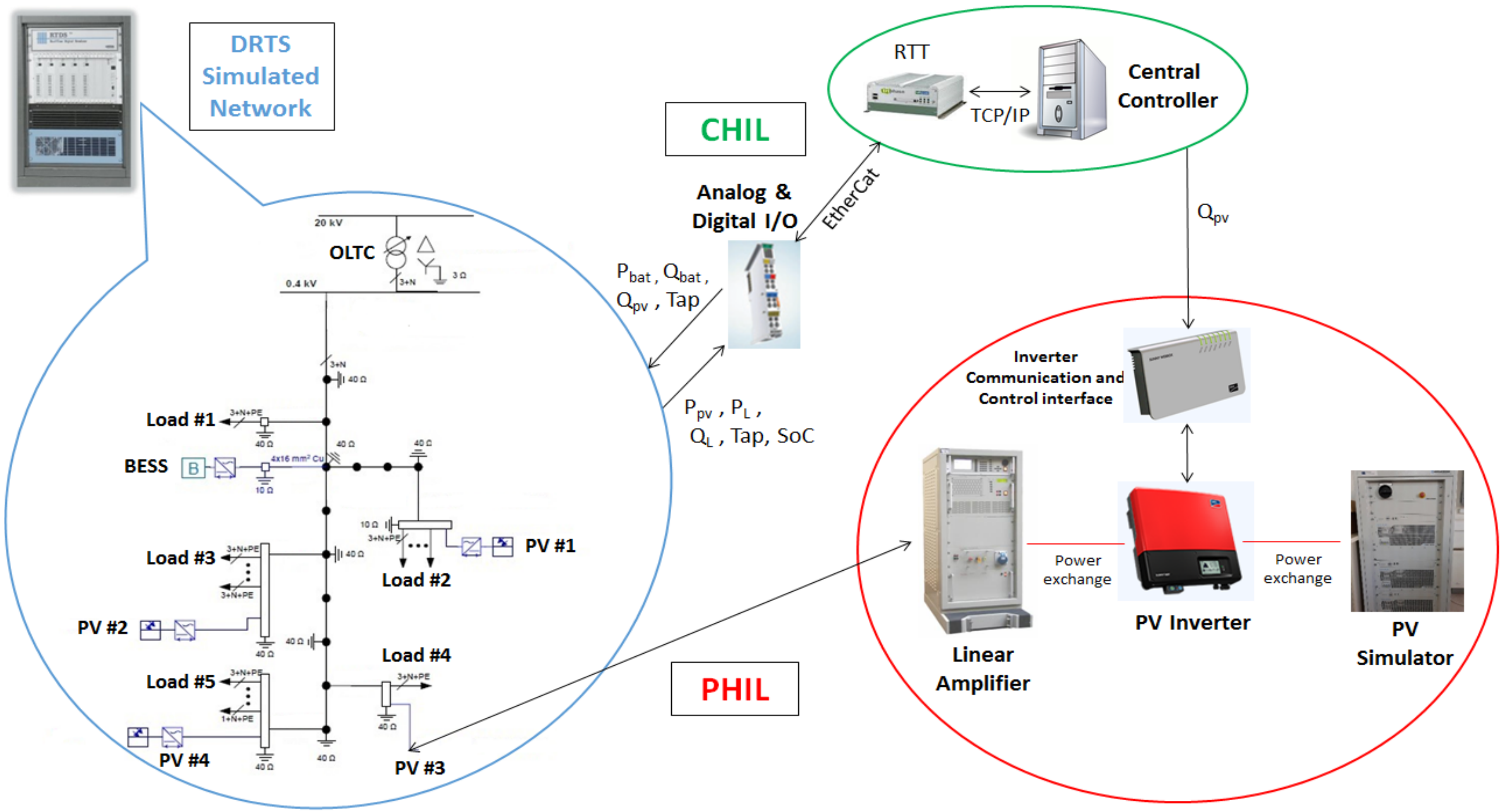
$$Q_{pv,i} - Q_{load,i} = V_i \sum_{j=1}^{n} V_j[G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}]$$

CVC validation: Laboratory Setup

- The CVC algorithm was tested in
  - pure simulation,
  - Software in Loop (SIL) - CHIL,
  - finally combined CHIL and PHIL
- Power Hardware in the Loop (PHIL):
  - Power equipment (e.g. motor, PV inverter) is incorporated into a simulated system
  - The RTDS handles low level signals. Power Amplification is necessary.



CVC validation: Laboratory Setup



Laboratory Setup for combined PHIL and CHIL of CVC algorithm

Conclusions

- Active distribution networks require advanced control functions and effective testing methods
- HIL testing proves to be an effective way of testing network controls and component controls in realistic and flexible conditions

Thank you for your attention

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