CHIL and PHIL Simulation for Active Distribution Networks

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@University of Strathclyde

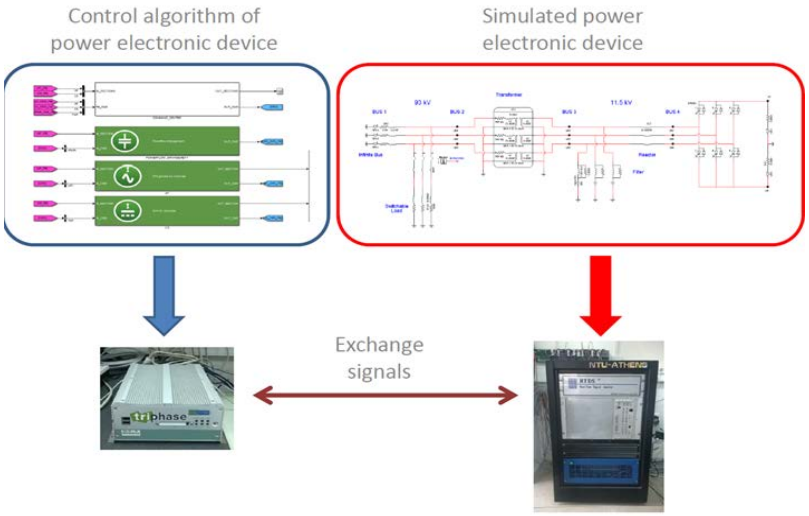
Overview

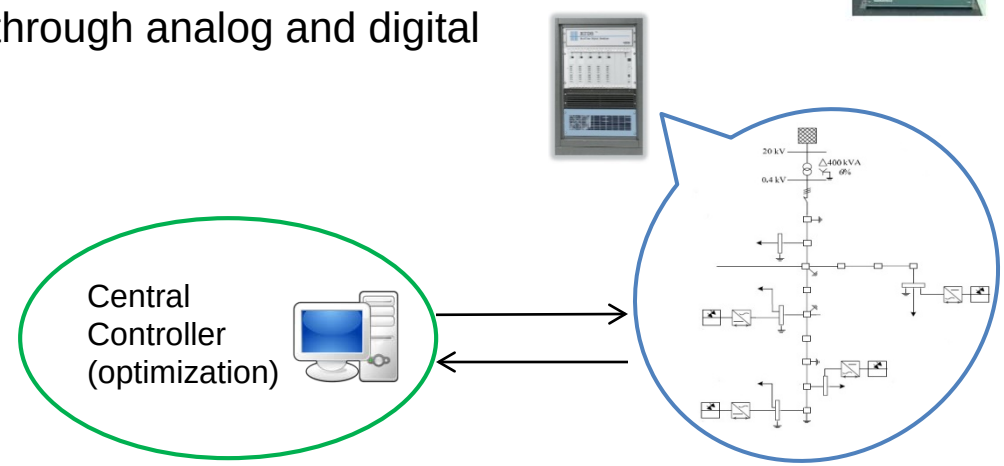
- **Coordinated voltage controller testing:** *Combined Controller HIL (CHIL) and Power HIL (HIL) simulation*
- **Adaptive protection scheme testing:** *CHIL simulation*
- **DER Inverter controls testing:** *CHIL simulation*

Controller Hardware in the Loop testing

- Testing of advanced control algorithms of power electronic converters (DC/DC, DC/AC, AC/DC/AC, etc.).
- Testing of distribution management system controls (e.g. coordinated voltage control)
- The communication between the RTDS and hardware controller is achieved through analog and digital signals.

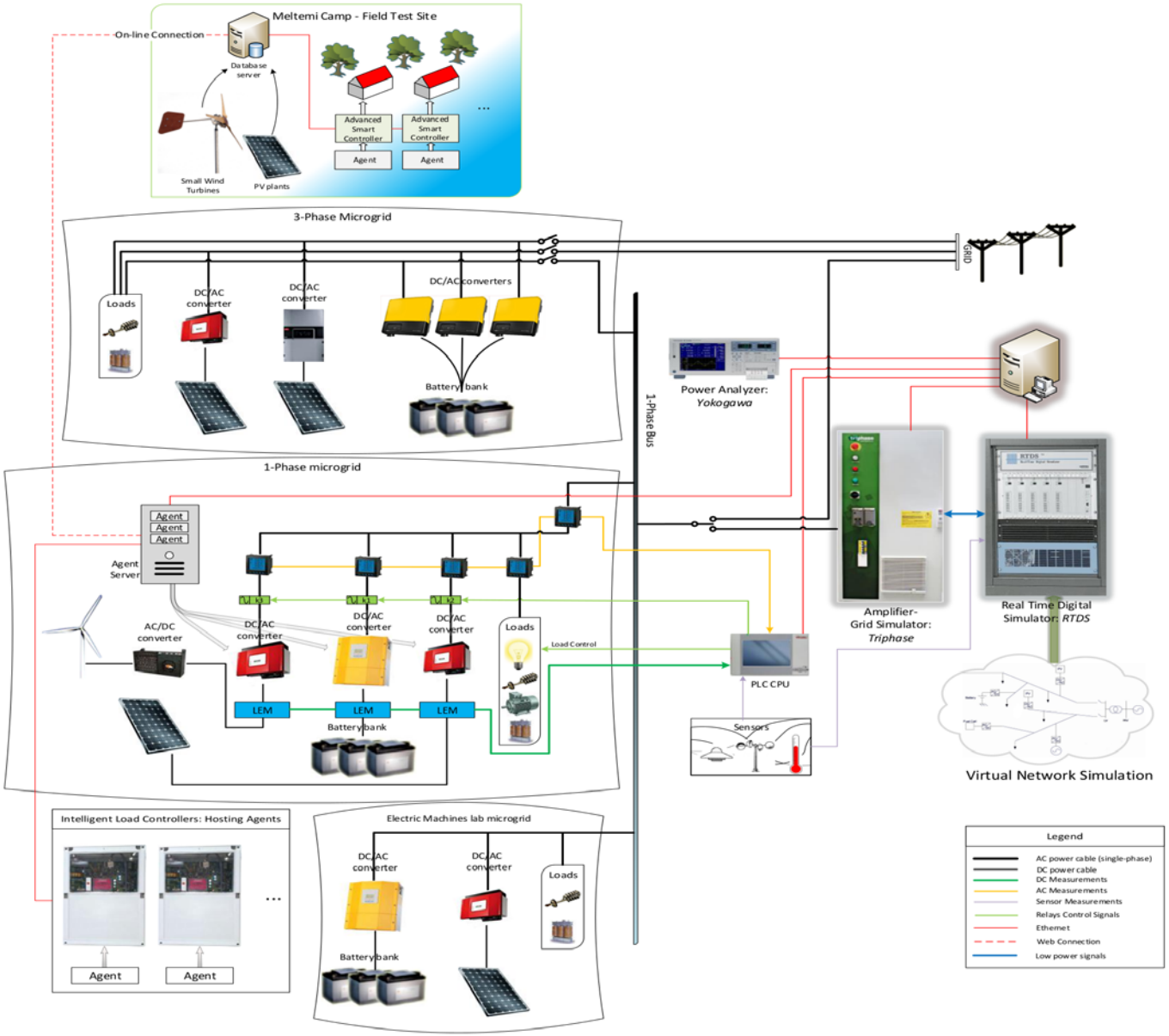
Inverter control testing





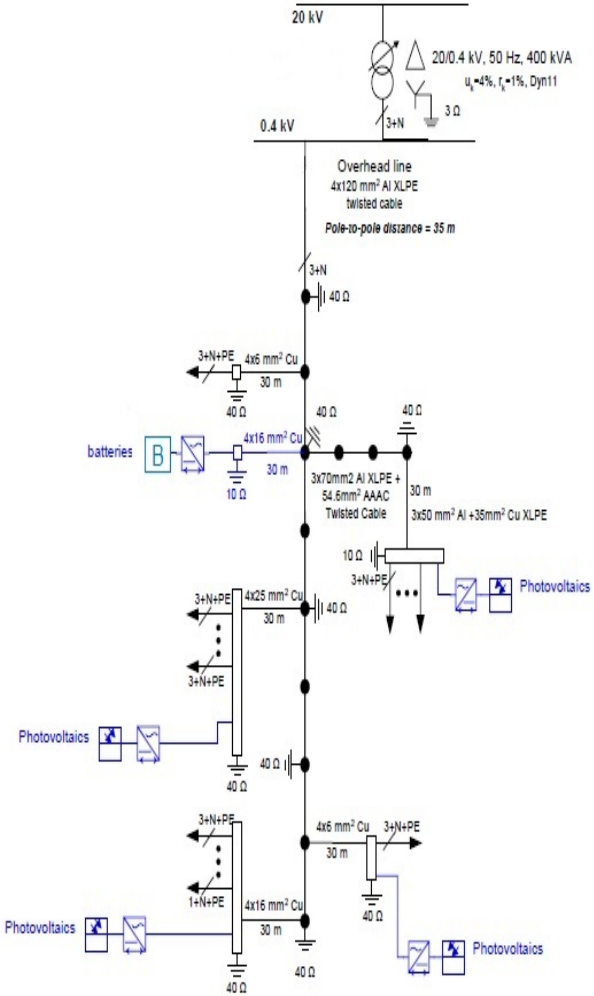
Network controls testing

NTUA lab


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

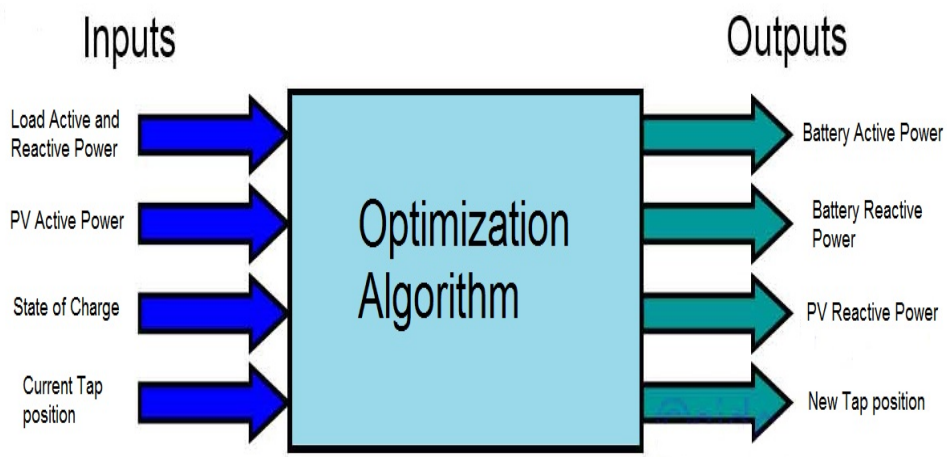
1) Coordinated Voltage Control - Simulated Network

- 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.*



Centralized Coordinated Voltage Control (CVC)

- Optimal solution to voltage rise (due to high DG penetration) and voltage drop (during peak load periods) problems
- Optimization problem: Mixed Integer Non-Linear Programming (MINLP)
- Inputs:
  - Load active and reactive power
  - PV active power
  - Battery SoC
  - Current Tap position
- Outputs (operational set-points):
  - Battery active and reactive power
  - PV reactive power
  - New Tap position
- Battery Management



Coordinated Voltage Control – Optimization Problem Formulation

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

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

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

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

$$w_1, w_2, w_3 = \text{weights for the objective function terms}$$

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:

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

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

$$Y_{ij} * (\widetilde{V_i} - \widetilde{V_j}) \le I_{ij,limit}$$

Equalities:

$$V_1 = 1$$

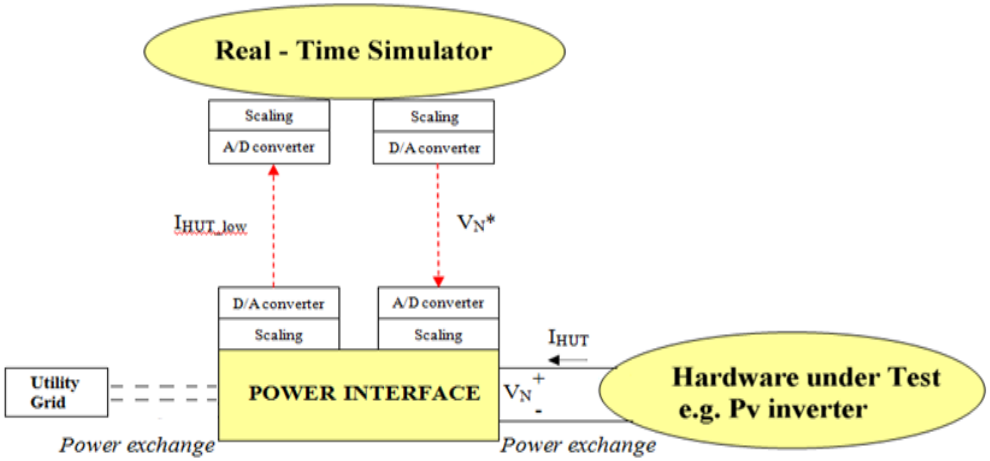
$$\delta_1 = 0$$

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

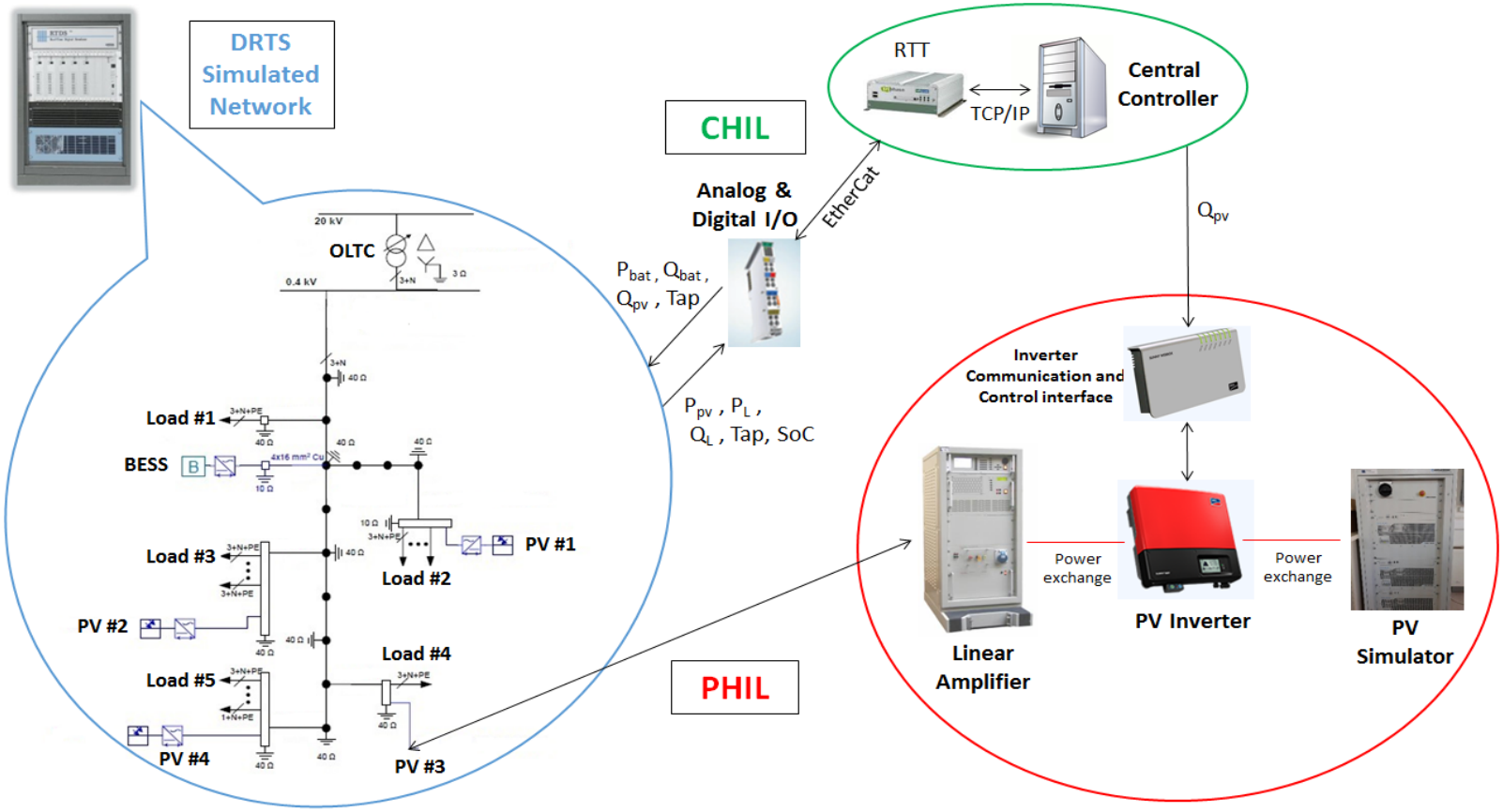
$$Q_{pv,i} - Q_{load,i} = V_i \sum_{j=1}^{n} V_j[G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}]$$

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.

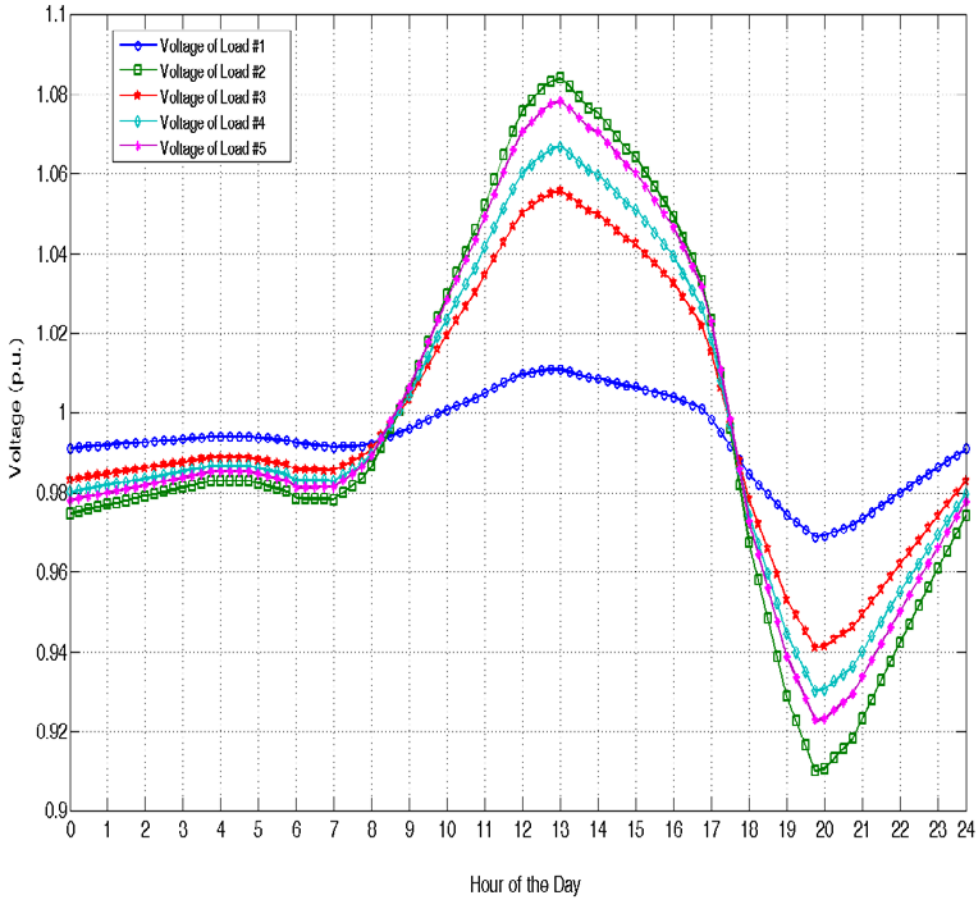


CVC validation: Laboratory Setup

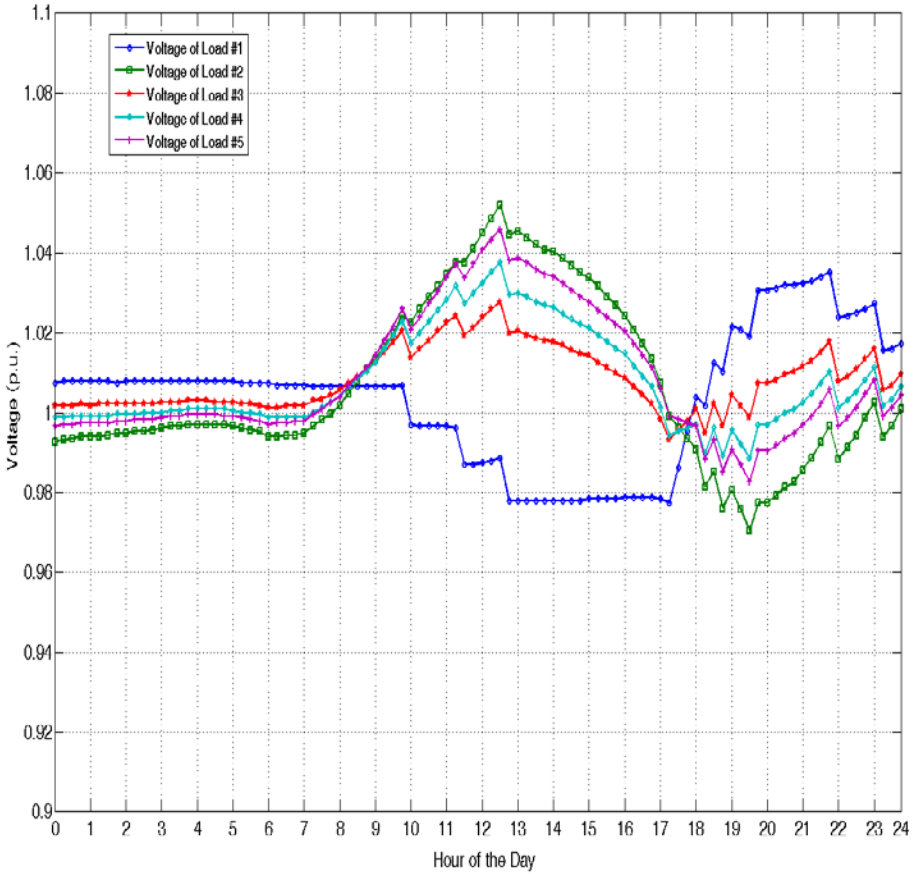


Laboratory Setup for combined PHIL and CHIL of CVC algorithm

CVC Results PHIL & CHIL

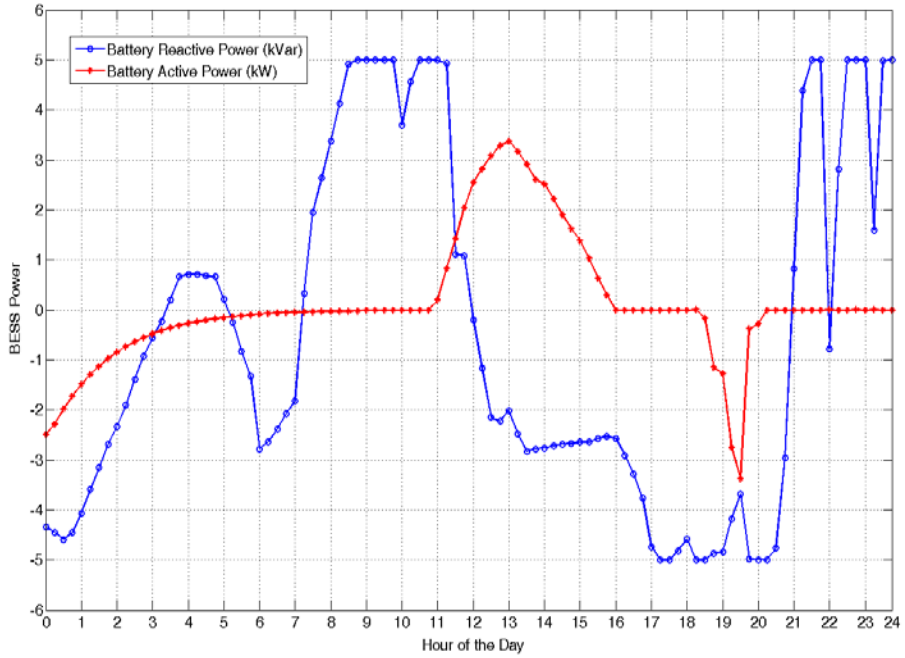


Voltage of all nodes without voltage control

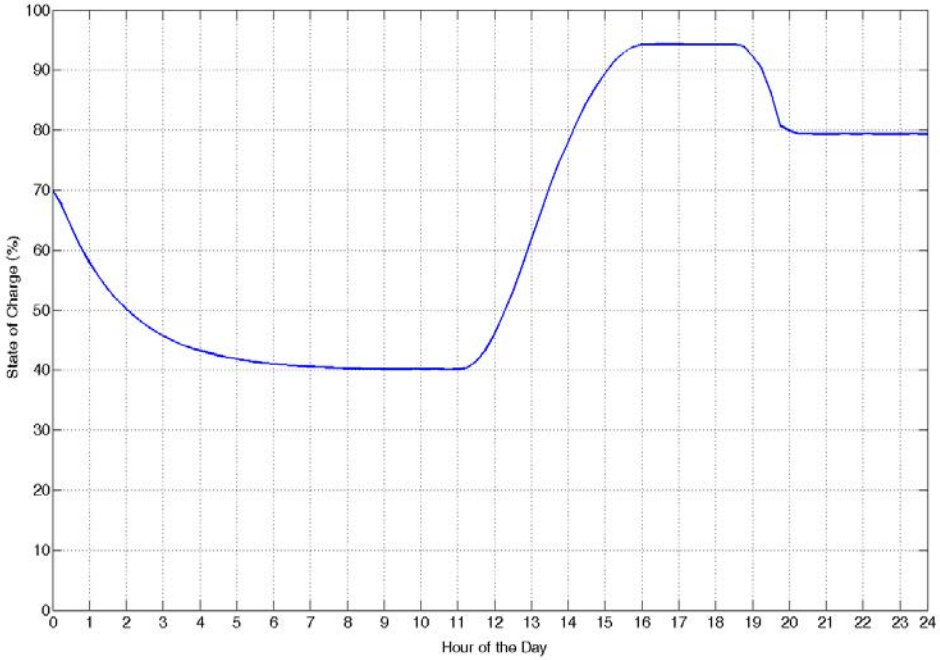


Voltage of all nodes with CVC

CVC Results PHIL & CHIL



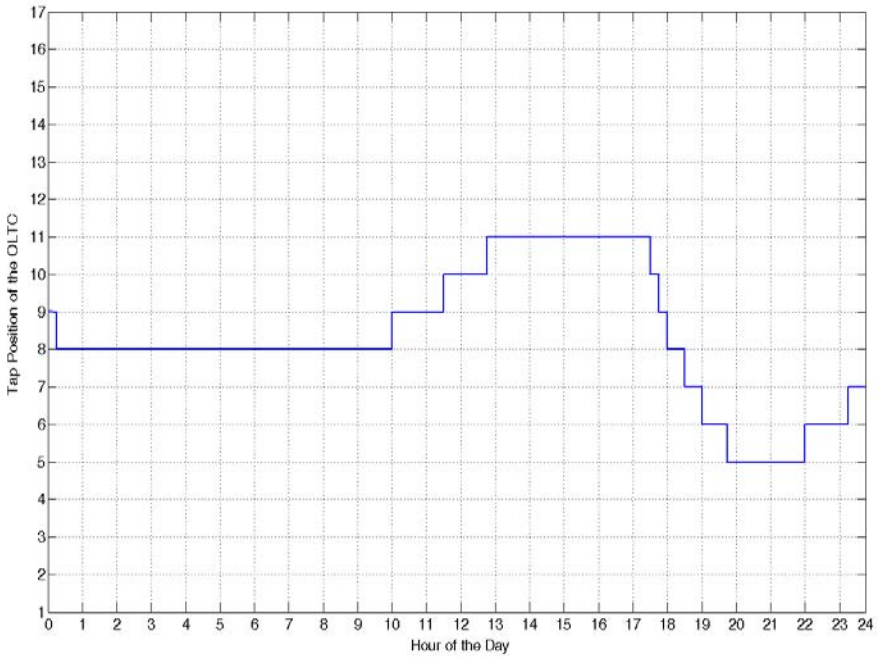
BESS active and reactive power



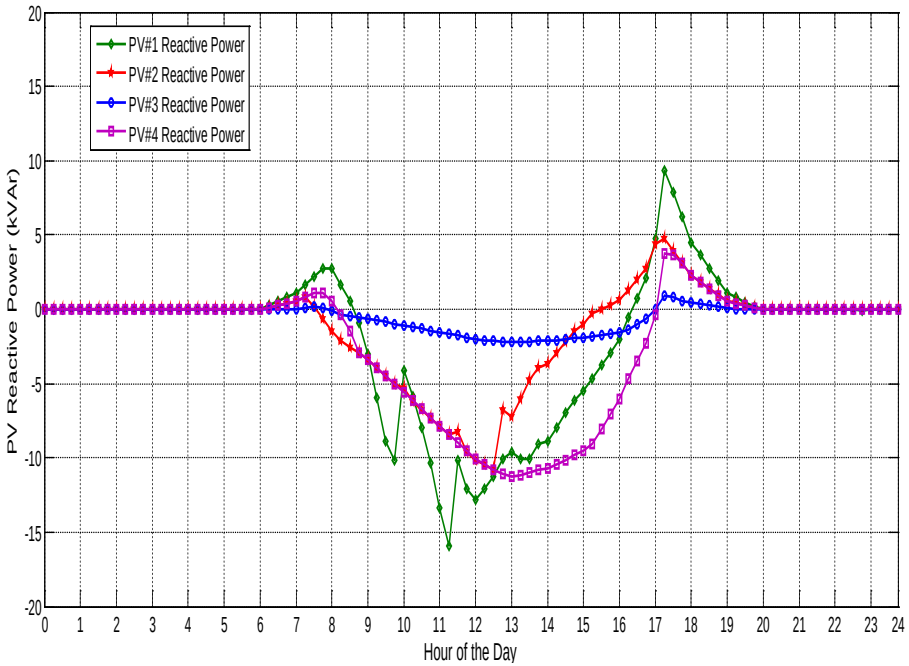
State of Charge of the BESS

- The SoC of the BESS was restored to the reference level of 40% during the night to early morning hours (12 a.m. to 9 a.m.), so that it is available for maximum charging during the midday hours of high irradiance.
- The active power exchange of the BESS was restricted to periods of either high irradiance (charge) or high load demand (discharge), where the voltage rise/drop problems are greatest.

CVC Results PHIL & CHIL



Tap Change operations of OLTC

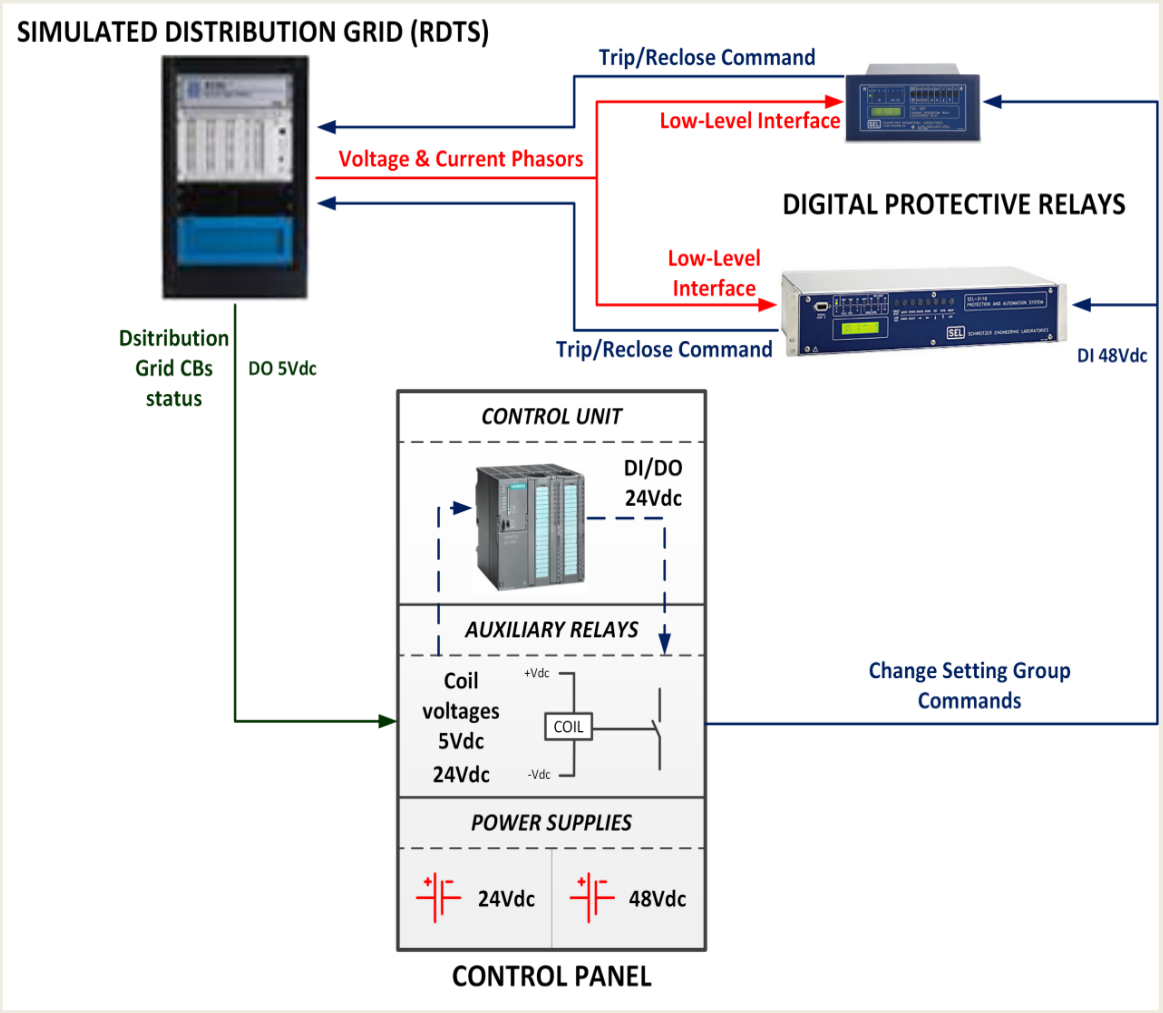


PV reactive Power exchanges

- The PV inverters contributed to voltage control by either absorbing (during hours of high irradiance to reduce the voltages) or generating (when an increase of the voltage is required) reactive power.
- The reactive power of PV inverters can only be utilized while they are also producing active power due to power factor limitation (0.8 leading or lagging).

2) Adapive protection testing scheme

- RTDS
- 2 multifunctional digital relays
- Programmable logic controller (PLC)



Adaptive protection testing scheme

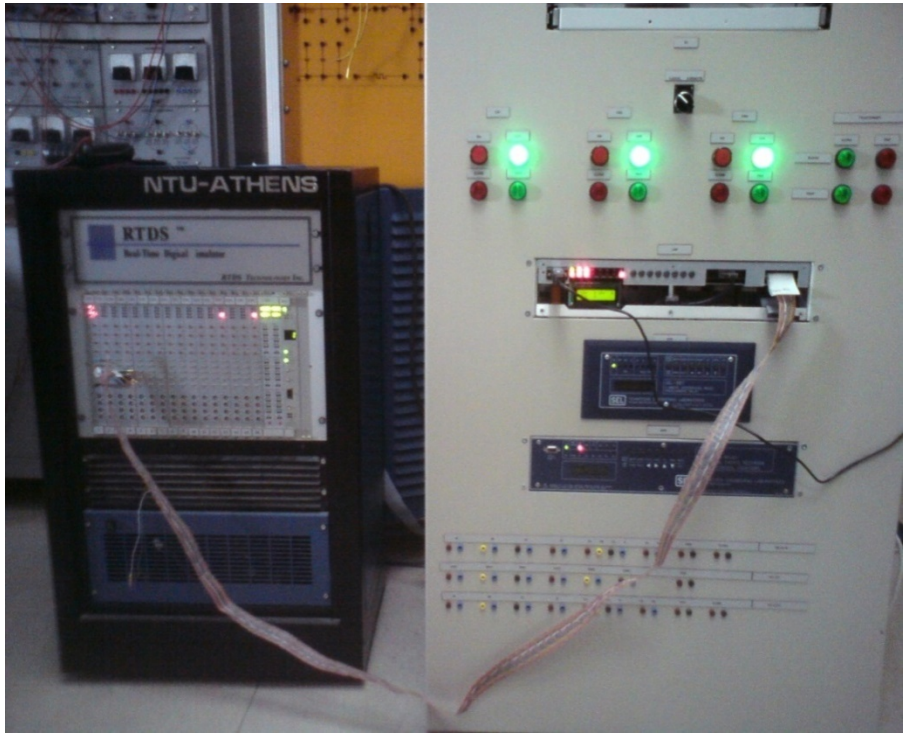
Operating Philosophy

- The examined distribution grid is simulated by means of the RTDS, while the digital relays undertake the supervision and protection of particular feeders.
- The SIMATIC S7-300 programmable logic controller is firstly responsible for the collection of the network circuit breaker statuses, and secondly for the relay transition to the proper setting group.
- Five setting groups are available and the setting values are pre-calculated according to each possible operational state of the examined distribution network.
- The RTDS also feeds the relay and the programmable controller with the on/off operation status of the grid components, such as distributed generation units, if any, network feeders and laterals and the main substation.
- The proposed logic ensures the proper adjustment of protective schemes considering every operational change, and thus can increase the dependability of distribution networks.

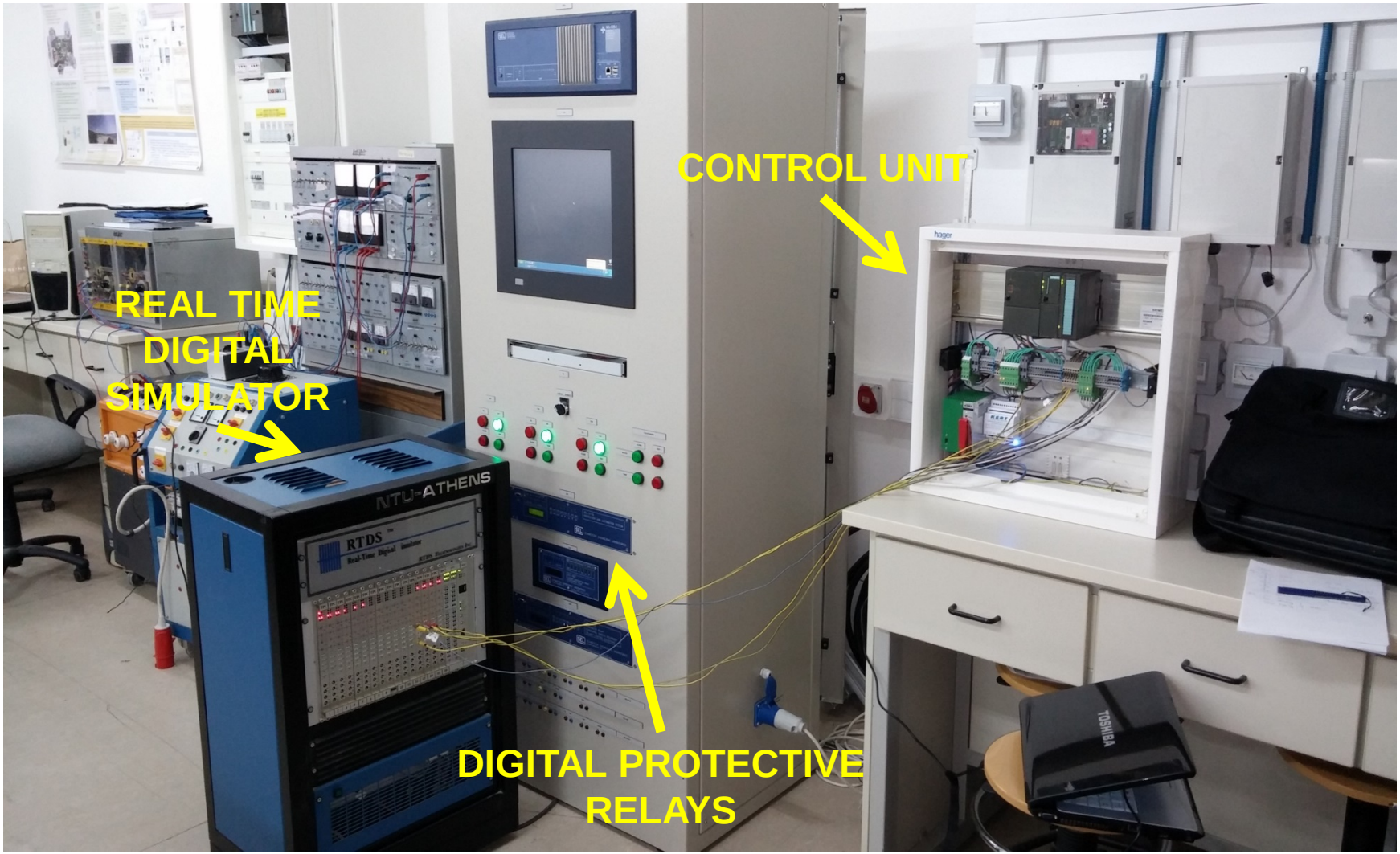
Test setup

Hardware-In-the-Loop Tests

- SEL-311B, and SEL-587 digital relays
- The relays are fed with analog signals (voltages, currents) via their low-level interface.

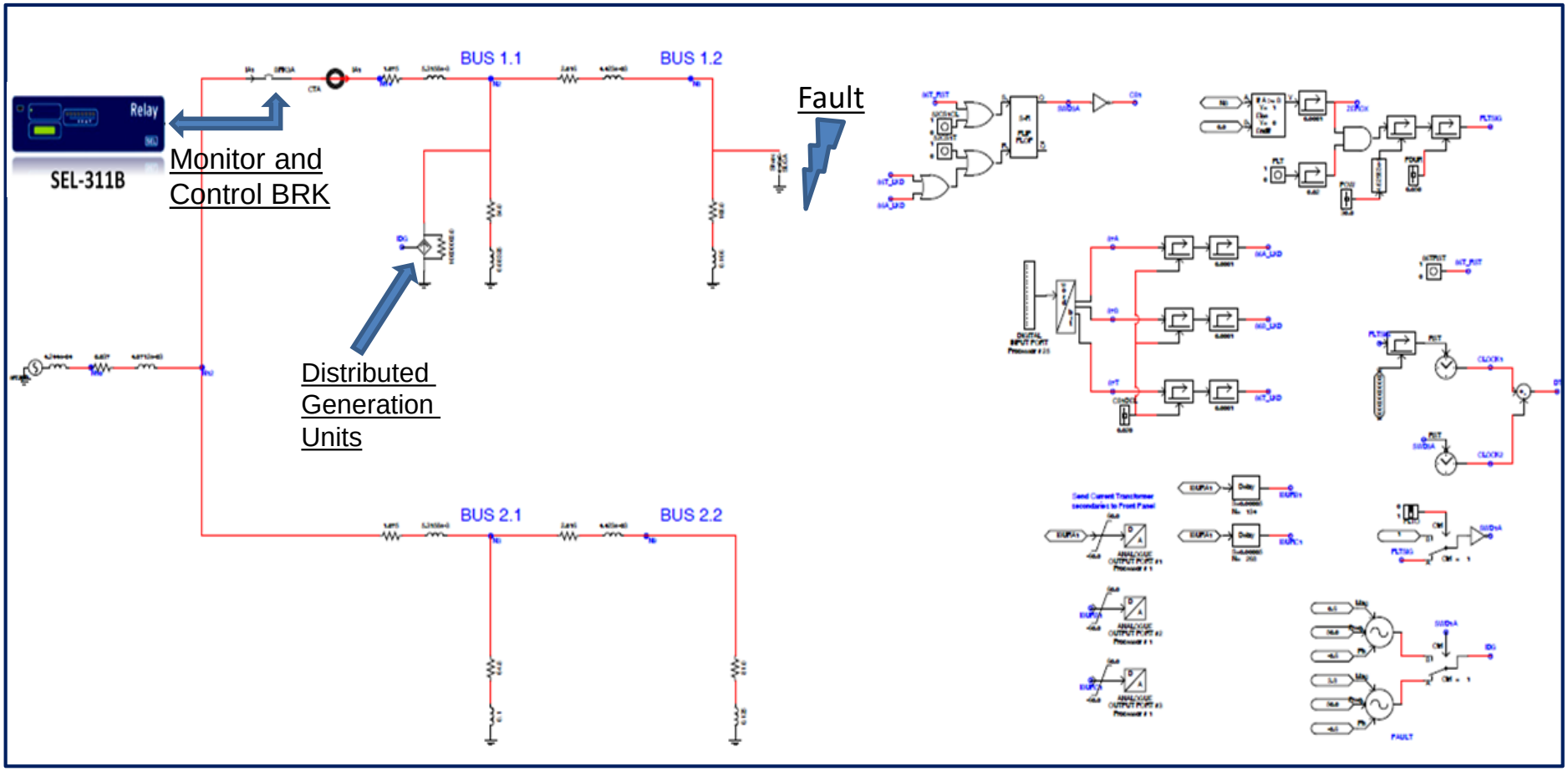


Test setup


CONTROL UNIT
REAL TIME DIGITAL SIMULATOR
NTU-ATHENS
RTDS
DIGITAL PROTECTIVE RELAYS
TOSHIBA

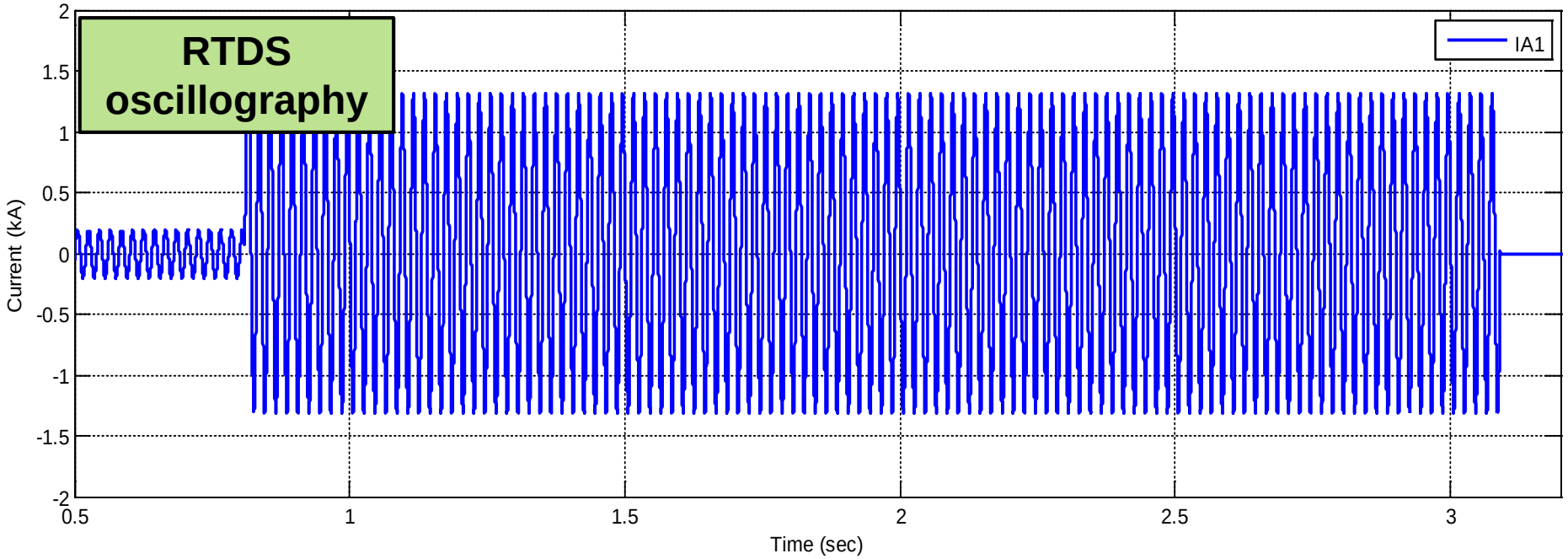
HIL testing-Protection Blinding

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

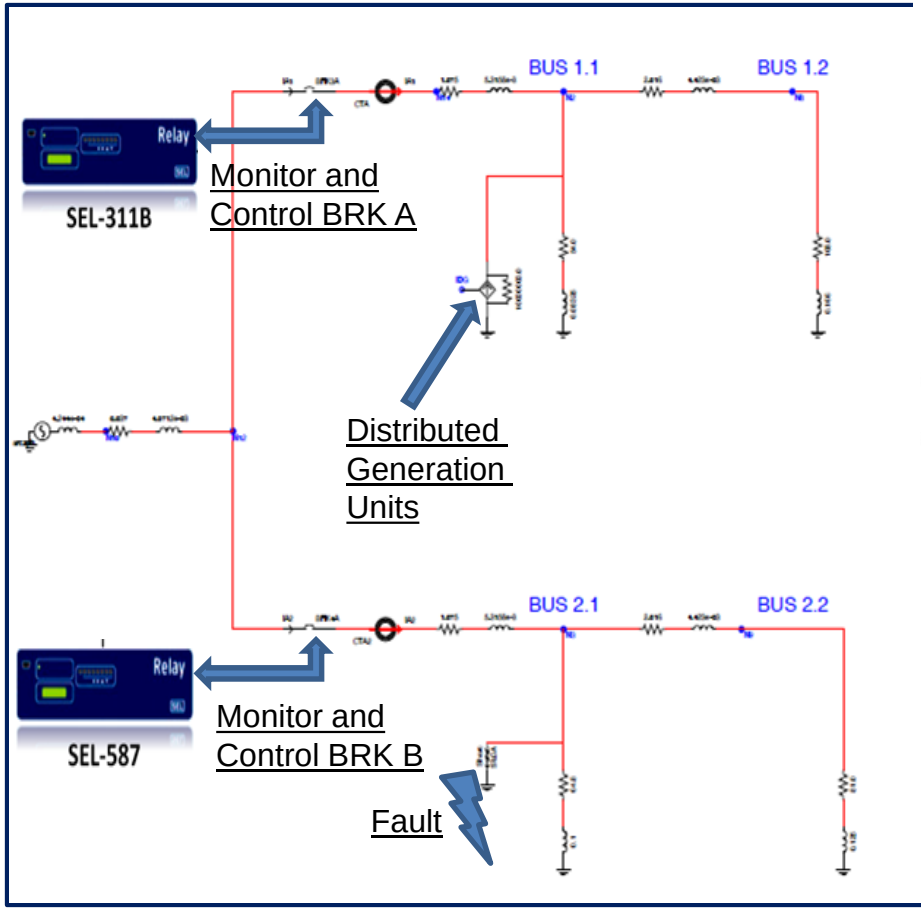


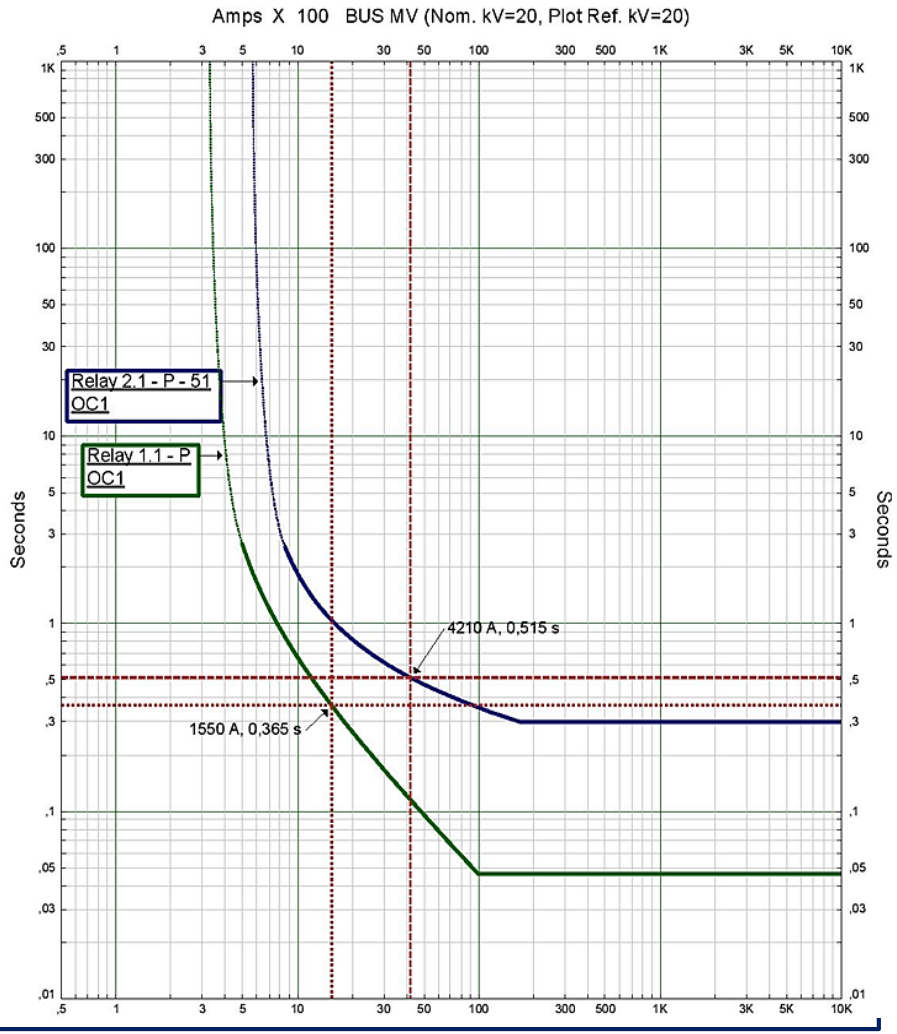
HIL testing-Protection Blinding

- 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



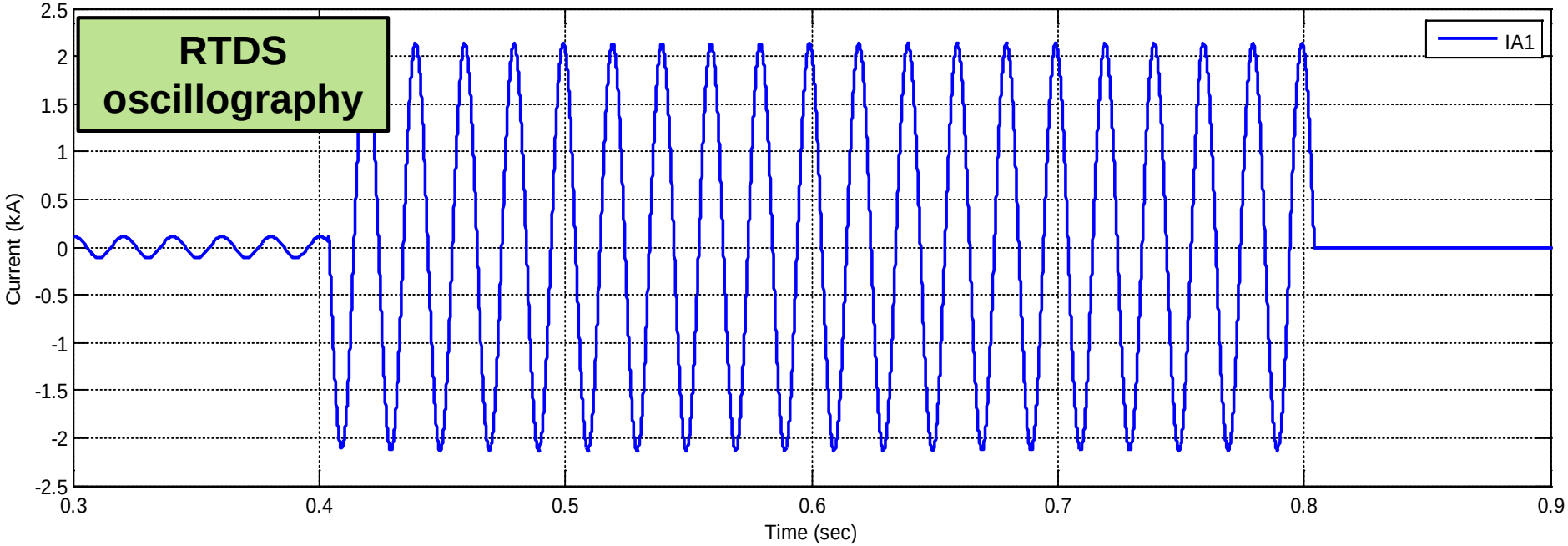
HIL testing-Sympathetic tripping





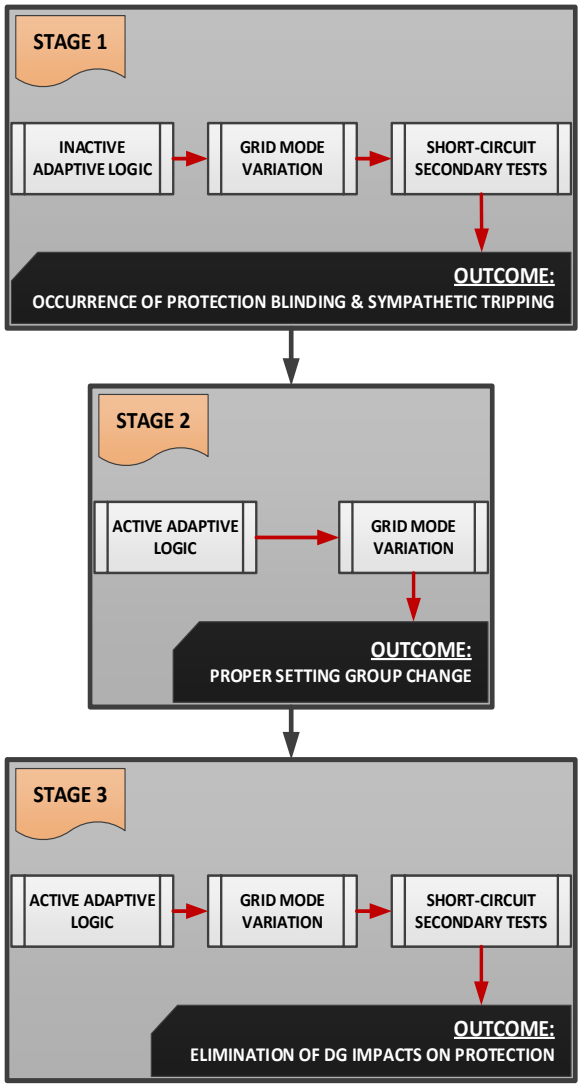
HIL testing-Sympathetic tripping

- 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
10:22:22.808   IN102                Deasserted
10:22:22.898   SG2                  Asserted
10:22:22.898   SG1                  Deasserted
10:22:24.763    Relay settings changed
```

- Signal to activate Setting Group 2
- Signal to deactivate Setting Group 1
- Setting Group 2 activated
- Setting Group 1 deactivated
- 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.*

3) CHIL for Islanded and grid connected operation of VSC

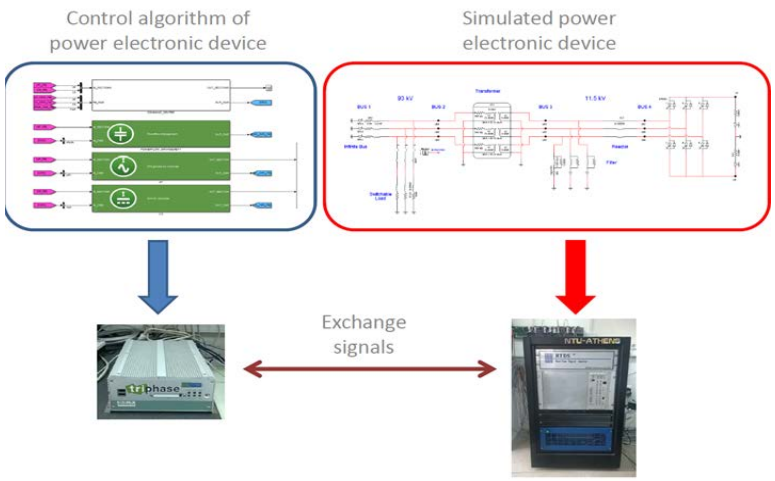
The converter and its control were tested in a CHIL simulation as a battery front end to the grid.

➢ Grid Connected Operation

- The DC/AC converter control regulates the DC BUS voltage through an outer control that provides an active power set-point.
- The reactive power is regulated according to a reactive power set-point which is sent to the DC/AC converter control.
- The batteries are connected to the DC BUS with a DC/DC converter. The control algorithm of the DC/DC converter regulates the power of the batteries.

➢ Islanded Operation

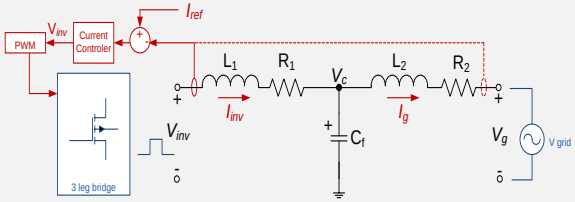
- The DC/AC control algorithm regulates the load voltage in order to keep it at nominal value.
- The DC/DC converter control regulates the DC BUS voltage through an outer control loop that provides an active power set-point.



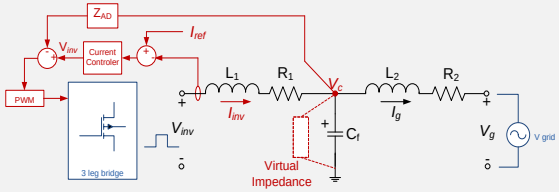
Investigated Control methods for VSC

Grid Connected operation

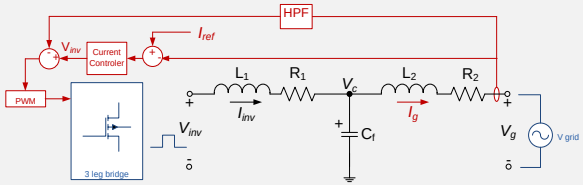
- **PI SF Voltage Control**



- **Virtual Resistance**

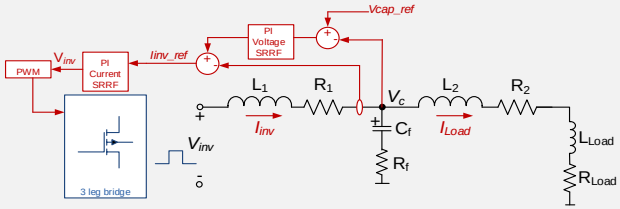


- **2DoF**

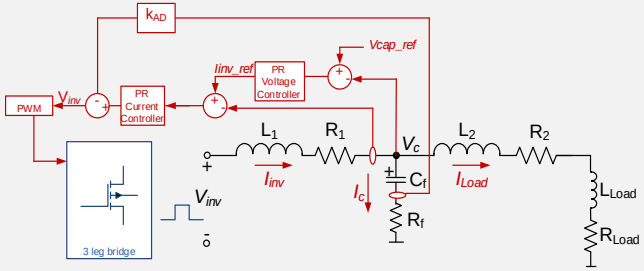


Islanded operation

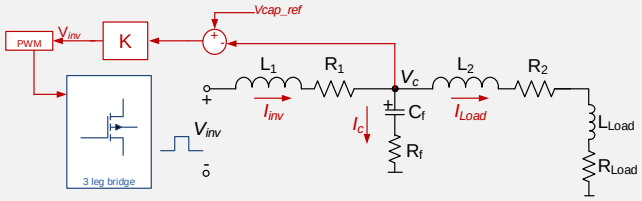
- **PI SRRF Voltage Control**



- **PR Voltage Control**

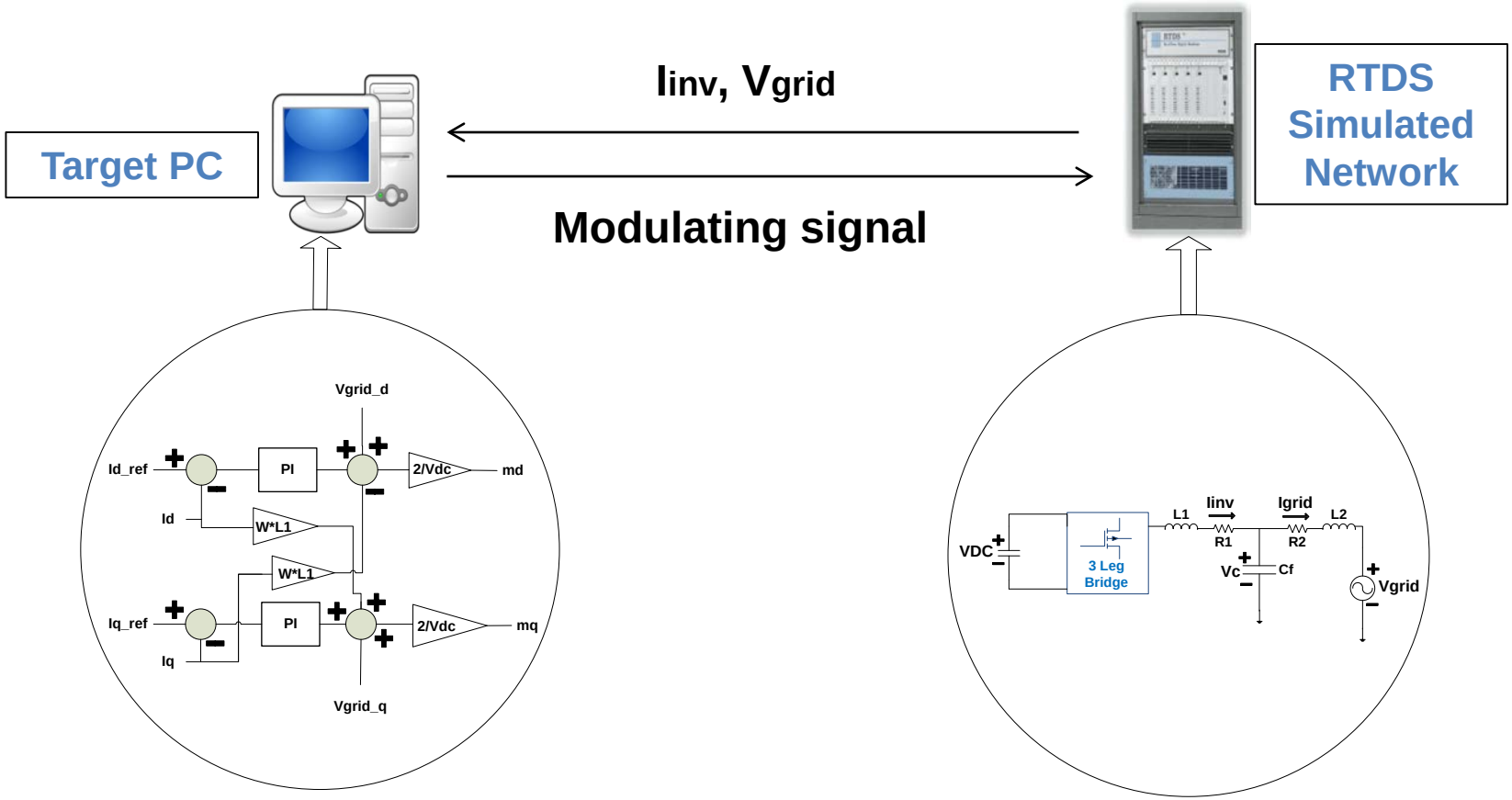


- **H-Infinity Control**

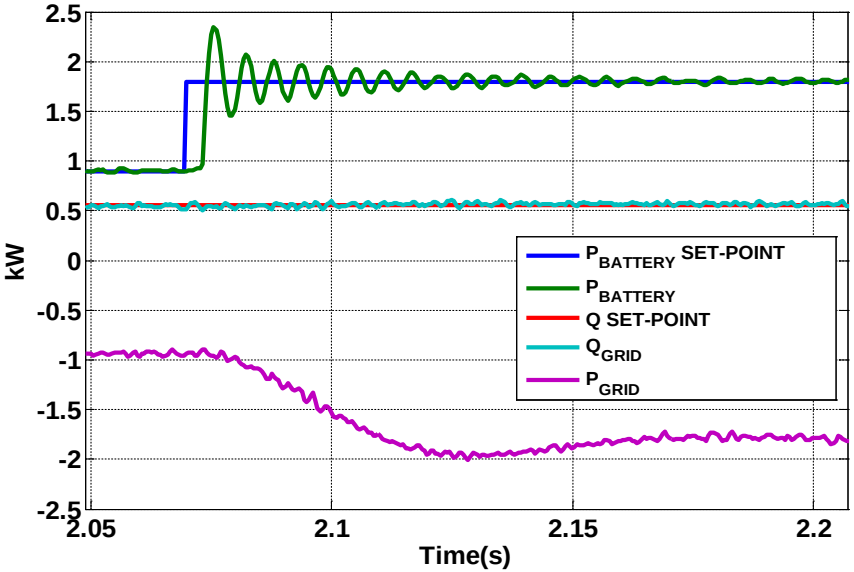


Grid Connected inverter-CHIL

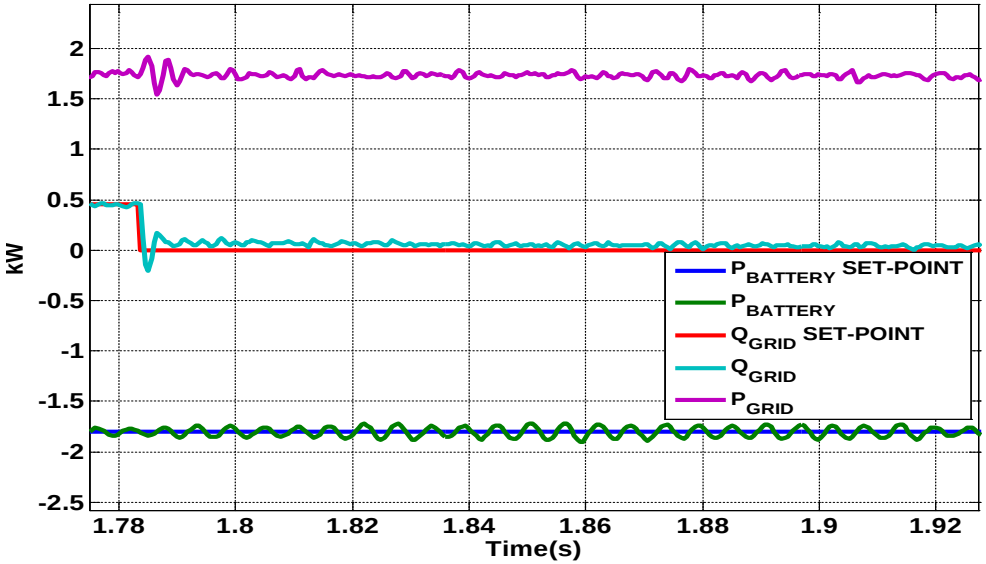
- The measurements from the RTDS are transferred to the target PC (controller)
- The target PC (controller) performs the control and sends the modulating signal back to the RTDS



CHIL Test Results-Grid Connected



Battery Active Power Tracking

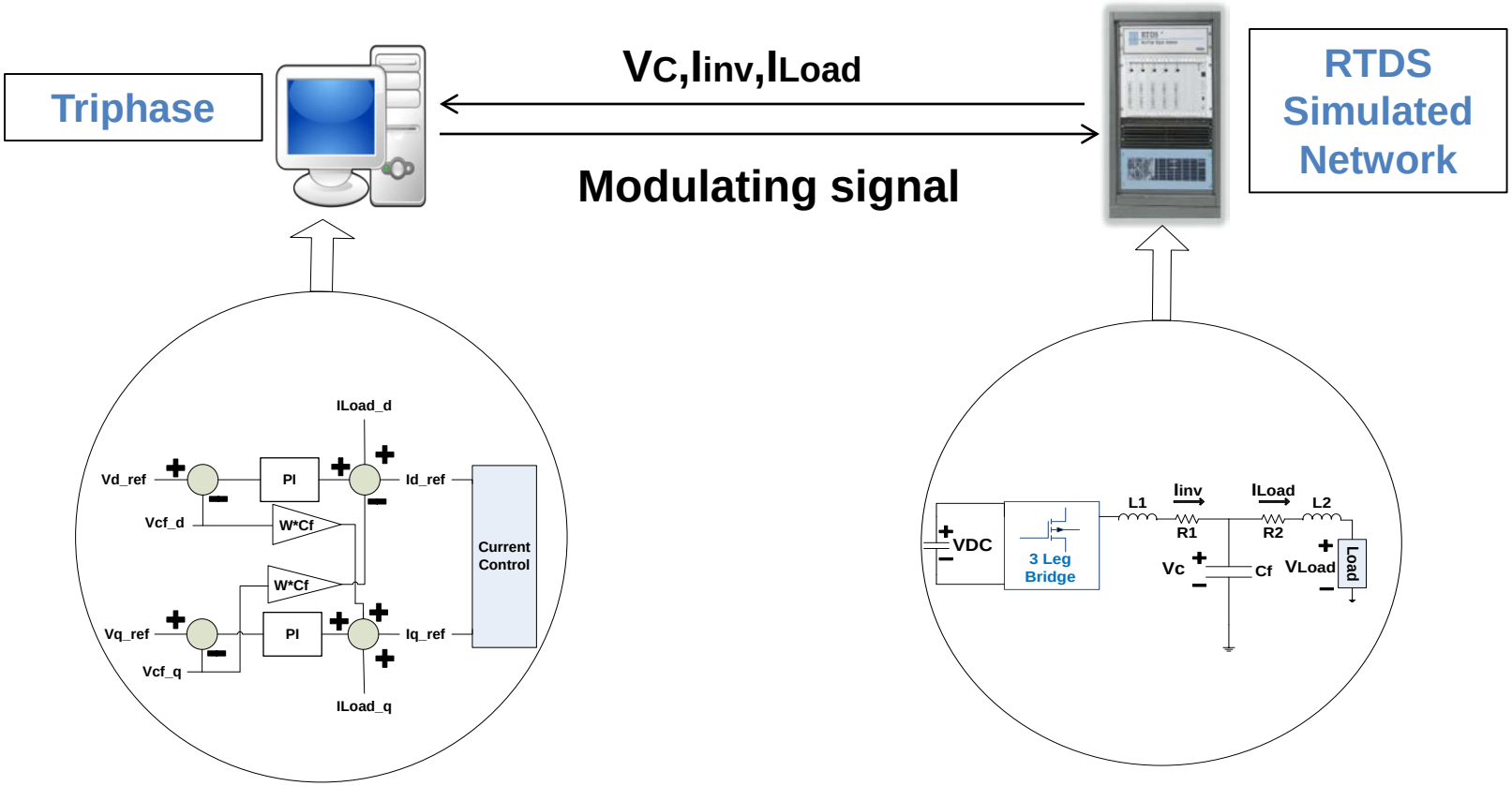


Reactive Power Tracking

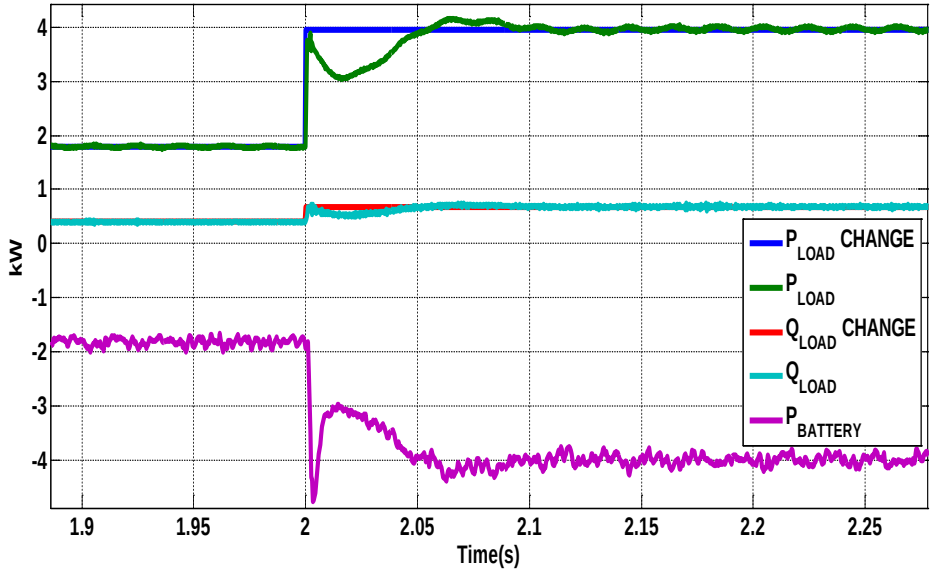
- The DC/DC control algorithm regulates the battery power to the new set-point (charge at 1,8kW).
- The DC/AC control algorithm provides that power from the grid by regulating the DC BUS voltage.
- The reactive power set-point is set to zero and the reactive power is regulated at that value.

Islanded inverter - CHIL

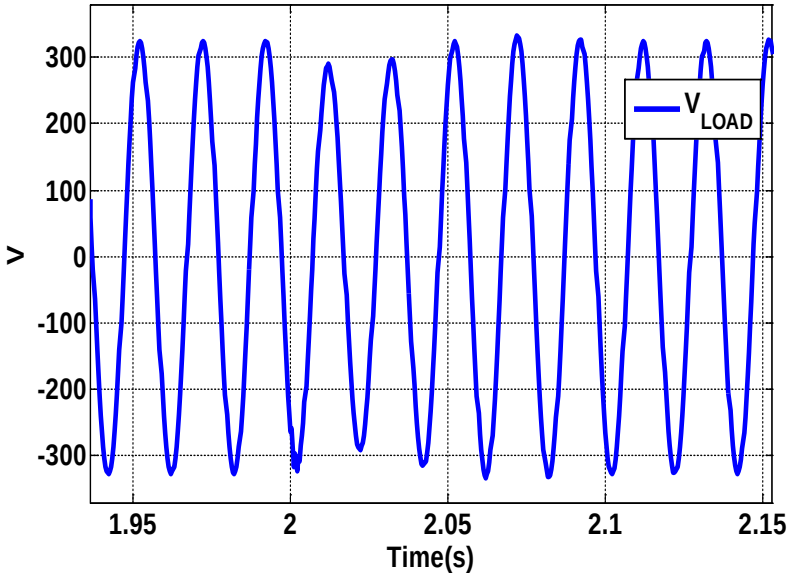
- The measurements from the RTDS are transferred to the target PC (controller)
- The target PC (controller) performs the control and sends the modulating signal back to the RTDS



CHIL Test Results-Islanded(1)



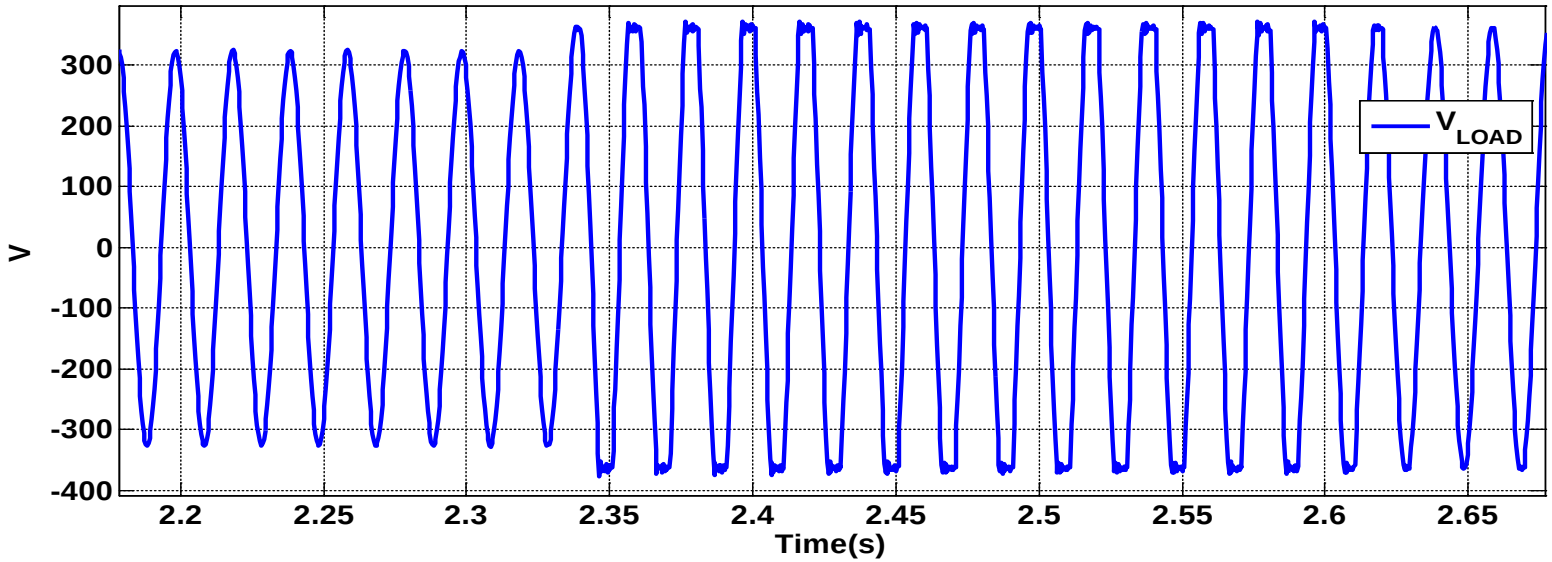
Pload - Qload Change



Voltage tracking at load change

- At 2s the load is increased 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.

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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