Adaptive Protection in Distribution power networks

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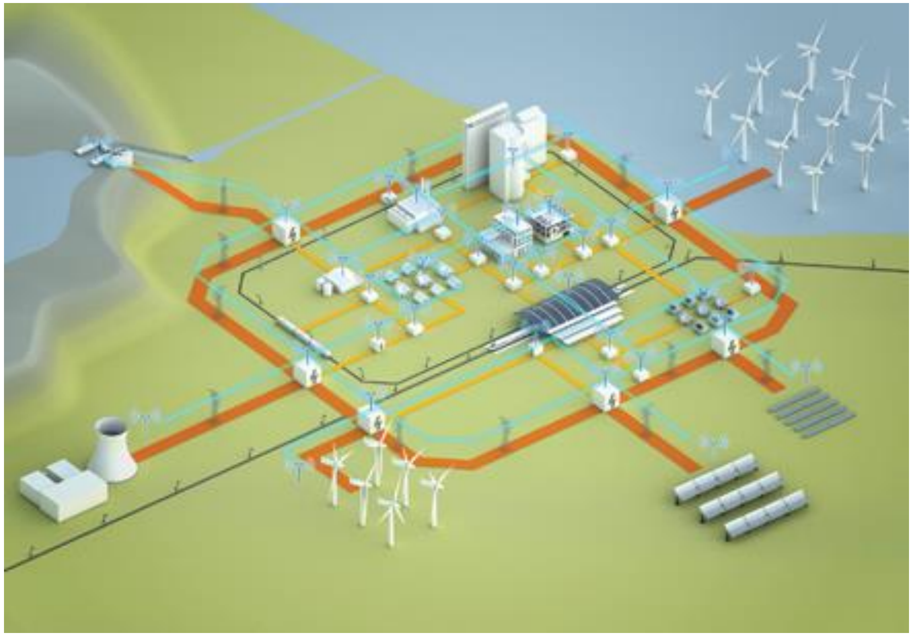
Introduction - Distributed Generation (1/4)

- *Distributed generation is a local electric power source connected at the substation, directly to the distribution feeder or on the customer load site.*
- Rating categories
  - **Micro** distributed generation: ~1 Watt < 5 kW
  - **Small** distributed generation: 5 kW < 5 MW
  - **Medium** distributed generation: 5 MW < 50 MW
  - **Large** distributed generation: 50 MW < 300MW

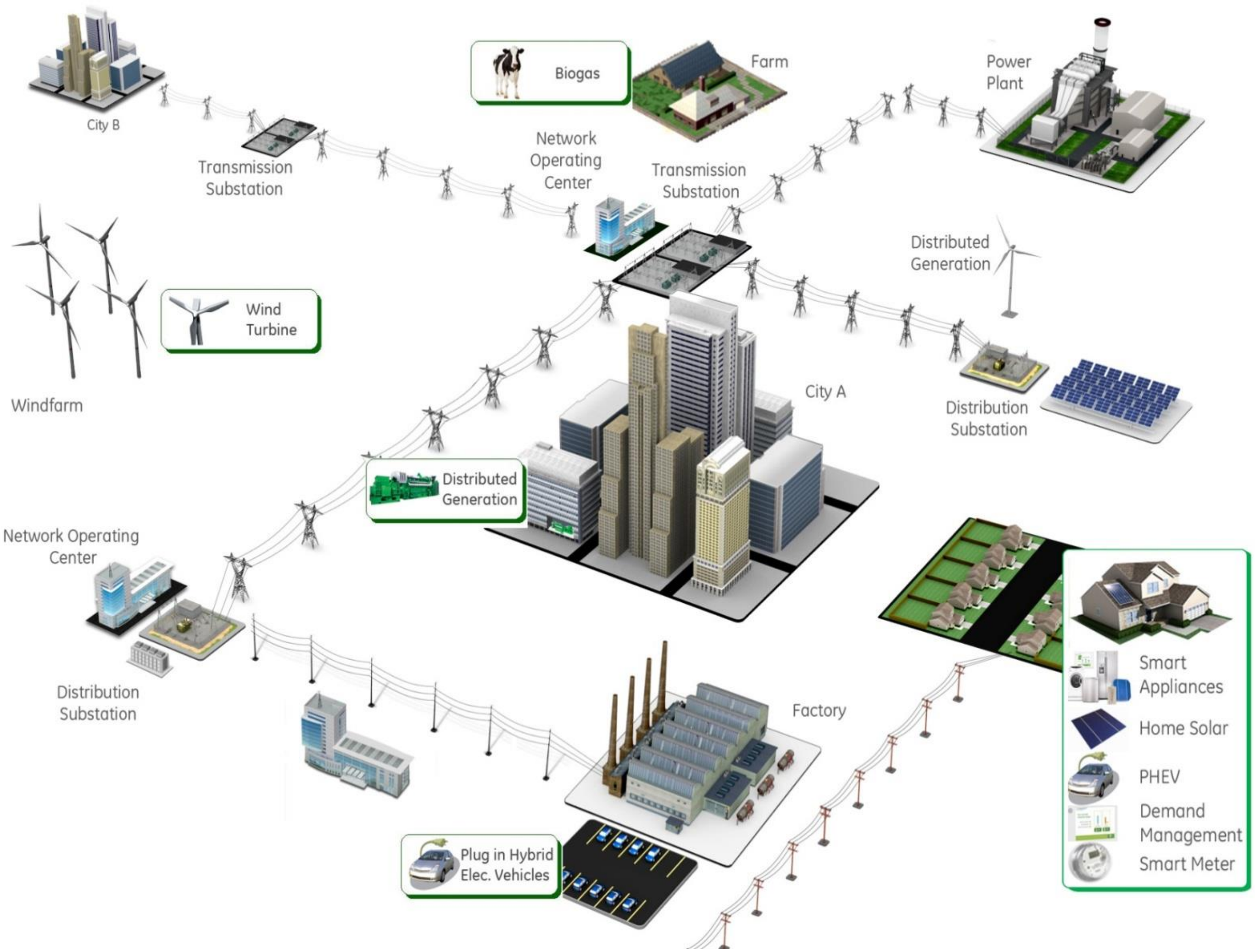


Introduction - Distributed Generation (2/4)

- Energy technologies for various distribution generation ratings

Technology	Typical size
Combined Cycle Gas Turbine	35 – 400 MW
Internal combustion engines	5 kW – 10 MW
Combustion turbine	1 – 250 MW
Micro hydro	25 kW – 1 MW
Small hydro	1 – 100 MW
Wind turbine	200 Watt – 3 MW
Photovoltaic arrays	20 Watt – 100 kW
Biomass	100 kW – 20 MW
Fuel cells	1 kW – 5 MW
Geothermal	5 – 100 MW
Ocean energy	100 kW – 1 MW
Battery storage	500 kW – 5 MW

Protection issues in distribution grids with DG



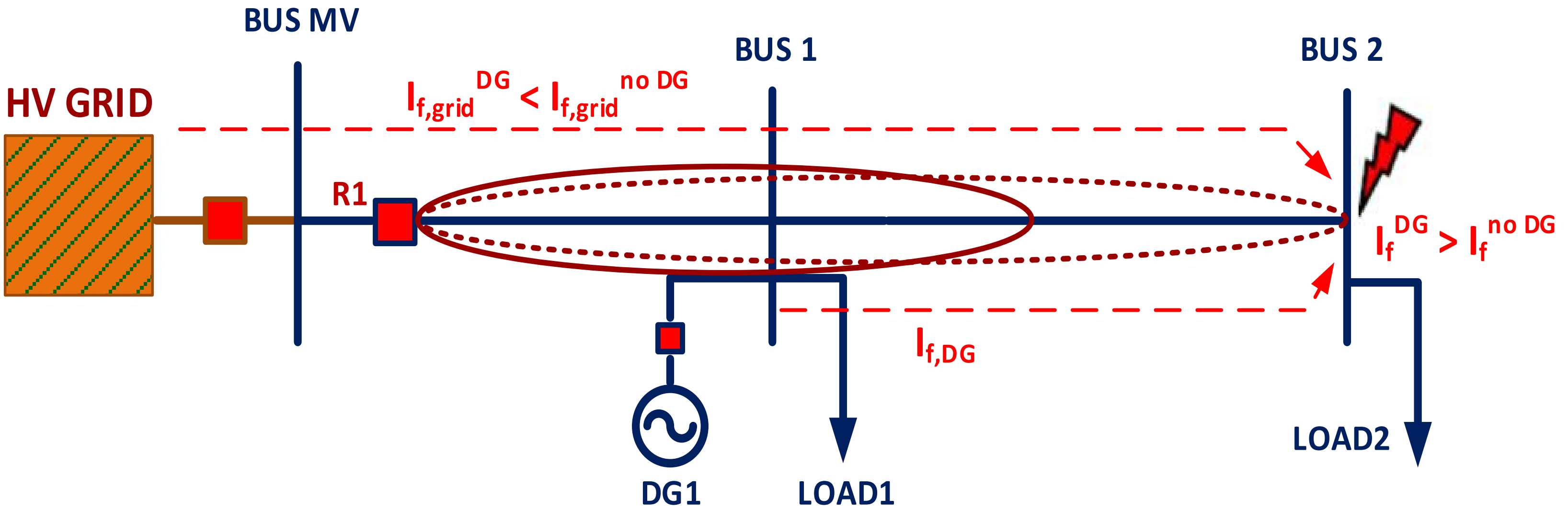
Protection issues in distribution grids with DG (1/7)

- Conventional distribution grids are radial and single point feeding networks, based on non-directional overcurrent relaying for their protection.
- Each relay includes a group of pre-calculated settings based on short-circuit studies and no complicated issues are dealt with during the initial design.
- DG penetration in modern distribution networks causes significant increase of fault current level and partial contribution in short-circuit cases, resulting in maloperation of existing overcurrent protective devices (relays, reclosers, fuses).
- For this reason, the development and application of adaptive protection schemes, with adjustable setting groups, would guarantee safe operation for smart grids with DG and sophisticated topologies.

Protection issues in distribution grids with DG (2/7)

Protection blinding (also called underreach)

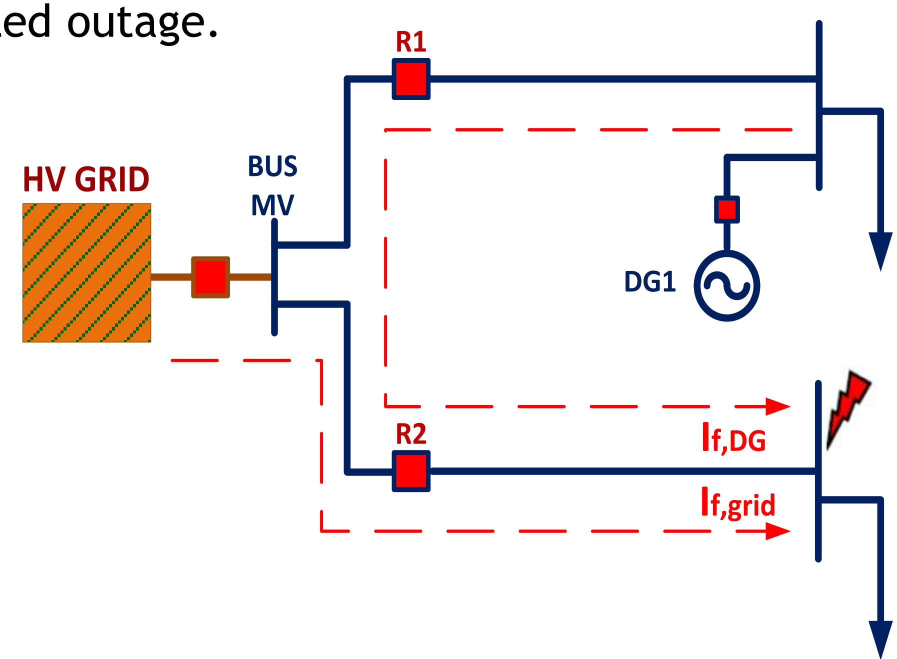
- This phenomenon occurs when a large-scale conventional DG unit is connected to a distribution feeder between the main grid and the fault location.
- Grid fault contribution is reduced due to the partial contribution from the DG unit, and the feeder relay R1 senses a lower short-circuit current value.
- As a consequence, the relay cannot be asserted and clear the fault, suffering from "blinding".



Protection issues in distribution grids with DG (3/7)

Sympathetic tripping

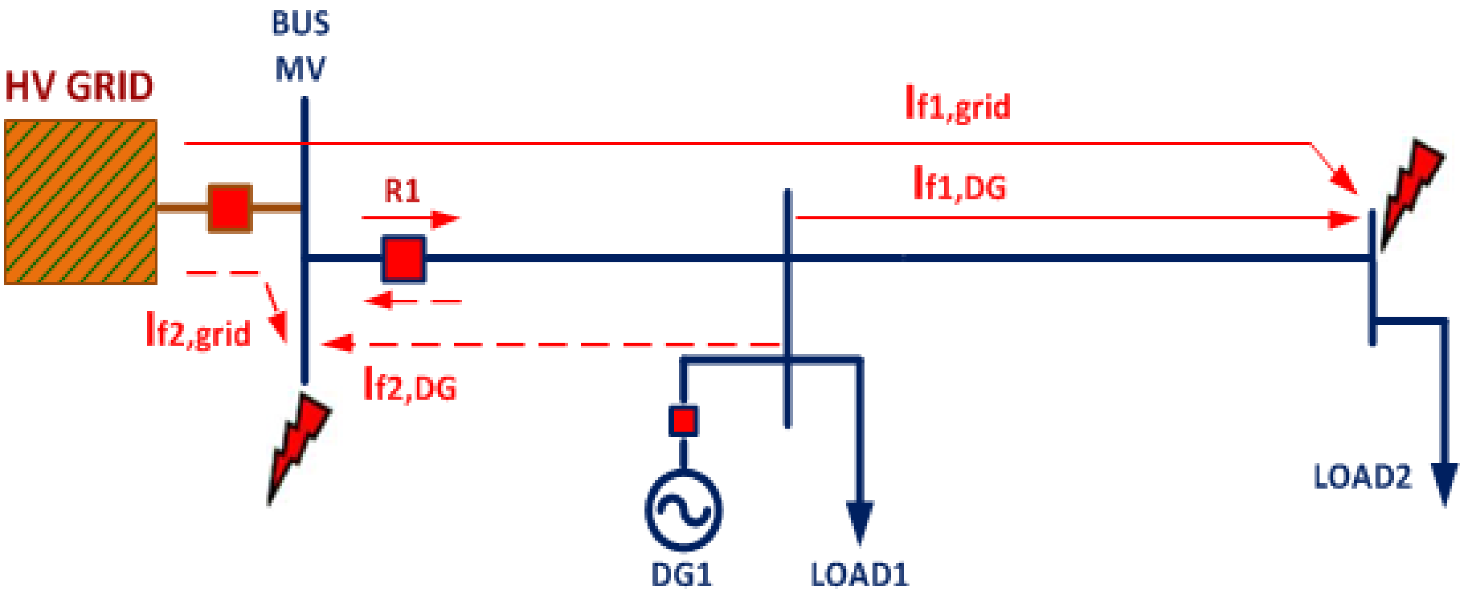
- In grid-connected operation mode, when a DG unit is connected to a specific feeder and a fault occurs on an adjacent one, the fault current contribution from the DG unit might exceed the pickup current setting of feeder's overcurrent relay, especially when DG capacity is sufficiently large.
- Therefore, the relay R1 trips sympathetically to relay R2. and the healthy feeder faces an unexpected outage.



Protection issues in distribution grids with DG (4/7)

Bi-directional current flow

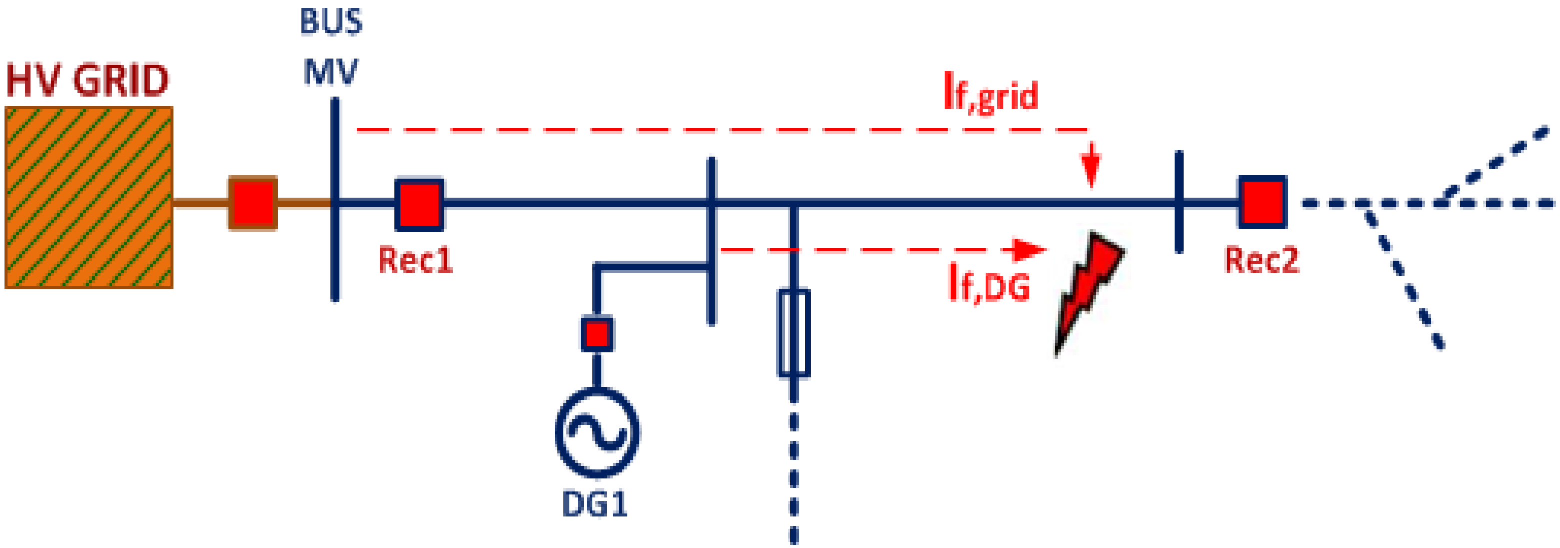
- In grid-connected and islanded operation mode, due to the presence of DG units, the power and fault current may flow bi-directionally.
- Impact to protection: Selectivity and coordination problem of traditional non-directional overcurrent protective devices.



Protection issues in distribution grids with DG (5/7)

Failed reclosing

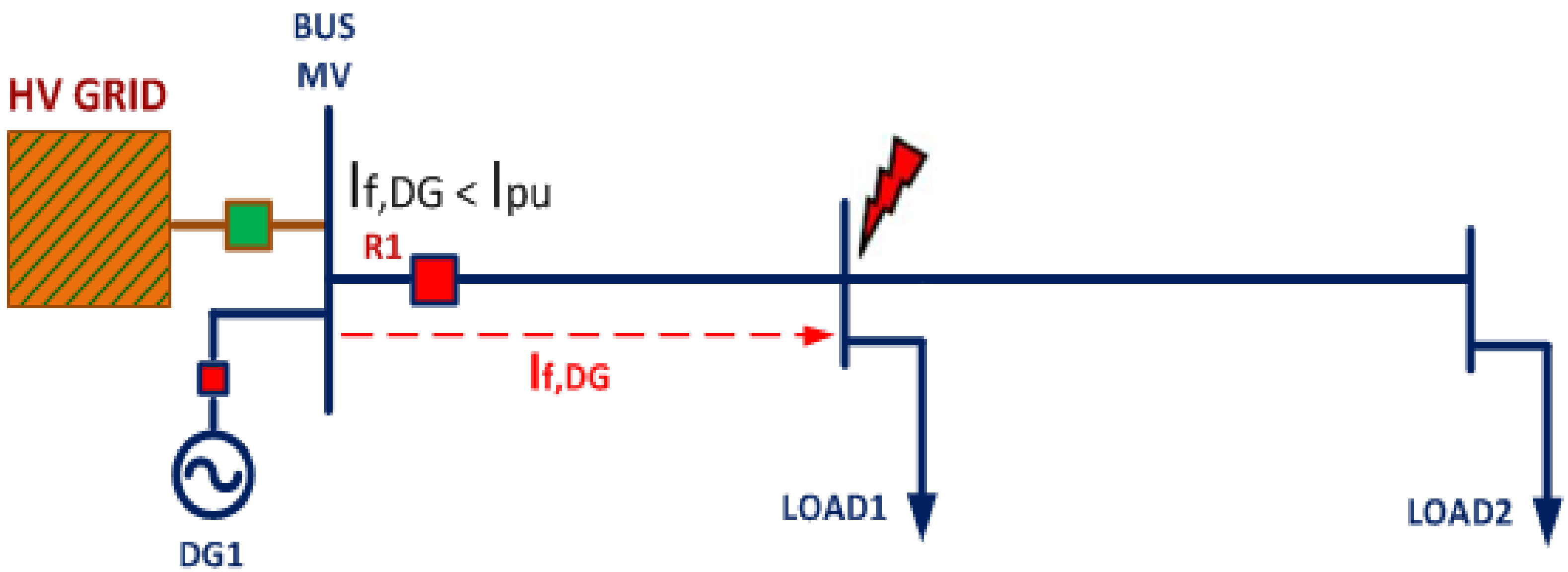
- In grid-connected operation mode, the fault current detection capability of recloser is affected by the DG contribution. It concerns another aspect of protection blinding.
- Impact to protection: Failed reclosing.



Protection issues in distribution grids with DG (6/7)

Insufficient fault current contribution

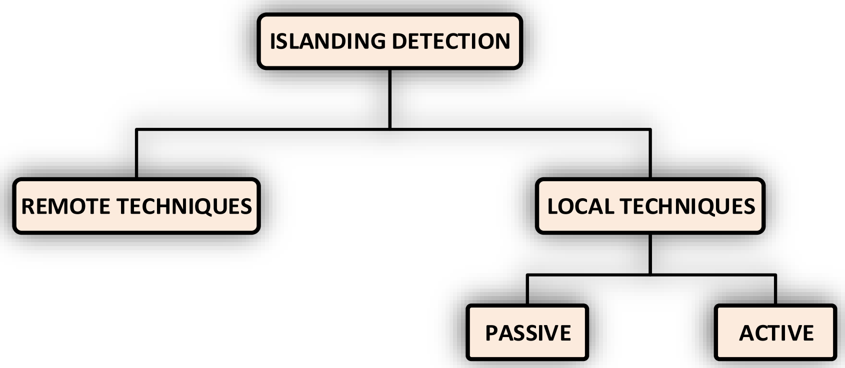
- In islanded operation mode, the fault current contribution from inverter-interfaced DG units is limited to about twice the rated current of the inverter.
- Impact to protection: Ineffective use of overcurrent protection. Insufficient fault current contribution could not reach overcurrent relay's pickup setting.

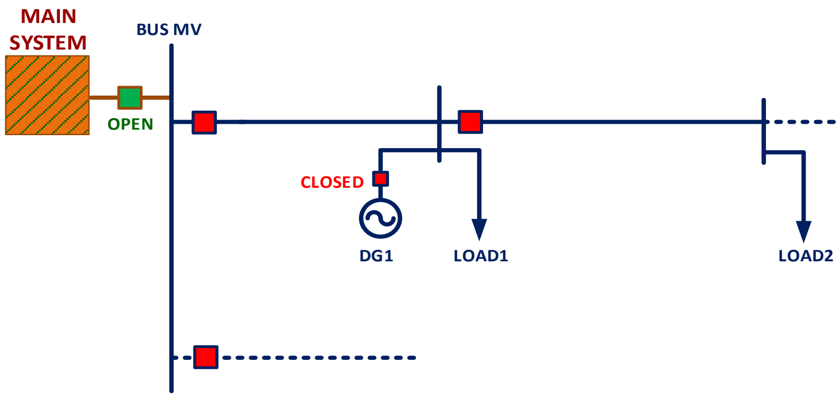


Protection issues in distribution grids with DG (7/7)

Loss-of-mains protection

- ❑ The islanding phenomenon occurs when one or more non-utility generation sources and a portion of the distribution network still operate, while isolated from the remainder of the main system.
- ❑ The basic operating principles of islanding detection techniques are:
  - ➢ The monitoring of main system and DG operating parameters
  - ➢ The decision on whether there is an islanding situation or not, based on the parameter variations.

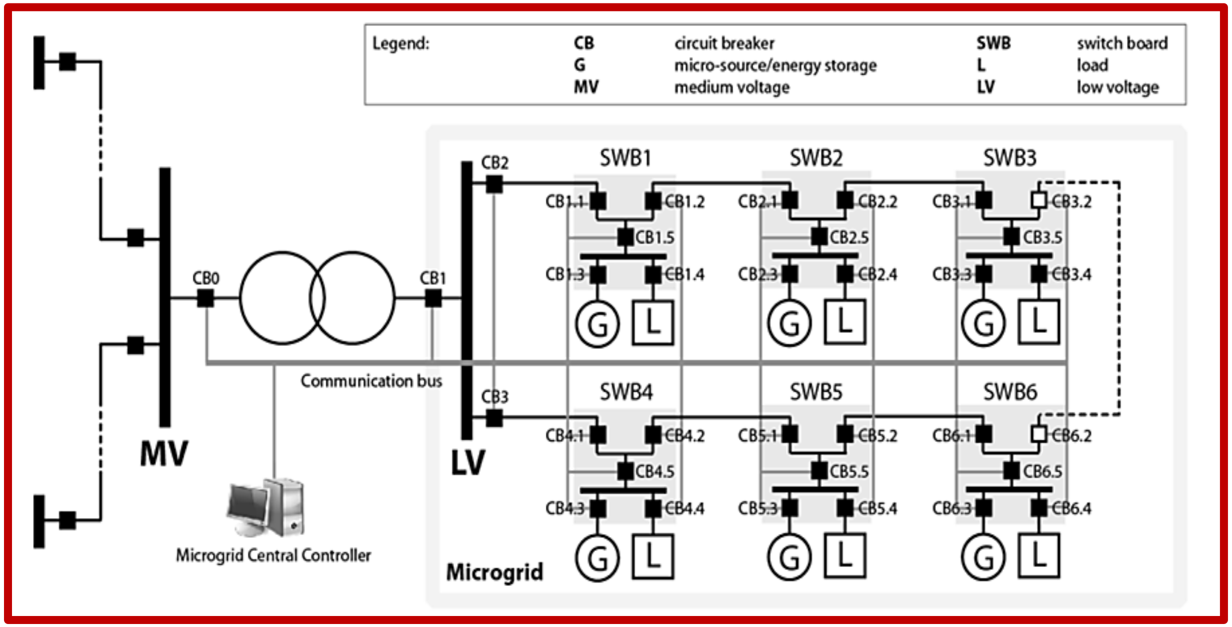




Adaptive Protection Systems (1/3)

Adaptive Protection Systems (2/3)

- **The use of adjustable protective relay settings that can change in real time (on-line), depending on the network configuration (topology, DG connection) changes, by using signals from local sensors or a central control system.**
- Adaptive protection systems solve the protection issues mentioned in the previous section.



Adaptive Protection Systems (3/3)

- Adaptive protection systems are based on pre-calculated information where protection settings are updated periodically by the central controller with regard to the networks operating state.
- **Technical requirements:**
  - Use of digital *directional overcurrent relays* (due to the bi-directional flow of short-circuit currents),
  - *Several setting groups* must be encapsulated in digital overcurrent relays,
  - Establishment of *communication infrastructure* and use of industrial communication protocols, e.g. Modbus, IEC 61850, DNP3 (necessity of communication between adjacent relays and individual relays with the central control system).
- Settings for non-directional or directional overcurrent relays are pre-calculated during off-line fault analysis of a given distribution network with DG, using power engineering software (Neplan, PSS/Viper, PowerFactory, ETAP).

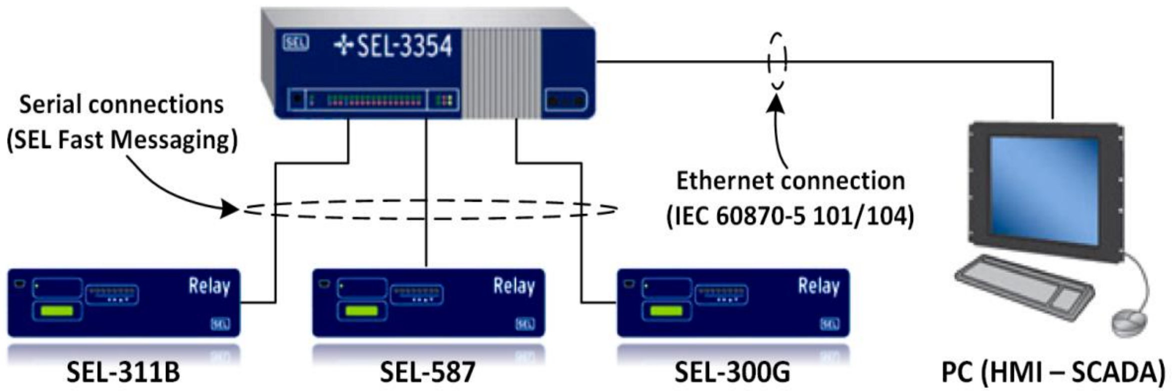
Laboratory Infrastructure (1/4)

- Real Time Digital Simulator (RTDS)

- RTDS Simulator is designed specifically to simulate electrical power systems & test physical equipment such as control and protection devices.
- RTDS is based on parallel processing.
- Each processor is assigned specific computing tasks depending on the network configuration.
- RSCAD software provides the ability to set up simulations, control, and modify system parameters during a simulation, data acquisition, and result analysis.
- RSCAD also includes libraries with a multitude of power system, control system and protection & automation component models, which can be used to create simulation cases.

Laboratory Infrastructure (2/4)

- **Digital Protective Relay Panel**
  - SEL-311B (distance and reclosing relay)
  - SEL-587 (differential/overcurrent relay)
  - SEL-300G (generator relay)
  - SEL-3354 (embedded automation computing platform)
  - All relays have **overcurrent elements with 2-6 setting groups**, that will be used for adaptive protection implementation.



Laboratory Infrastructure (3/4)

➢ Protective Panel Hardware Components

❑ <u>SEL – 311B directional & overcurrent features</u>

- ✓ 67P/Q/G directional overcurrent element
- ✓ 50 – 51/P/Q/G overcurrent elements
- ✓ 79 Auto-reclosing element
- ✓ **6 Setting Groups**
- ✓ **6 Digital Inputs (48 V DC)**
- ✓ **7 Digital Outputs**

❑ <u>SEL – 587 overcurrent features</u>

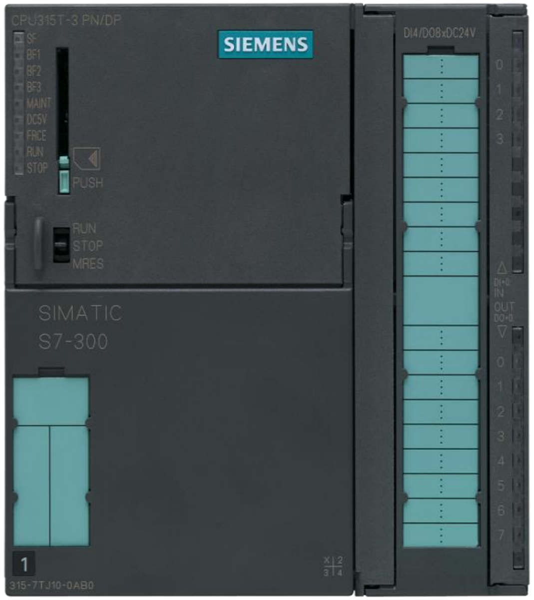
- ✓ 2 groups of 50 – 51P/Q/N overcurrent elements
- ✓ **1 Setting Group**
- ✓ **2 Digital Inputs (220 V DC)**
- ✓ **4 Digital Outputs**

❑ <u>SEL – 300G directional & overcurrent features</u>

- ✓ 50 – 51P/Q/G/N overcurrent elements
- ✓ 32 power directional element
- ✓ **2 Setting Groups**
- ✓ **6 Digital Inputs (220 V DC)**
- ✓ **7 Digital Outputs**

Laboratory Infrastructure (4/4)

PLC SIMATIC S7 - 300



- SIMATIC S7-300 universal controller is an integrated solution for industrial automation systems and is composed of:
  - ✓ Power Supply (PS 307 2A): 110 ÷ 230 V AC – 24 V DC
  - ✓ Central Processor Unit (CPU 312C)
  - ✓ Signal Modules (SM):
    - 10 Digital Inputs – 6 Digital Outputs (10D.I. – 6D.O.) hybrid card
    - 8 Analog Inputs (8A.I.) card

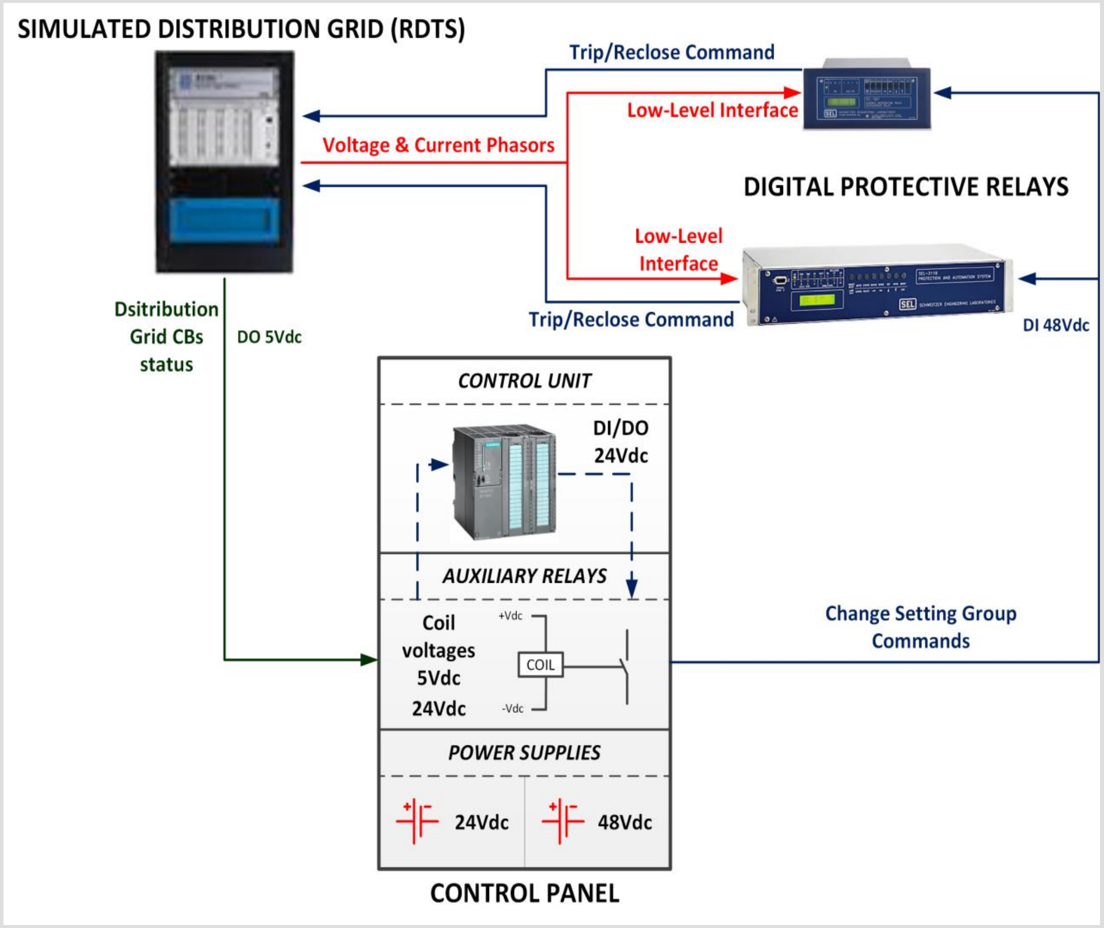
- The desired automation schemes are programmed and downloaded to SIMATIC S7-300 by using STEP7 software and its programming languages:
  - ✓ Ladder Diagram (LAD)
  - ✓ Statement List (STL)
  - ✓ Function Block Diagram (FBD)

Testbed Integration (1/4)

Components & Interfaces

- An innovative testbed infrastructure for adaptive protective schemes has been developed in the Electric Energy Systems Laboratory (EESL) of ICCS-NTUA.

- This specific testbed is actually a hardware-in-the-loop (HIL) topology, which consists of a Real Time Digital Simulator, two multifunction digital relays, and also a programmable logic controller (PLC).



Testbed Integration (2/4)

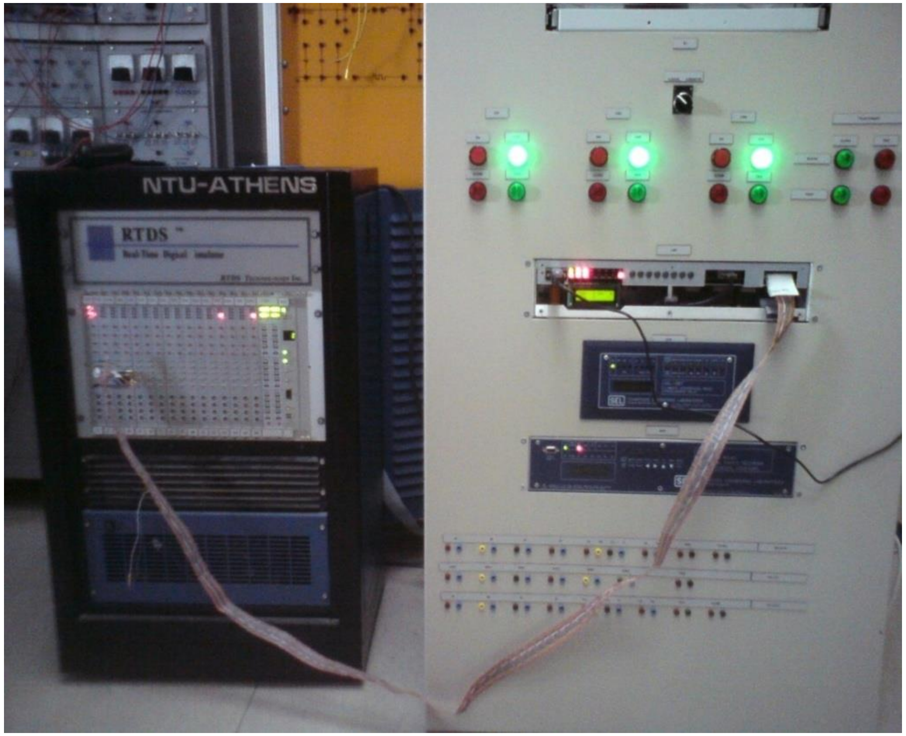
Operating Philosophy

- 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.

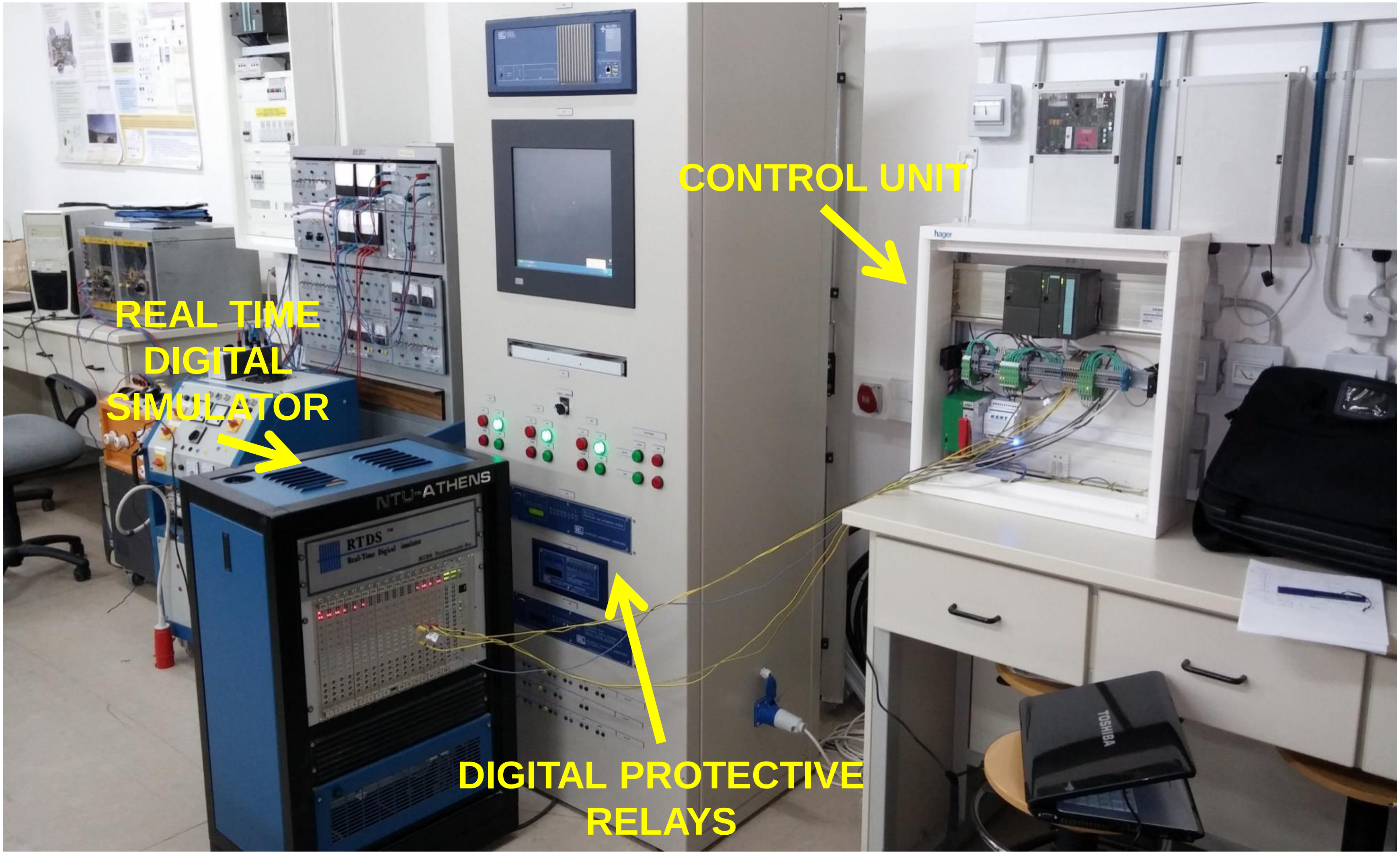
Testbed Integration (3/4)

Hardware-In-the-Loop Tests

- The HIL tests are conducted utilizing RTDS simulator as well as SEL-311B, and SEL-587 digital relays.
- SEL relays are fed with analog signals (voltages, currents) via their low-level interface.

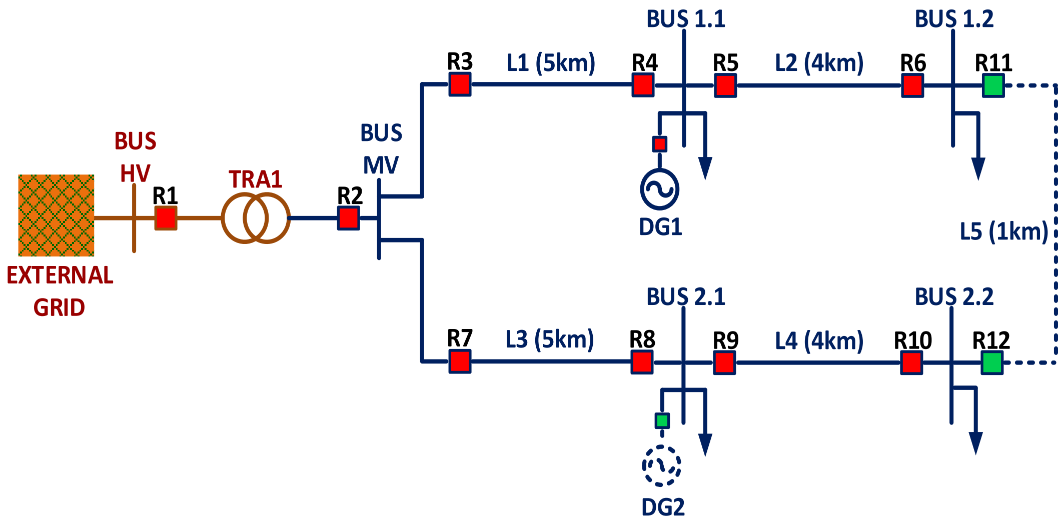


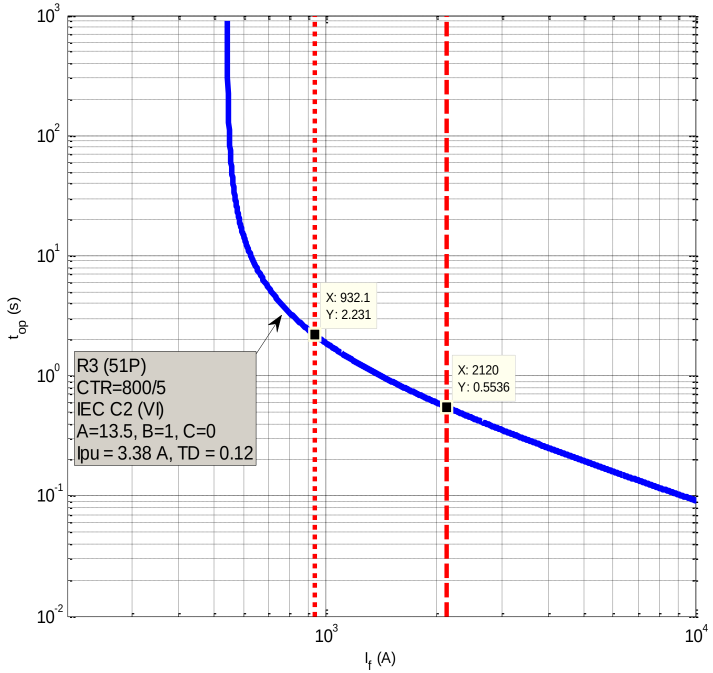
Testbed Integration (4/4)



Hardware in the Loop experiments (1/6)

- *The distribution system under examination is a simplified configuration of the Rhodes HV/MV Substation "Gennadi" and its outgoing feeders R-22 and R-26, which are protected by R3 and R7 protection relays, respectively.*
- *DG connection at Bus 1.1, symmetrical fault at Bus 1.2.*
- *R3 operating time increases from 0.55 s to 2.23 s => Protection blinding.*

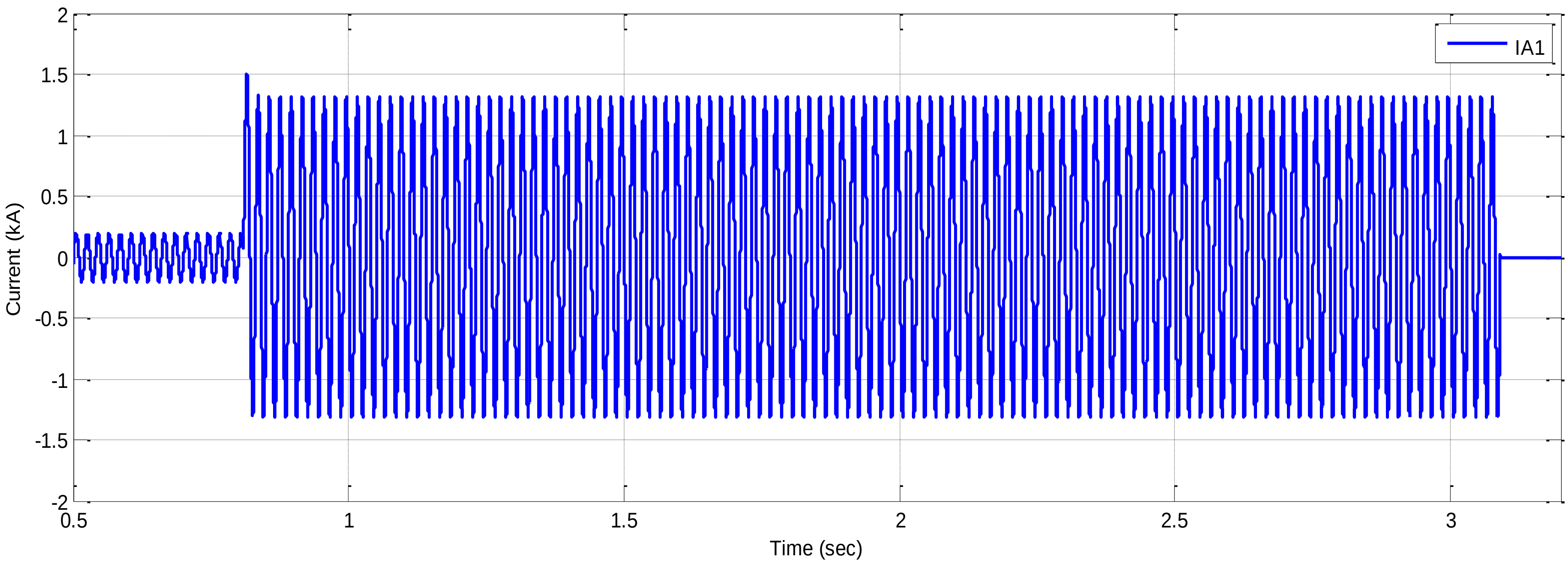




Hardware in the Loop experiments (2/6)

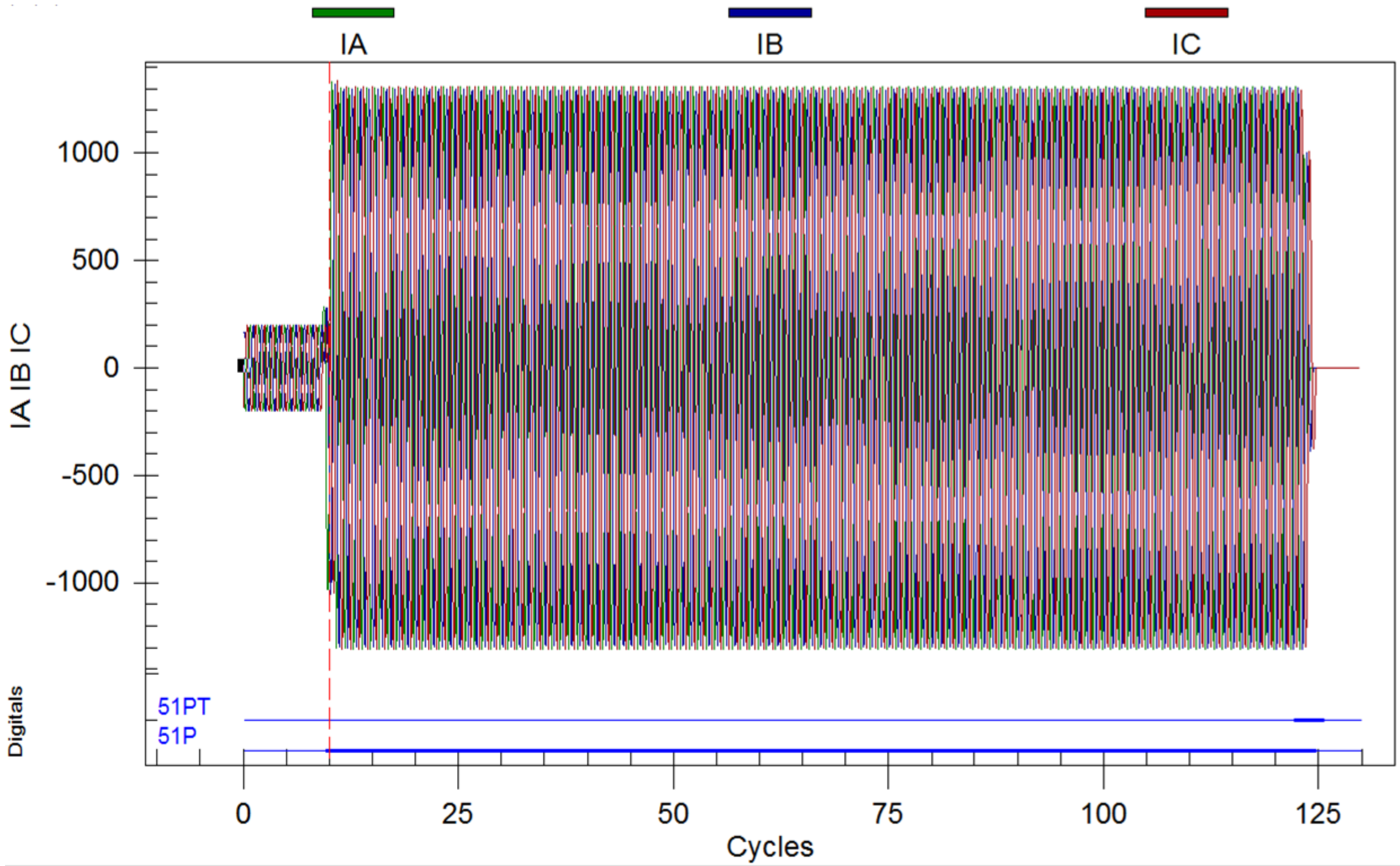
- 3-phase fault at Bus 1.2
- Total short-circuit current = 3,43 kA
- Short-circuit current through SEL-311B (main grid contribution) = 0,932 kA (primary)
- Time for fault clearance = 2,23 s

RTDS oscillography



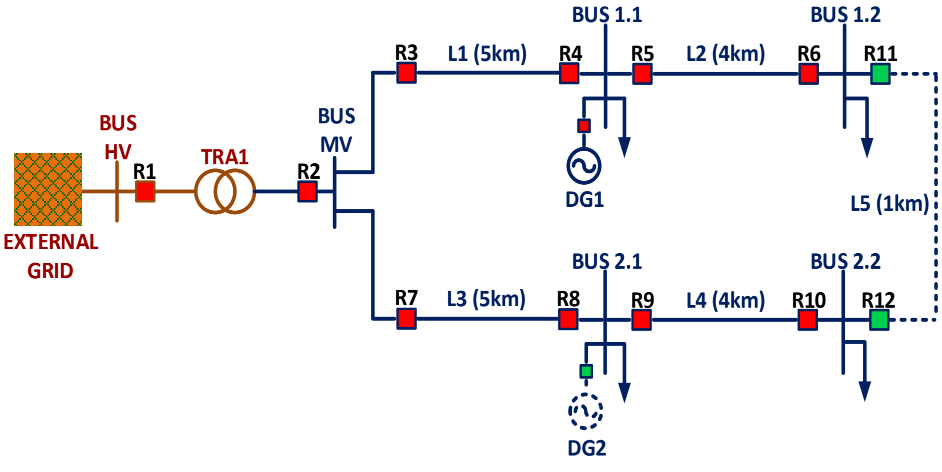
Hardware in the Loop experiments (3/6)

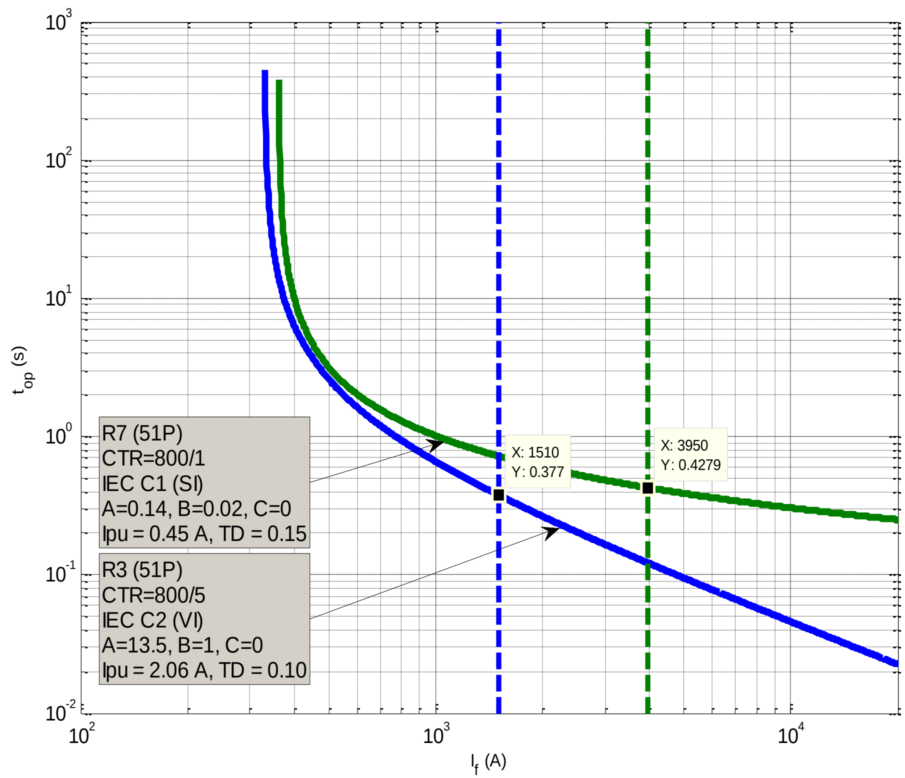
SEL-311B oscillography



Hardware in the Loop experiments (4/6)

- *DG connection at Bus 1.1, symmetrical fault at Bus 2.1.*
- *R3 operates faster (0.38 s) than R7 (0.43 s) due to the DG contribution => Sympathetic tripping & outage of a healthy feeder.*

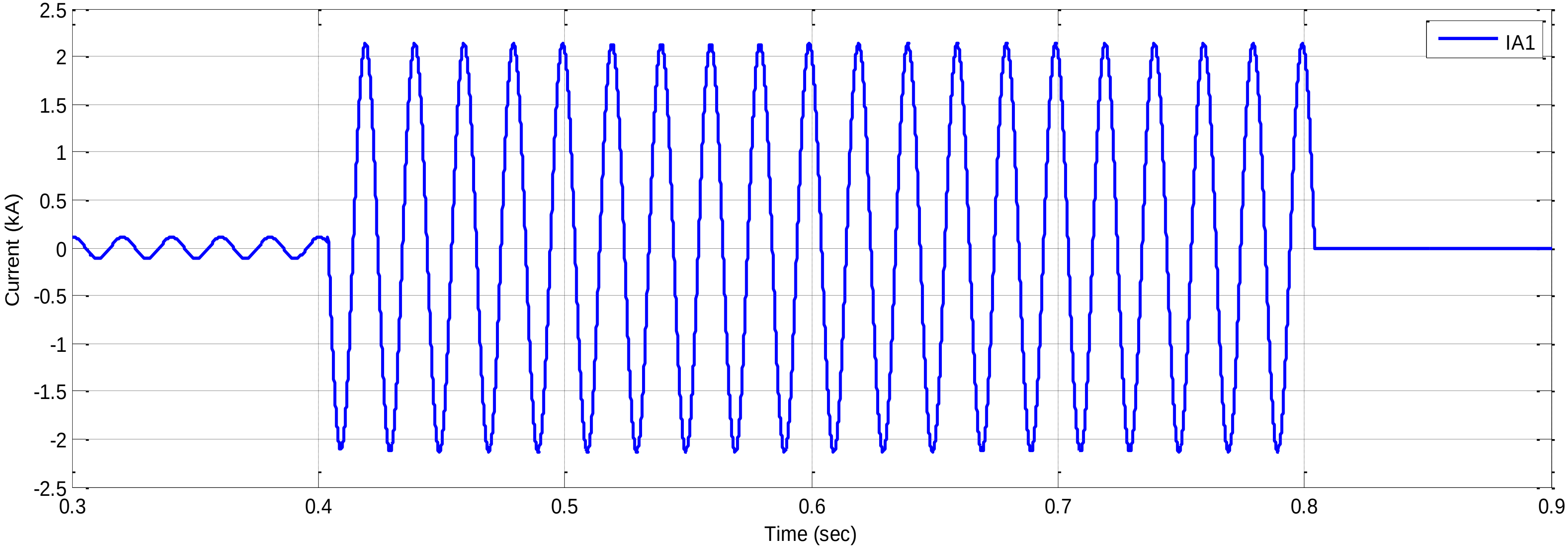




Hardware in the Loop experiments (5/6)

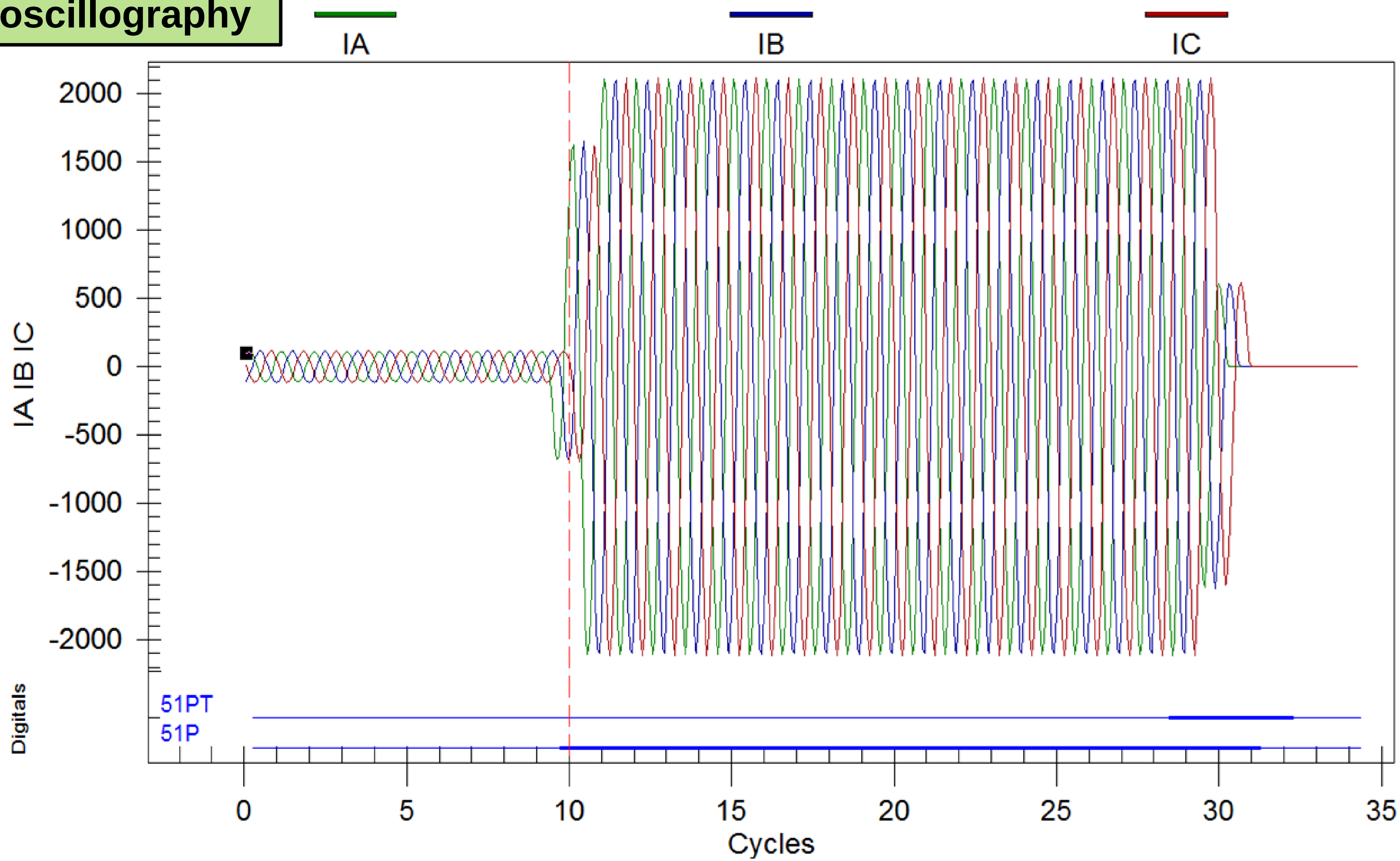
- 3-phase fault at Bus 2.1
- Short-circuit current through SEL-311B (Feeder 1) = 1,51 kA (primary)
- Short-circuit current through SEL-587 (Feeder 2) = 3,95 kA (primary)

RTDS oscillography (SEL-311B)



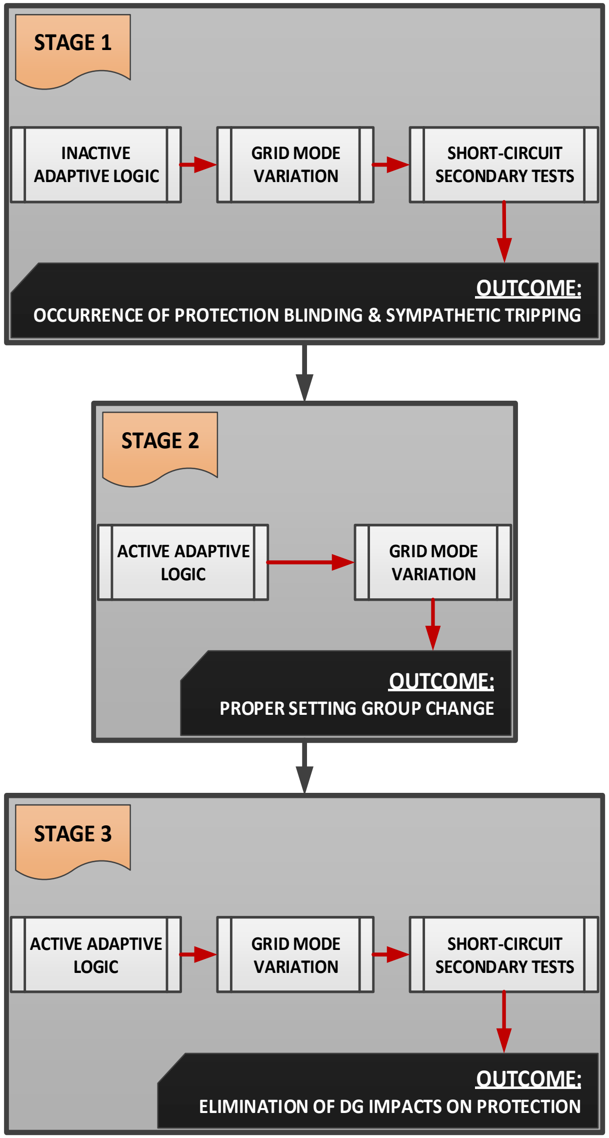
Hardware in the Loop experiments (6/6)

SEL-311B oscillography



Evaluation of ICCS Adaptive Protection System (1/3)

- *The evaluation procedure is composed of three stages, as illustrated.*
- *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 (2/3)

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.*

Evaluation of ICCS Adaptive Protection System (3/3)

$$min \;\; z_k = \sum_{f=1}^{N_F} \sum_{\forall (i,j) \in \mathcal{P}} \left(t_{i,f}^{k} + t_{j,f}^{k} \right), \; k = 1, \ldots, N_G$$

$$t_{i,f}^{k} = TD_i^k \left(\frac{A_k}{\left(I_{f,i} / I_{pu,i}^{k} \right)^{B_k} - 1} + C_k \right)$$

References

[1] V. Papaspiliotopoulos, G. Korres and N. Maratos, "A Novel Quadratically Constrained Quadratic Programming Method for Optimal Coordination of Directional Overcurrent Relays", *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 3-10, 2017.

[2] V. Papaspiliotopoulos, G. Korres, V. Kleftakis and N. Hatziargyriou, "Hardware-In-the-Loop Design and Optimal Setting of Adaptive Protection Schemes for Distribution Systems With Distributed Generation", *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 393-400, 2017.

[3] V. Papaspiliotopoulos and G. Korres, "Innovative solution for overcurrent relay coordination studies in power delivery networks using optimisation techniques", *The Journal of Engineering*, vol. 2018, no. 15, pp. 1103-1108, 2018.

Thank you for your attention

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