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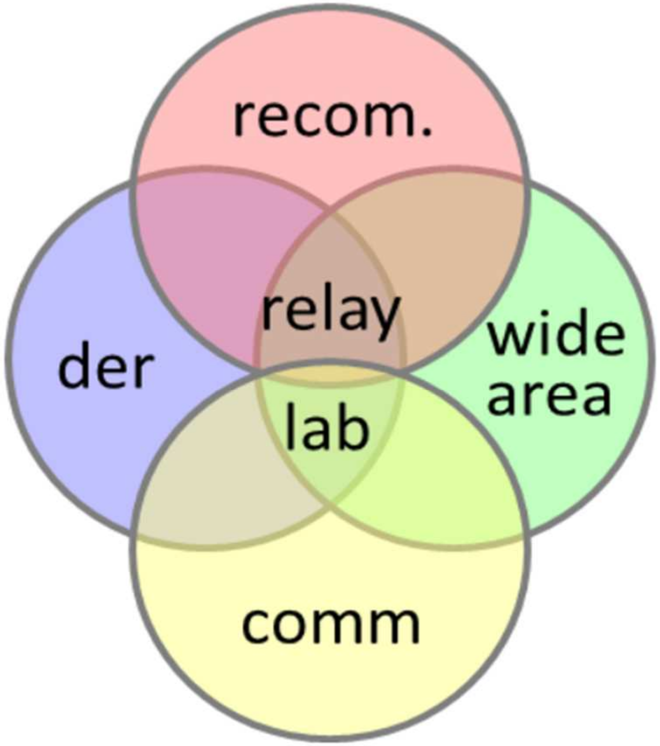
ProSmart Project - An outlook on Laboratory developments for IEC61850 based communication and protection

Part 1 – Overview of NTNU ProSMART Project and Real-Time HIL Testing of IEC61850 based µProcessor Hardware.

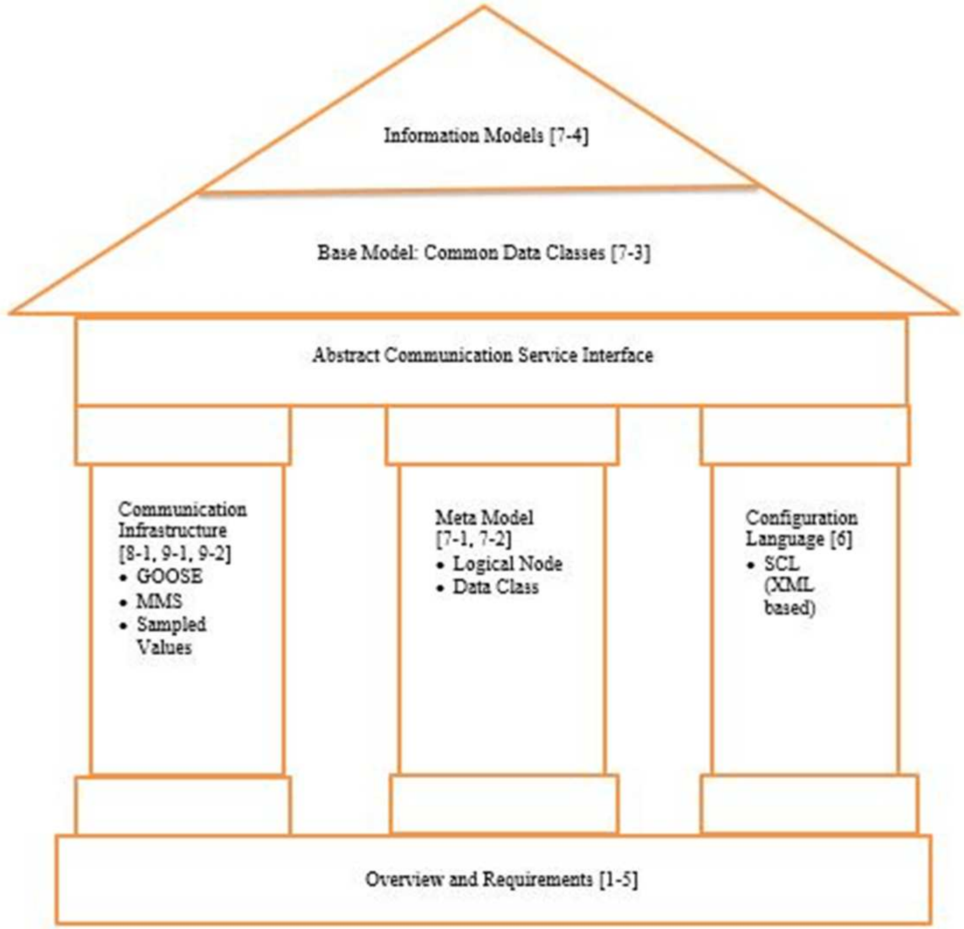
ProSMART Project



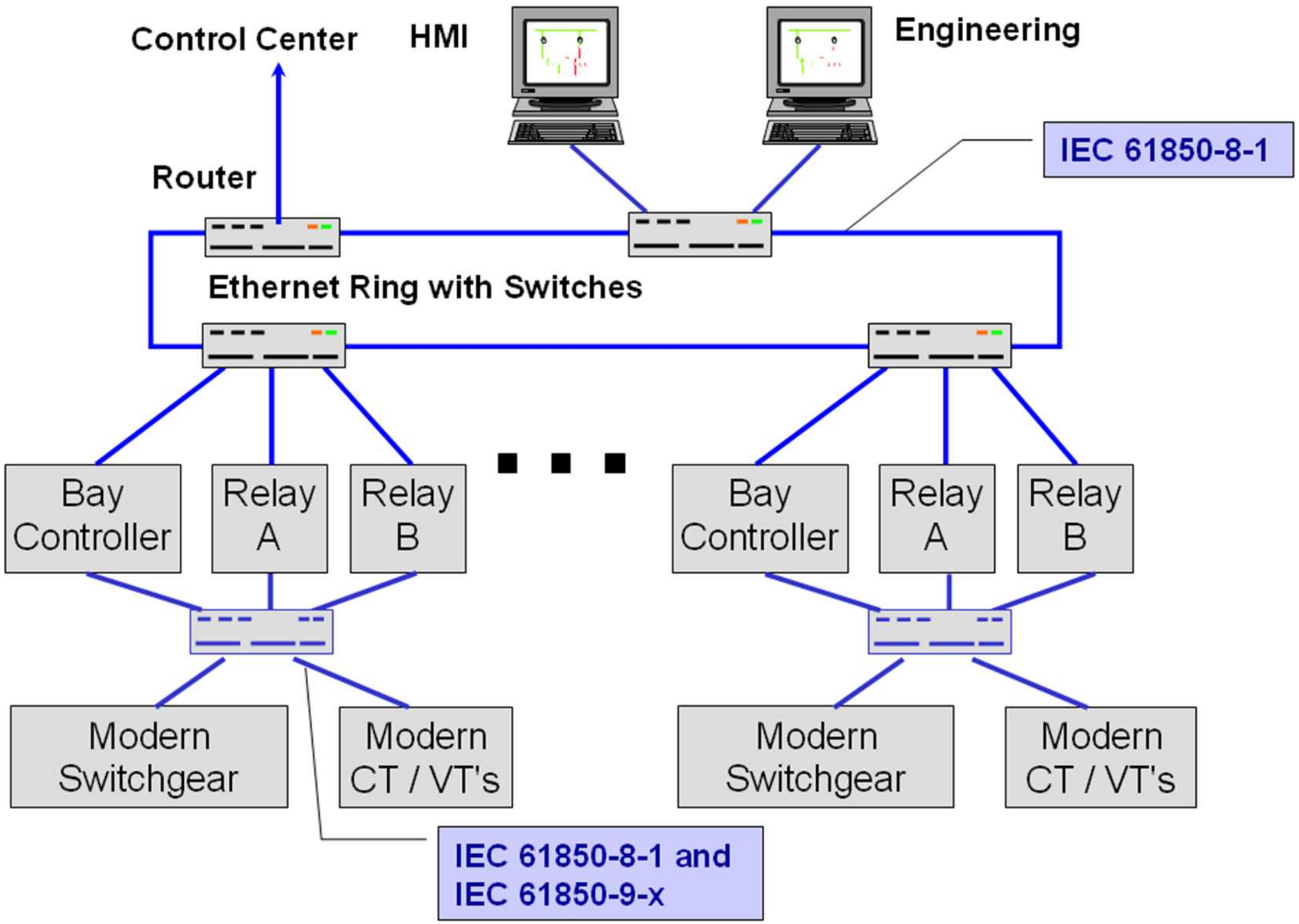
- Recommendations
- Distributed energy resources
- Wide-area protection
- Relay laboratory
- Communication

IEC61850

- IEC 61850 is designed to work inside the substation and assist SCADA systems with faster update on measurements and status messages.
- Station Bus: transfer GOOSE messages (e.g. a Trip) from the Protection Device to an Intelligent Electronic Device (Typically a breaker or a relay).
- Process Bus: send sampled values (SV) of V,I from the Merging Unit to the Protection device.

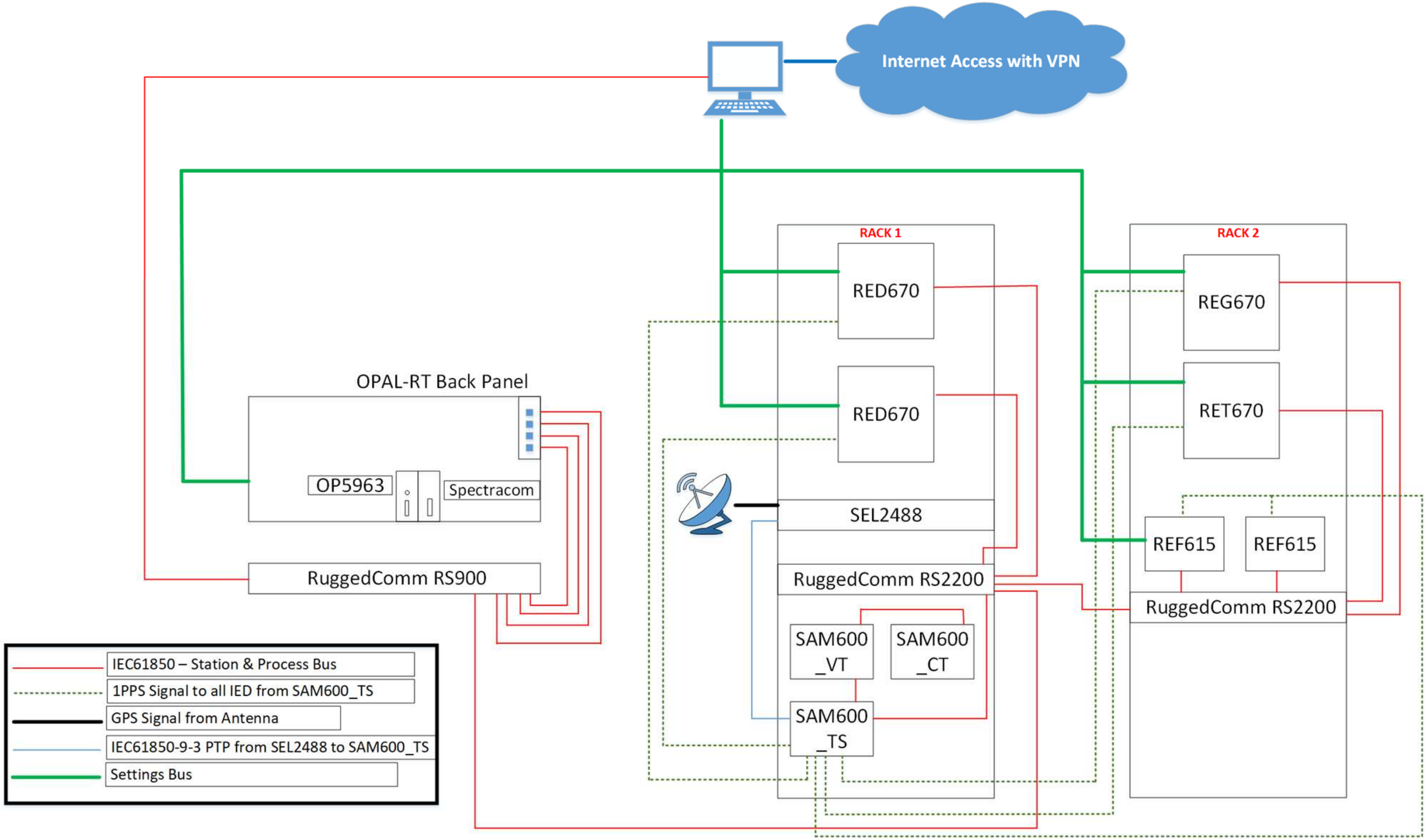


IEC61850

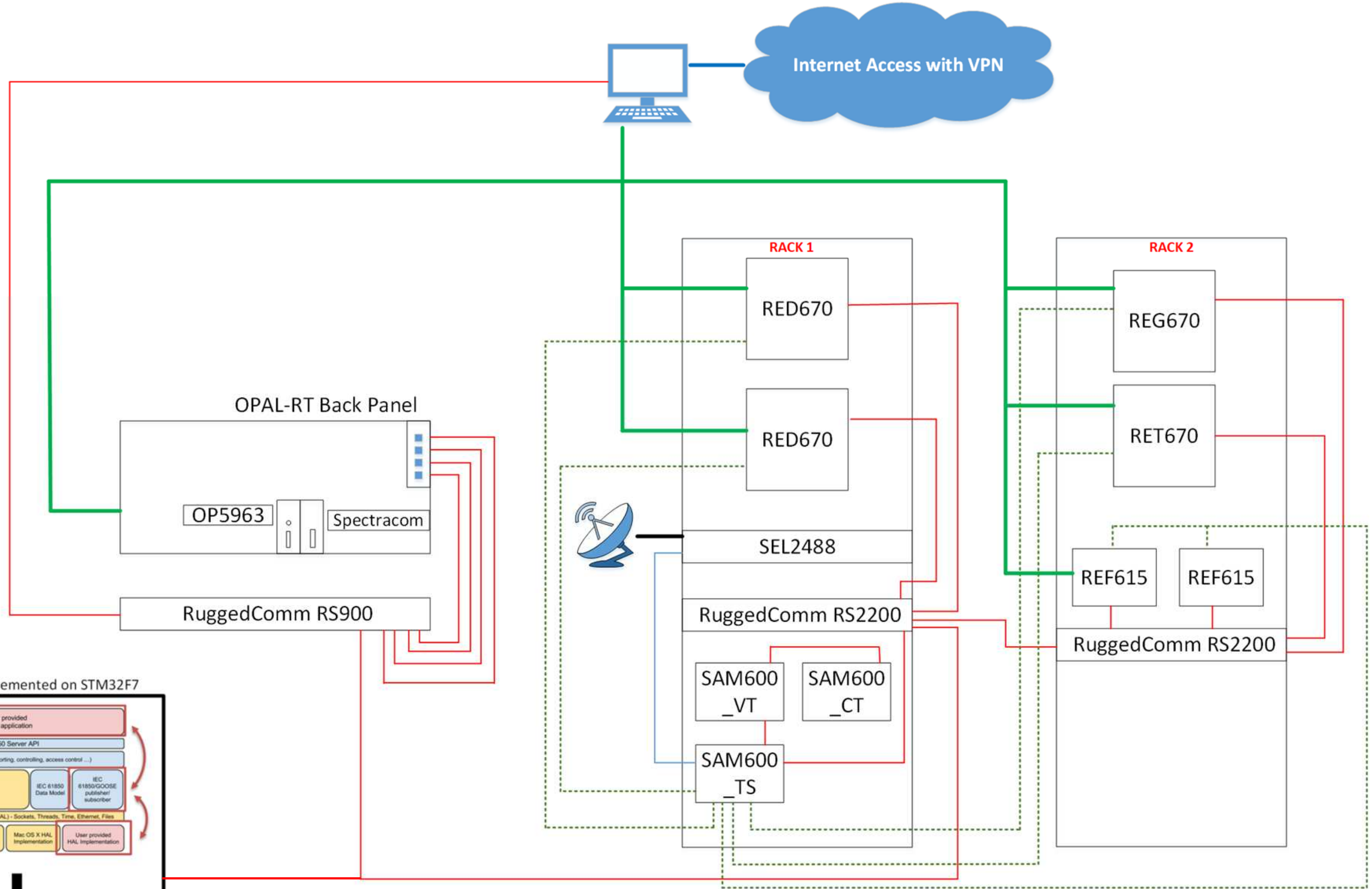


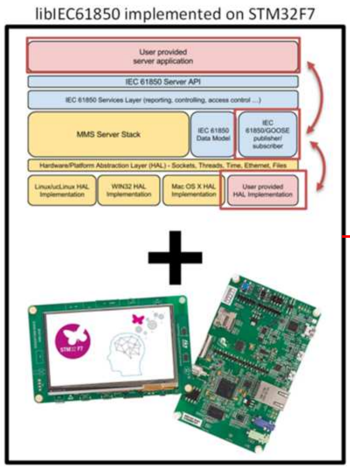
- Station Bus – Ring & Process Bus - Star

NTNU Laboratory Developments



NTNU Laboratory Developments

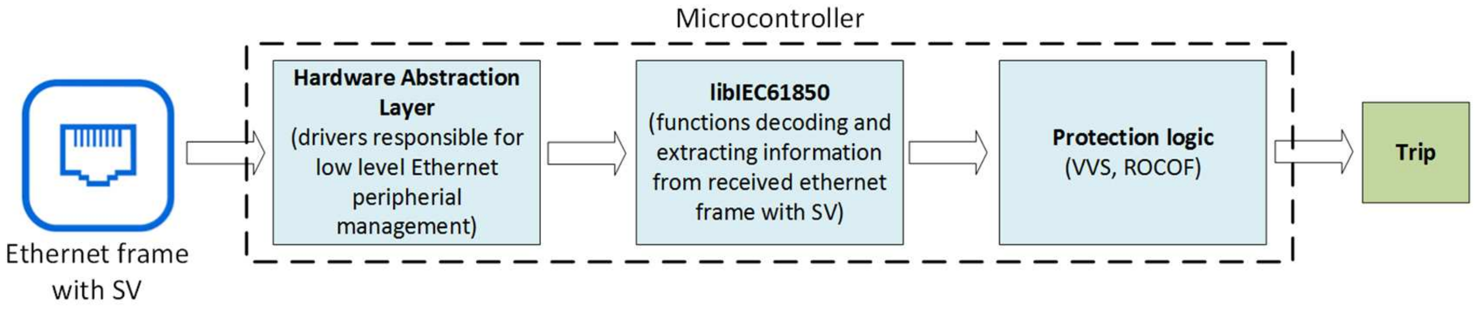




µP based IED for HIL testing

IEC61850 – Implementation on the µProcessor

Sampled Values Subscription	Estimation	Protection
Receive Sampled Value measurements from the substation bay level.	Estimate the phase, angle and frequency Filter the unwanted frequencies and compensate data loss.	Detect and Protect the network from faults. Trip the breakers by GOOSE Message

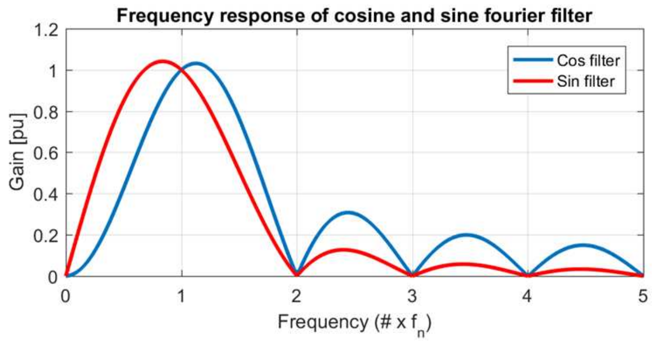


Phasor estimation methods implemented

Full cycle DFT

$$X_c(n) = \frac{2}{N}\sum_{k=0}^{N-1} x_k \cos\left(\frac{2\pi f}{N}k\right)$$

$$X_s(n) = \frac{2}{N}\sum_{k=0}^{N-1} x_k \sin\left(\frac{2\pi f}{N}k\right)$$



Least squares error

$$v = a_1 x_1 + a_2 x_2 + \cdots + a_m x_m$$

$$\begin{bmatrix} v(0) \\ \vdots \\ v(n) \end{bmatrix} = \begin{bmatrix} a_{01} & \cdots & a_{0m} \\ \vdots & \ddots & \cdots \\ a_{n1} & \cdots & a_{nm} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_m \end{bmatrix}$$

Frequency estimation methods implemented

FREQUENCY ESTIMATION

Zero crossing

$$t_{zc} = \frac{t_{n-1} \cdot V_n - t_n \cdot V_{n-1}}{V_n - V_{n-1}}$$

$$f = \frac{1}{2(t_{zc} - t_{zclast})}$$

Discrete fourier transform

$$f = \frac{\alpha_n - \alpha_{n-1}}{\Delta t} \cdot \frac{N}{2\pi} \cdot f_b$$

Adjustment of points to pure sine wave eq.

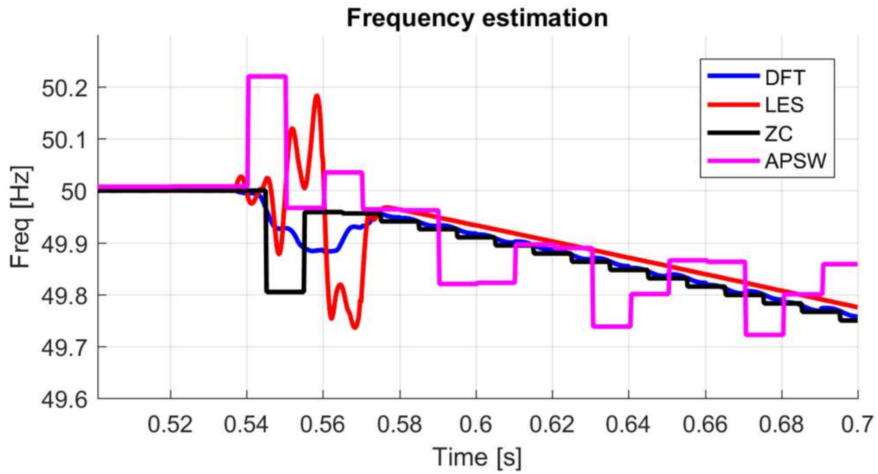
$$f = \frac{1}{2\pi\Delta t} \cdot cos^{-1}(\frac{V_{n-2} + V_n}{2V_{n-1}})$$

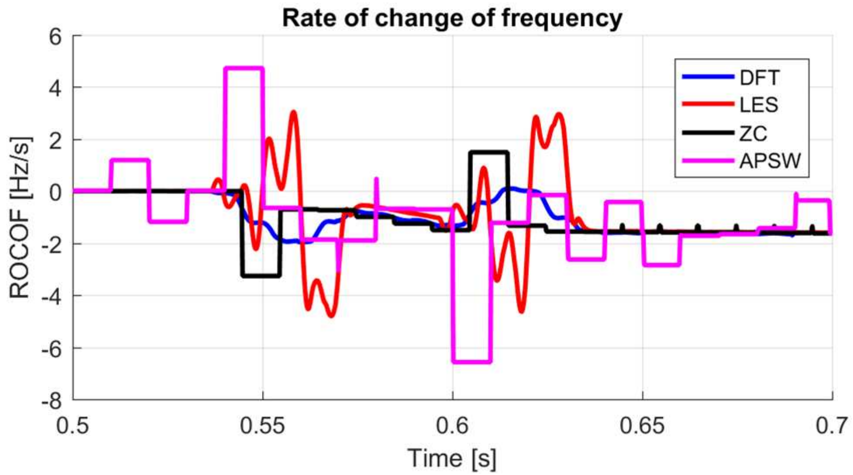
Least squares error

$$\begin{bmatrix} v(0) \\ v(1) \\ . \\ . \\ v(n) \end{bmatrix} = \begin{bmatrix} a_{01} & a_{02} & a_{03} & a_{04} & a_{05} & a_{06} \\ a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & a_{n6} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix}$$

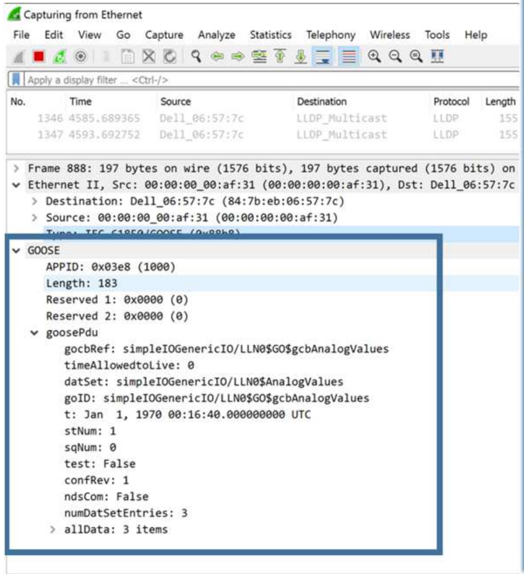
$$(f - f_0) = \Delta f = \frac{x_2}{x_1} = \frac{(f - f_0)V_m cos\Theta}{V_m cos\Theta}$$

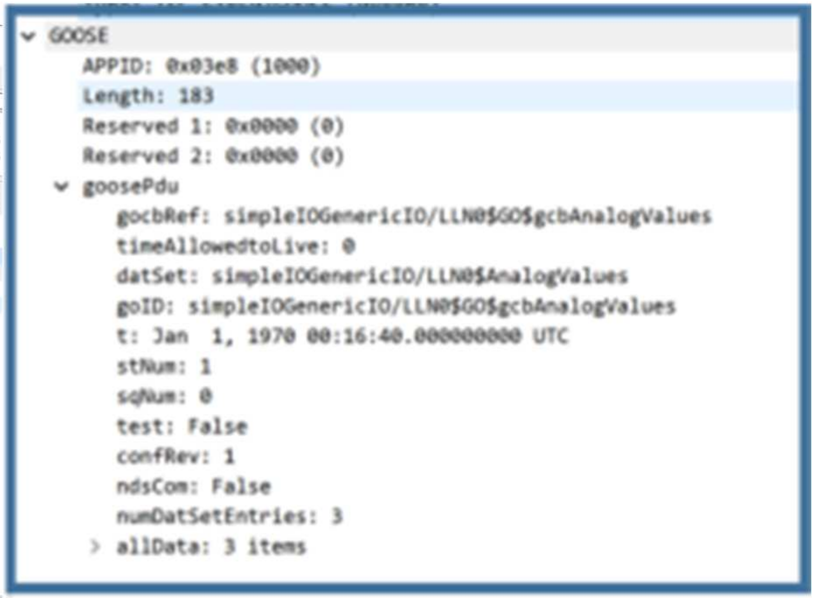
Frequency estimation in RT-HIL simulations of islanding cases



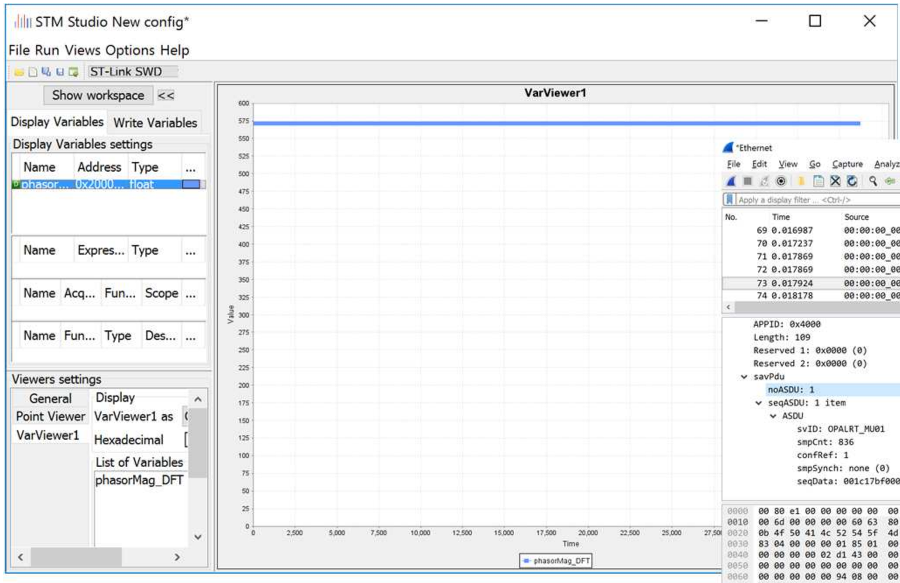


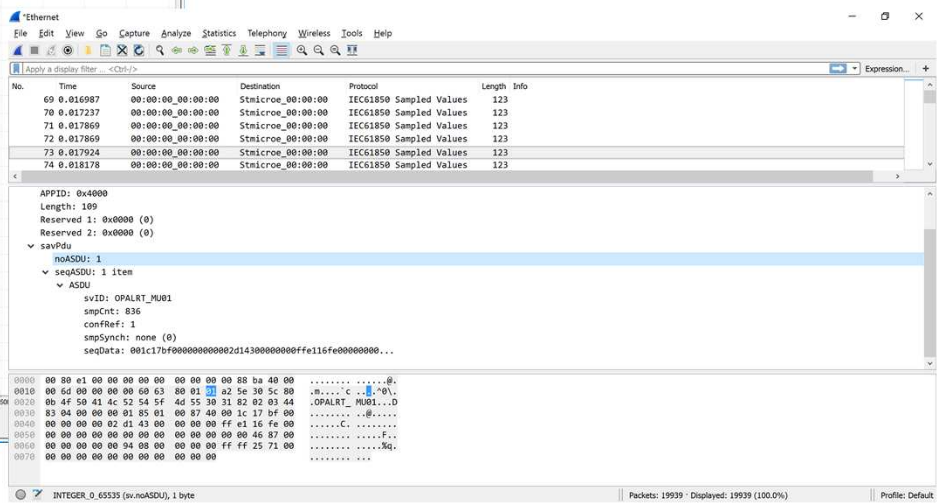
Results





Wireshark capture of GOOSE frame





Phasor magnitude estimated from SVs

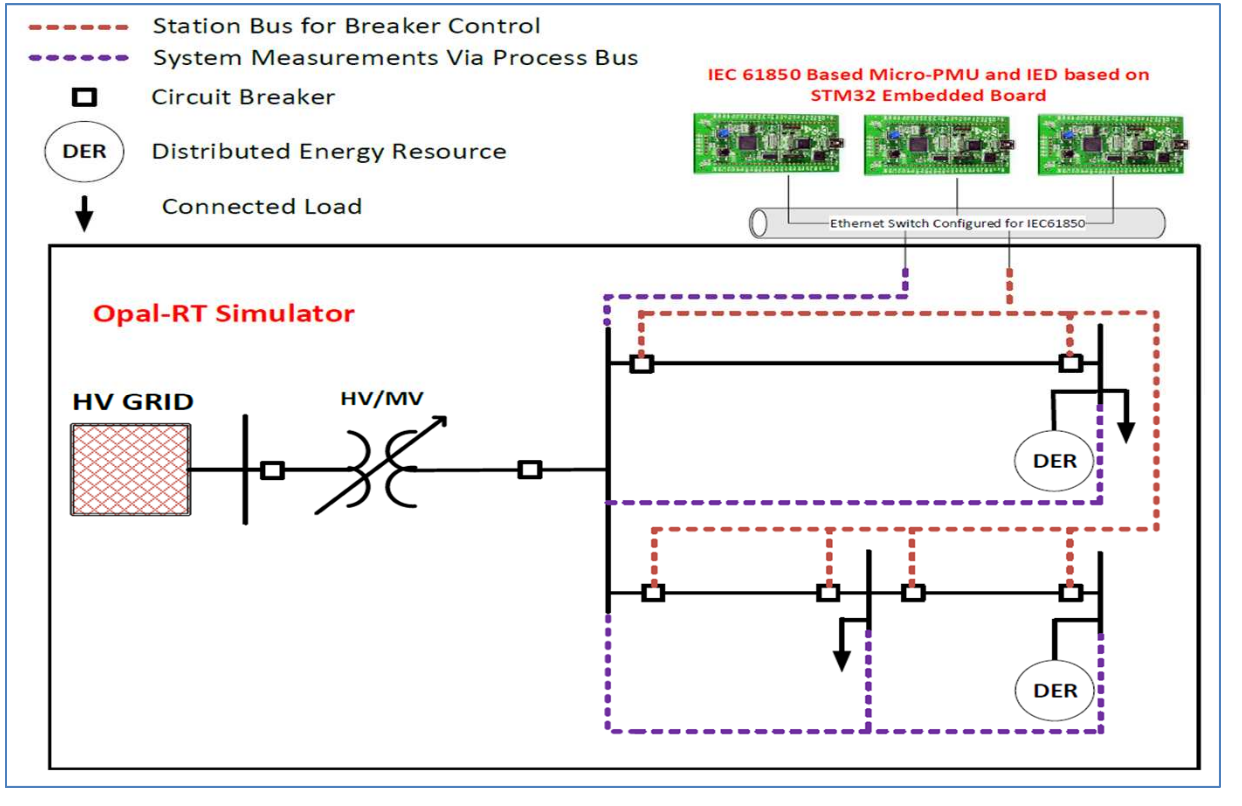
Future Aspects

Algorithms:

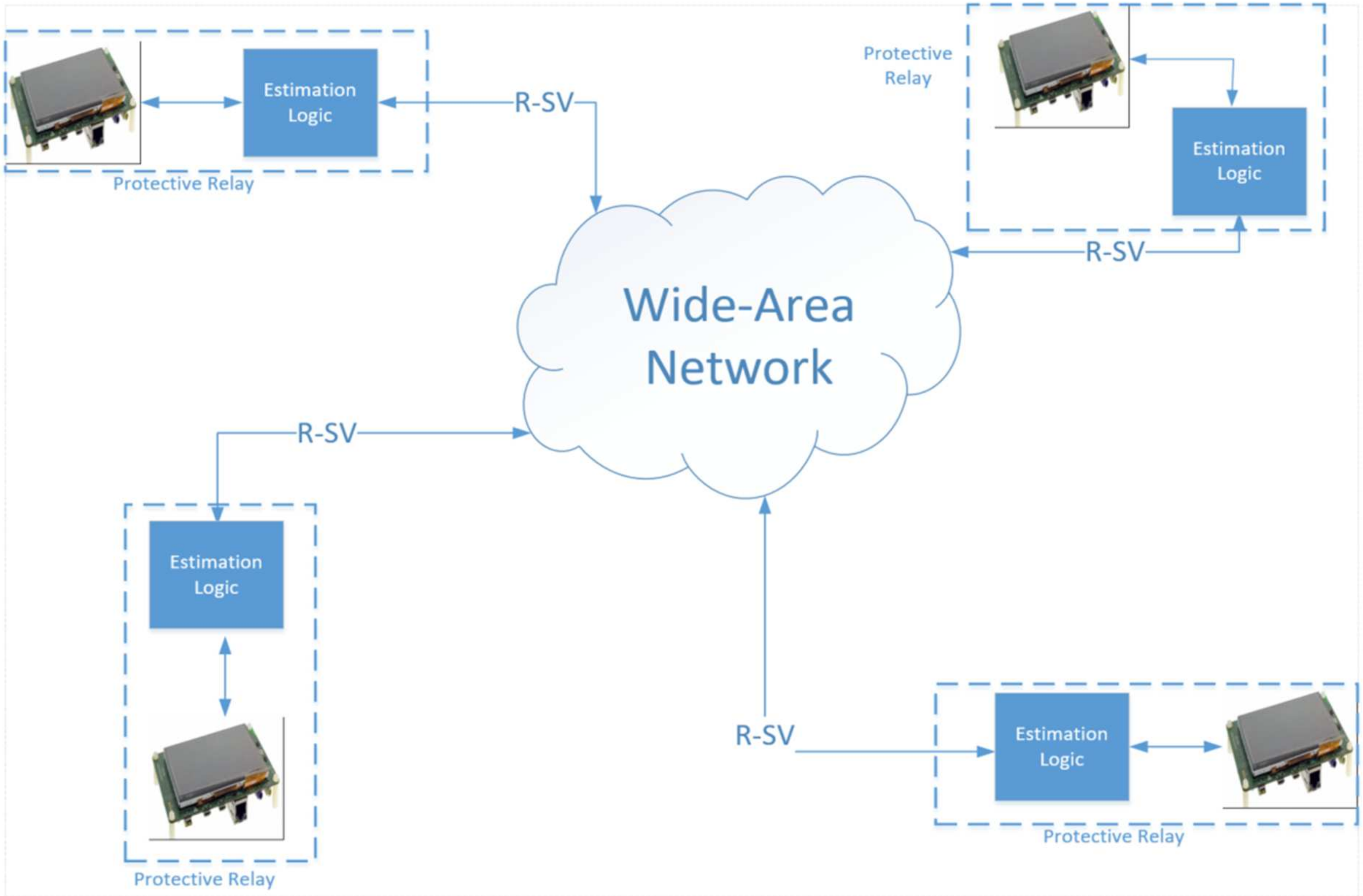
- Sampled Values Estimation using Kalman filter.
- Implementation of Dynamic filter to address communication issues related with publishing sampled values in wide-area.

Applications:

- Multi-Terminal Line Differential protection based on IEC61850, to remove vendor dependency.
- µPMU & IED design based on IEC61850, to design DER protection algorithms.



IEC61850 based Wide-Area Network Setup



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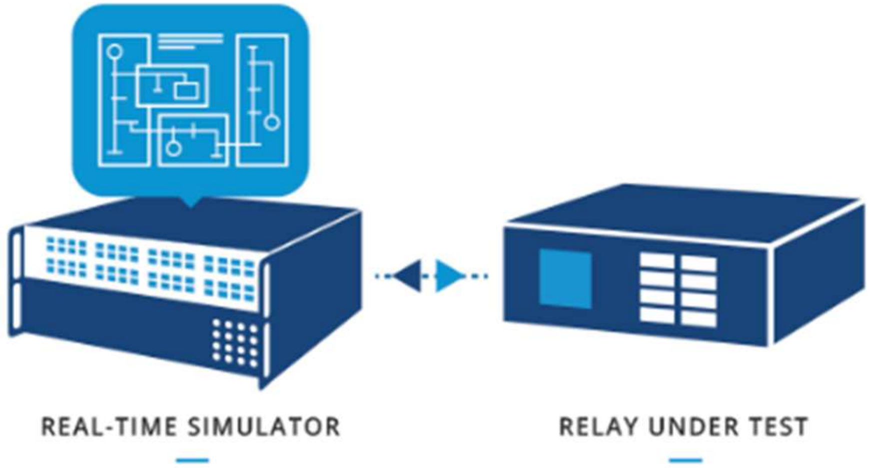
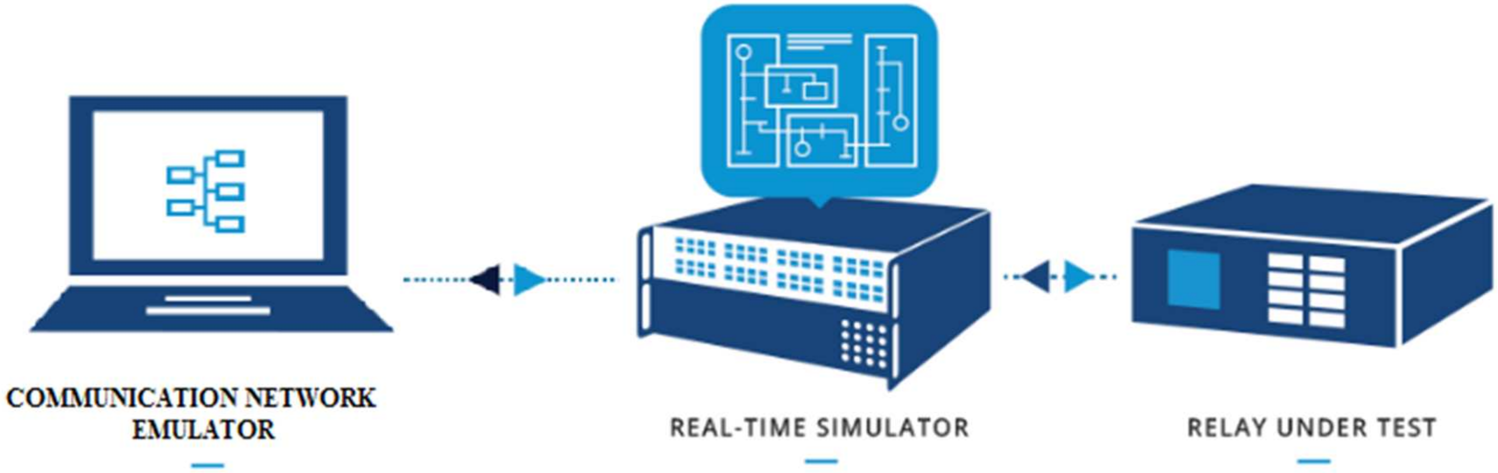
Part 2 - Laboratory tests of New Protection Schemes using Co-Simulation Platform.

Hardware-in-the-loop relay testing



- Faster and reliable results due to availability of actual power system model and components.
- Solving the problem in presence of actual environmental conditions, such as noise, none ideal conditions as well as hidden or neglected factors which may be concealed in simulation-only techniques.
- Identification of factors when accomplishing the solution through replication of experiments.
- Compare different solutions and approaches in the existing power system.

Communication network inclusion in HIL tests



- Validation and deployment of new protective schemes involving communication technologies.
- Investigation of communication network parameters appearing at intra/inter substation traffic and their impact on protection performance.
- Real time simulator has limited ability to simulate communication network impairments.

Communication network emulator

Click Modular Router

a software framework for building flexible and configurable routers

- Flexibility
  - Adding new features to enable experimentation
- Openness
  - Allow users to build and extend
- Modularity
  - Simplify the composition of existing features & addition of new features

Emulator is capable of:

- Controlling communication properties between multiple source relays and destination relays.
- Impairing specific subsets of the network traffic.
- Changing delays, jitters and packet corruption in real time.
- Bandwidth restriction.
- Emulation different queueing schemes and traffic priorities.

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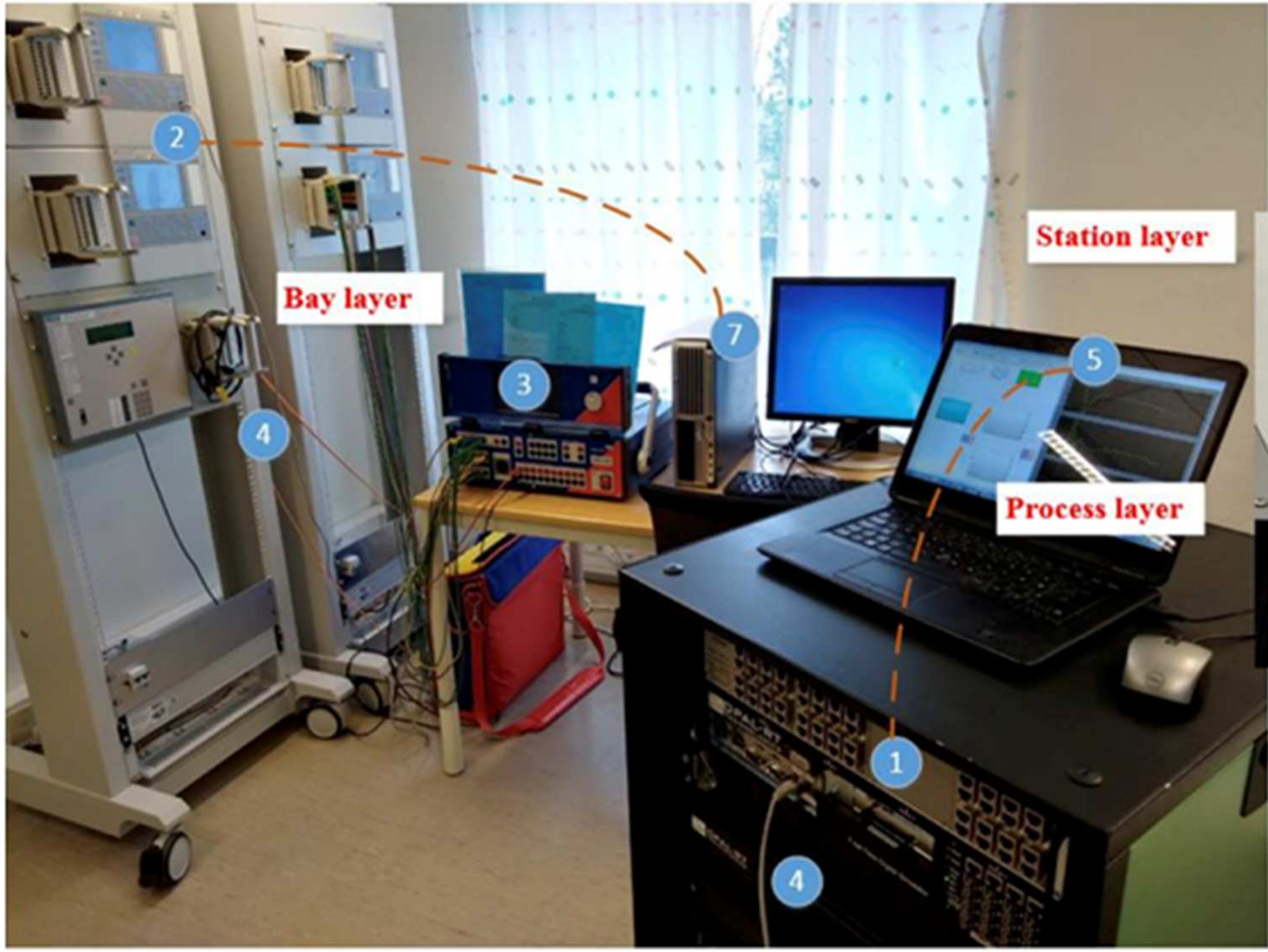
Real-time HIL test platform at NTNU

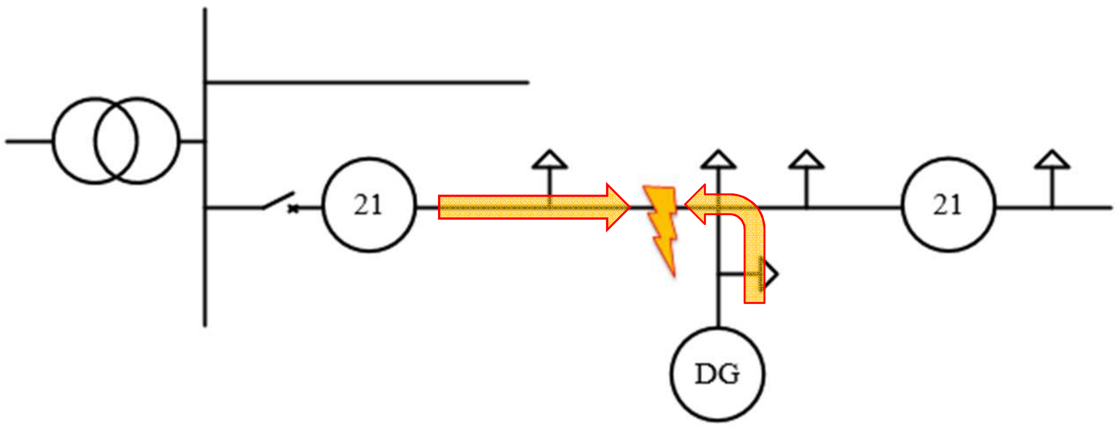


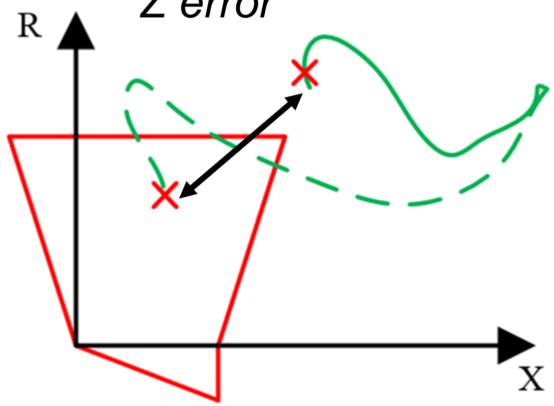
1. Opal-RT simulator
2. ABB Relion 670 relays
3. OMICRON CMC 356
4. IEC61850 based communication network

5. Host PC and HMI for Opal simulator and network analyzer
6. Communication switch emulator-Click and Network analyzer-Wireshark
7. Host PC and HMI for PCM 600 and ABB relays

Application example: problem statement

- Testing of impedance protection with compensation of fault impedance and DG infeed current.
- Problem:

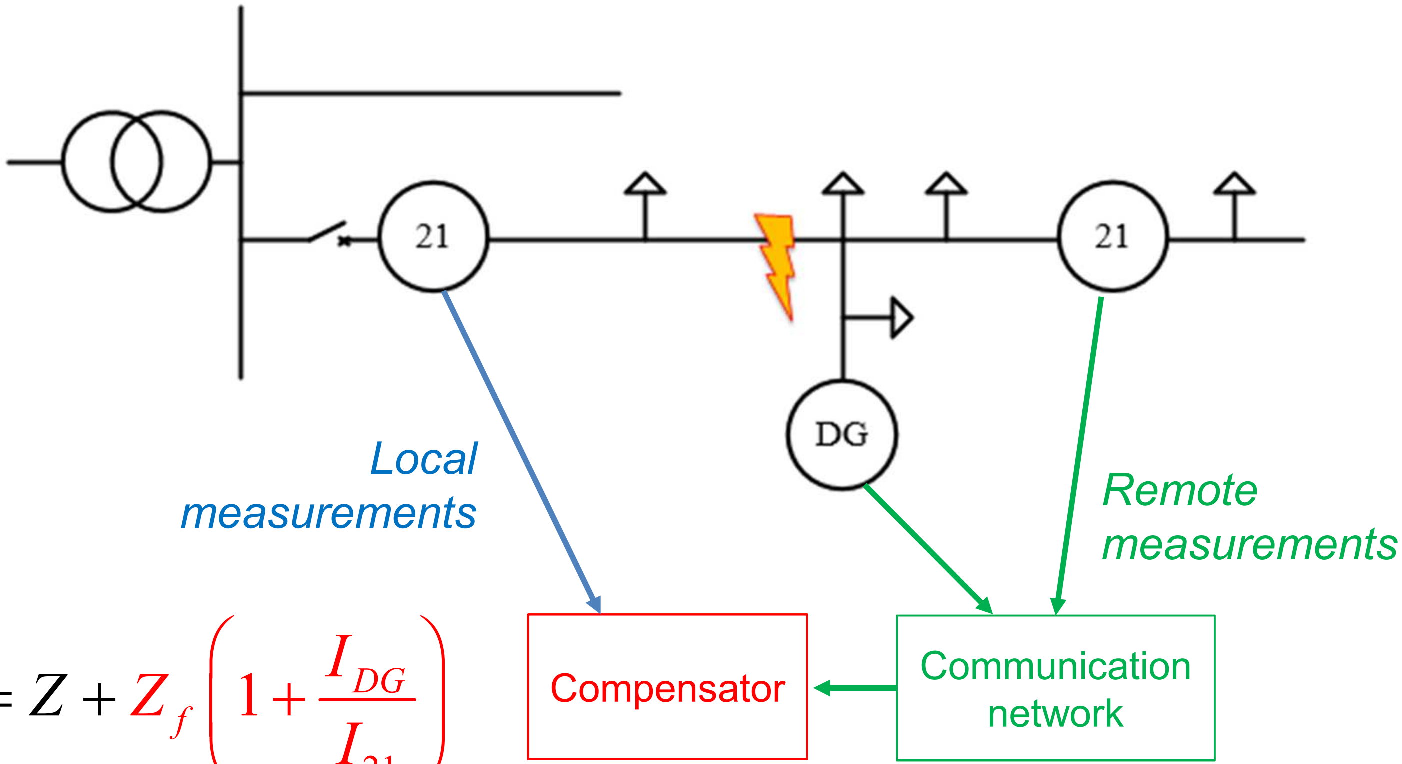




$$\frac{U_{21}}{I_{21}} = Z + Z_f\left(1 + \frac{I_{DG}}{I_{21}}\right)$$

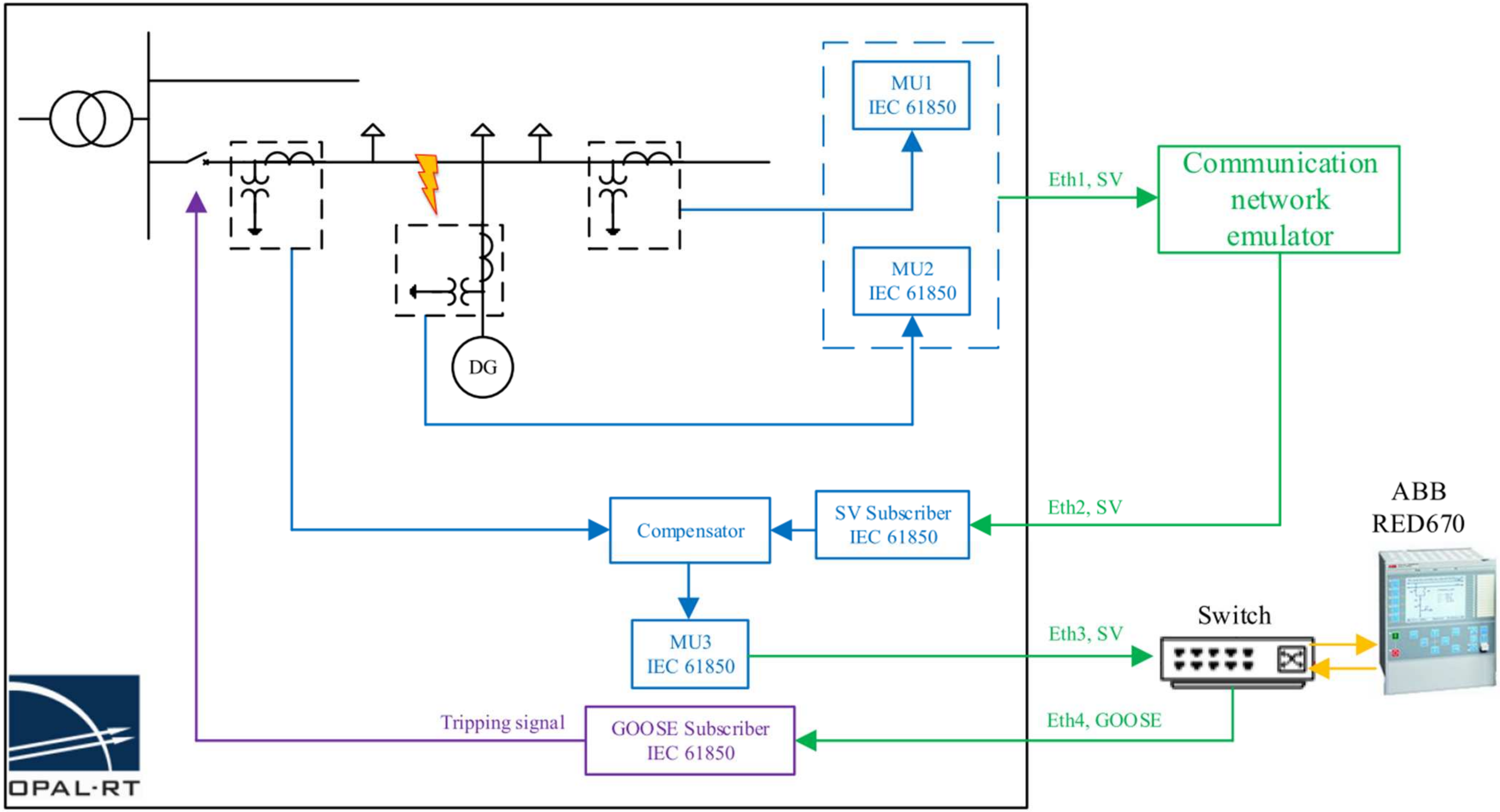
Application example: problem solution

- Universal communication based compensation method (interphase faults), ISGT 2017
- No need in information about detailed multitapped system topology and loads

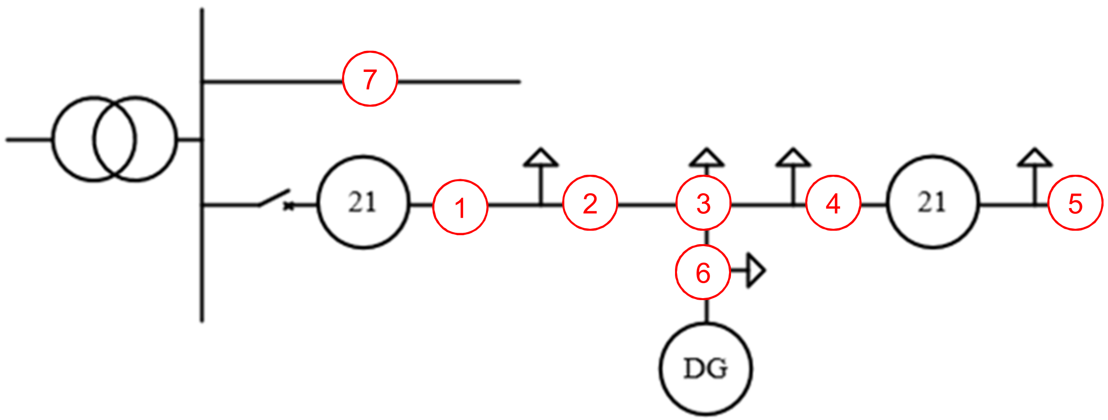


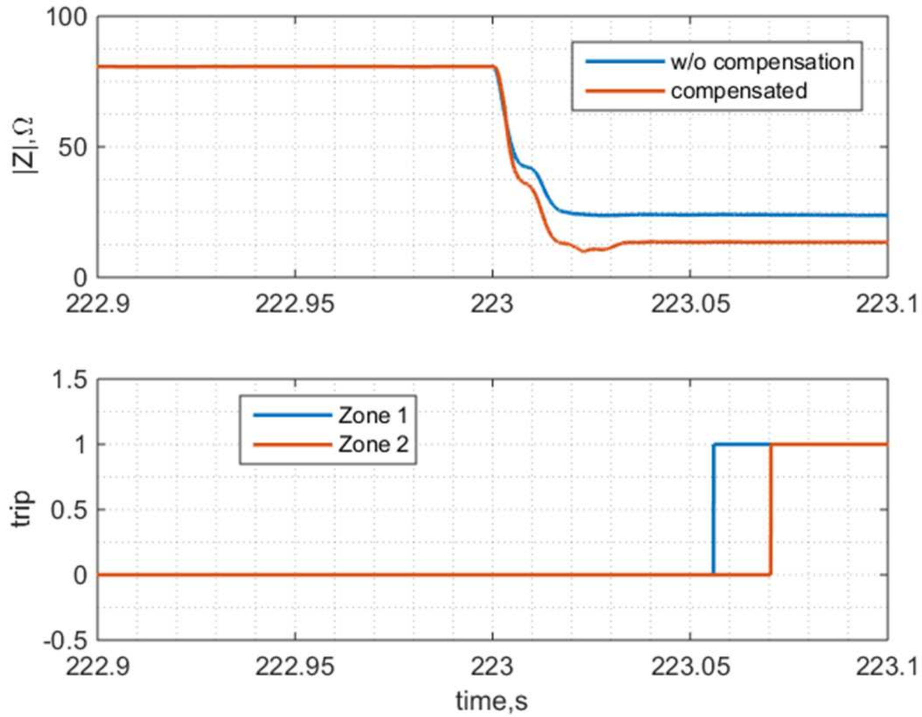
$$\frac{U_{21}}{I_{21}} = Z + Z_f\left(1 + \frac{I_{DG}}{I_{21}}\right)$$

Application example: test setup



Results: no network imperfections





- Proper appearance of tripping signals for all fault locations (except adjacent feeder) and different fault resistances
- Acceptable operation time
- Impact on fault location accuracy:
  - Overreaching (tripping signal is always present)

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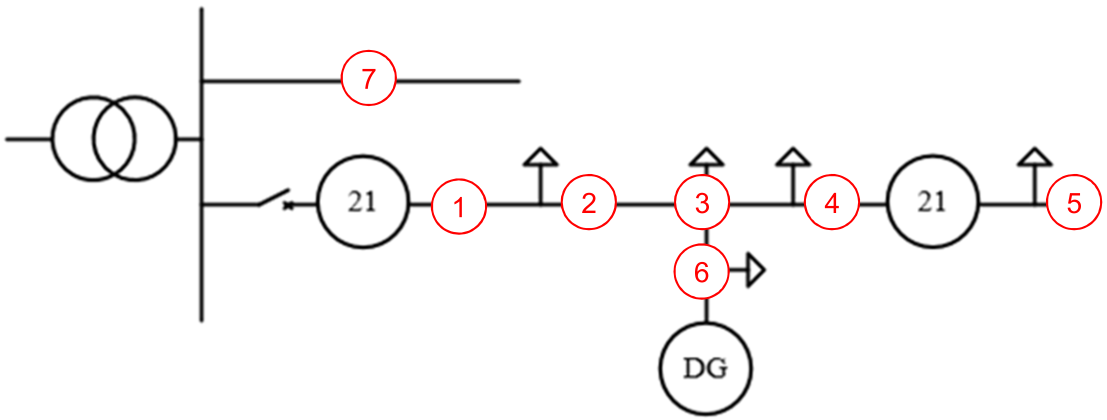
Results: impact of jitters on protection performance



Percentage of successful tripping (Zone1/Zone2) among 30 consecutive faults

Fault location	Low-ohmic faults		High impedance faults	
	Jitters 0.1-0.5 ms	Jitters 1-5 ms	Jitters 0.1-0.5 ms	Jitters 1-5 ms
1	100%/100%	100%/100%	100%/100%	6.7%/53.3%
2	100%/100%	100%/100%	100%/100%	3.3%/13.3%
3	100%/100%	100%/100%	40%/100%	10%/26.7%
4	100%/100%	13.3%/100%	0%/100%	3.3%/20%

Dependability analysis in case of unsynchronized signals (i.e. no GPS)

Results: impact of data loss on protection performance

- Low-ohmic fault at the middle of the feeder
- Packets of sample values from DG are dropped with probability 20% and 80%