WP6
Implementation of a Wide-Area Protection, Automation and Control system (WAMPAC) applied to Cross-Border Transmission Systems

CIRCE – WP Leader

FARCROSS

Dec 1st 2022

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Contributing partners and their roles

- Main Contribution partners:
  - IPTO: TSO and Greek transmission grid owner, hosting the WAMPAC Demo and being in charge of communications and installation of the equipment.
  - SEL– Spain: Providing/developing algorithms, experience and equipment for the demo
  - STER: Providing /developing algorithms, experience and equipment for the demo.
  - CIRCE: Research center, WP leader, developer of algorithms and responsible of the Lab-scaled demo.
- Additional Contribution partners:
  - UBITECH, UBE, ESO, OST, CINTECH, IEIT, SC, IBEX

ipto INDEPENDENT POWER TRANSMISSION OPERATOR

SEL SCHWEITZER ENGINEERING LABORATORIES

STER

circe Creating together

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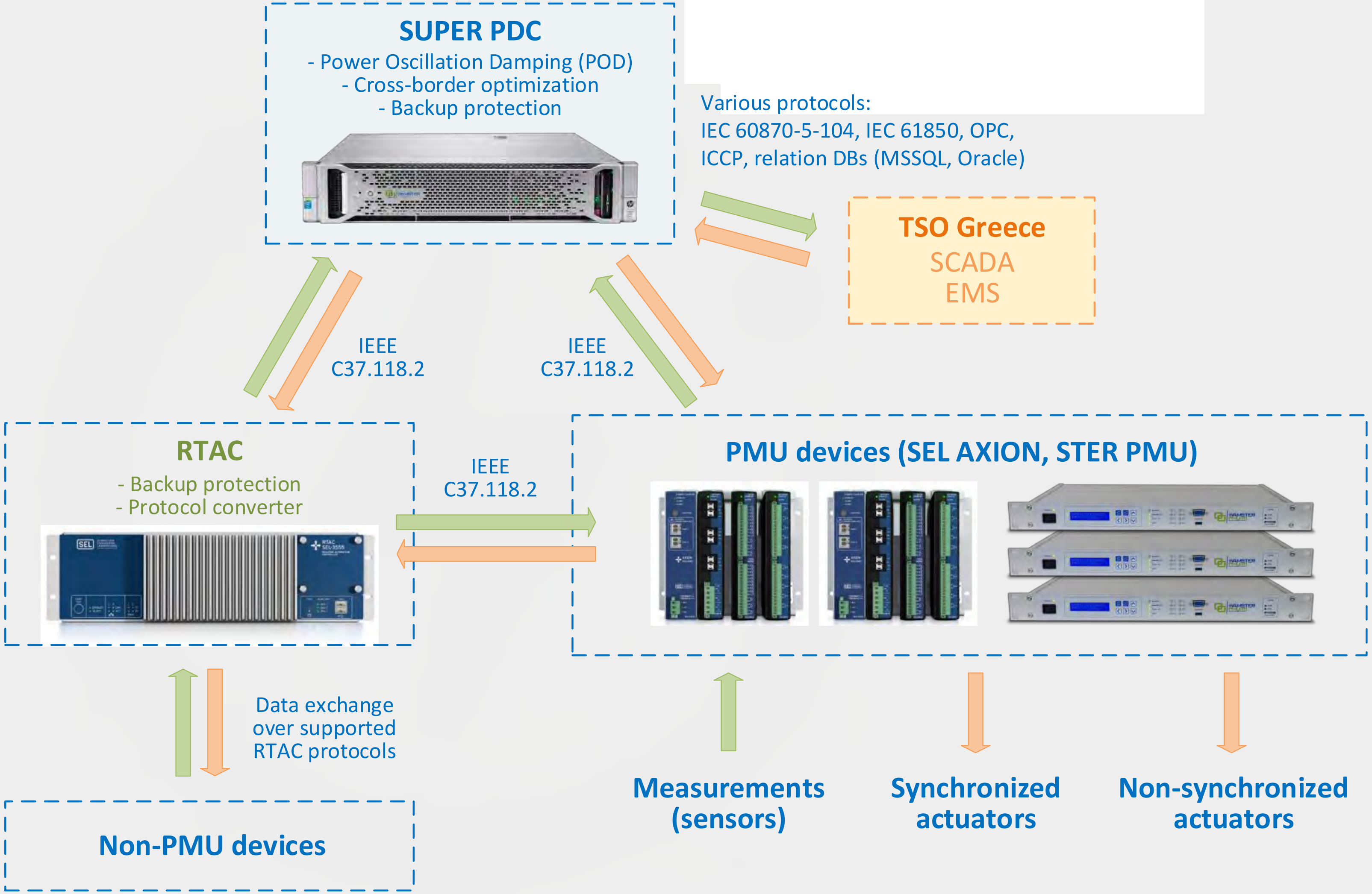
Objectives of the DEMO

- Application of cross-border analysis for power oscillations
- Increase power system security
- Demonstration of associated communication infrastructure

General diagram of the equipment in the DEMO



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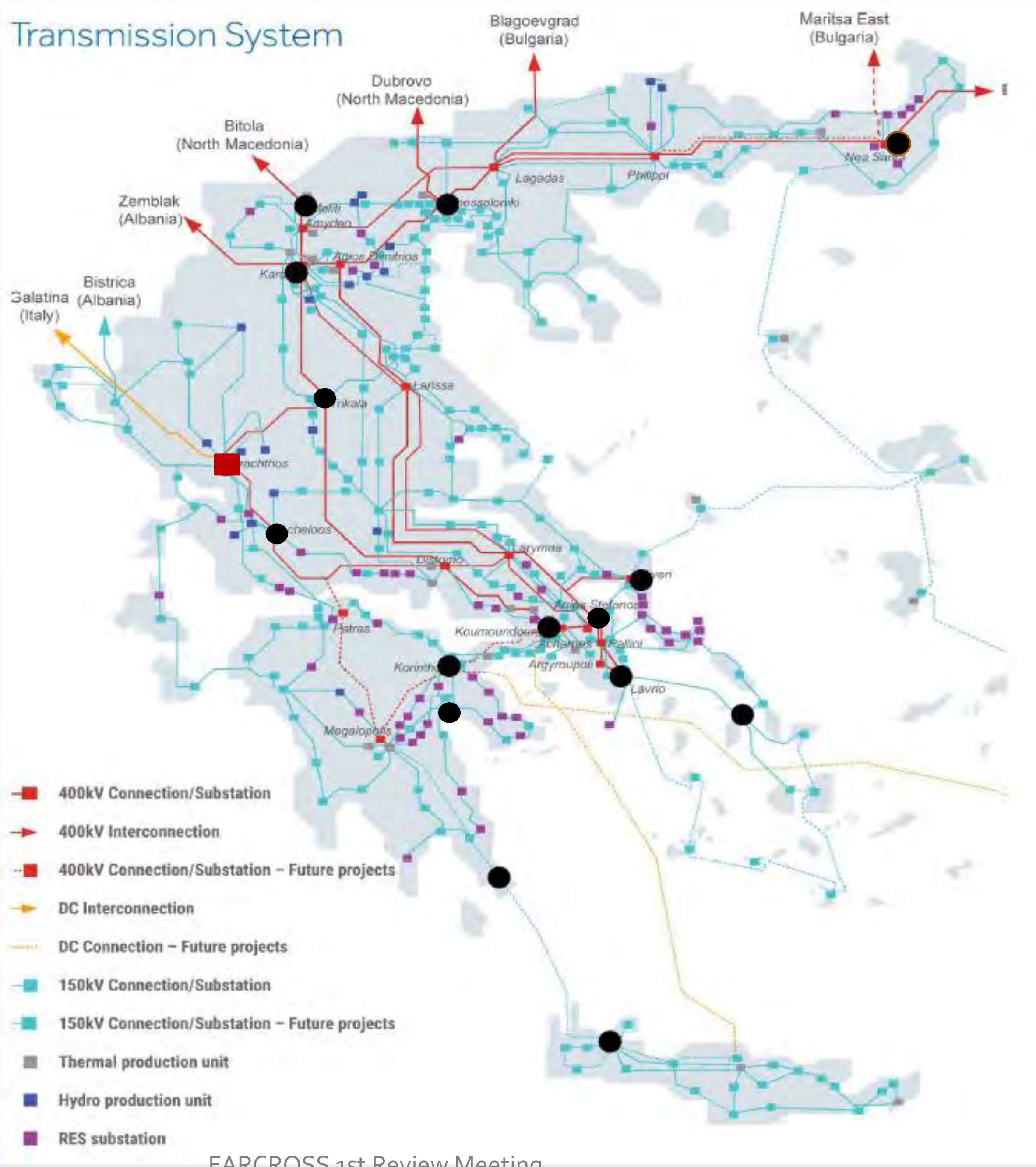
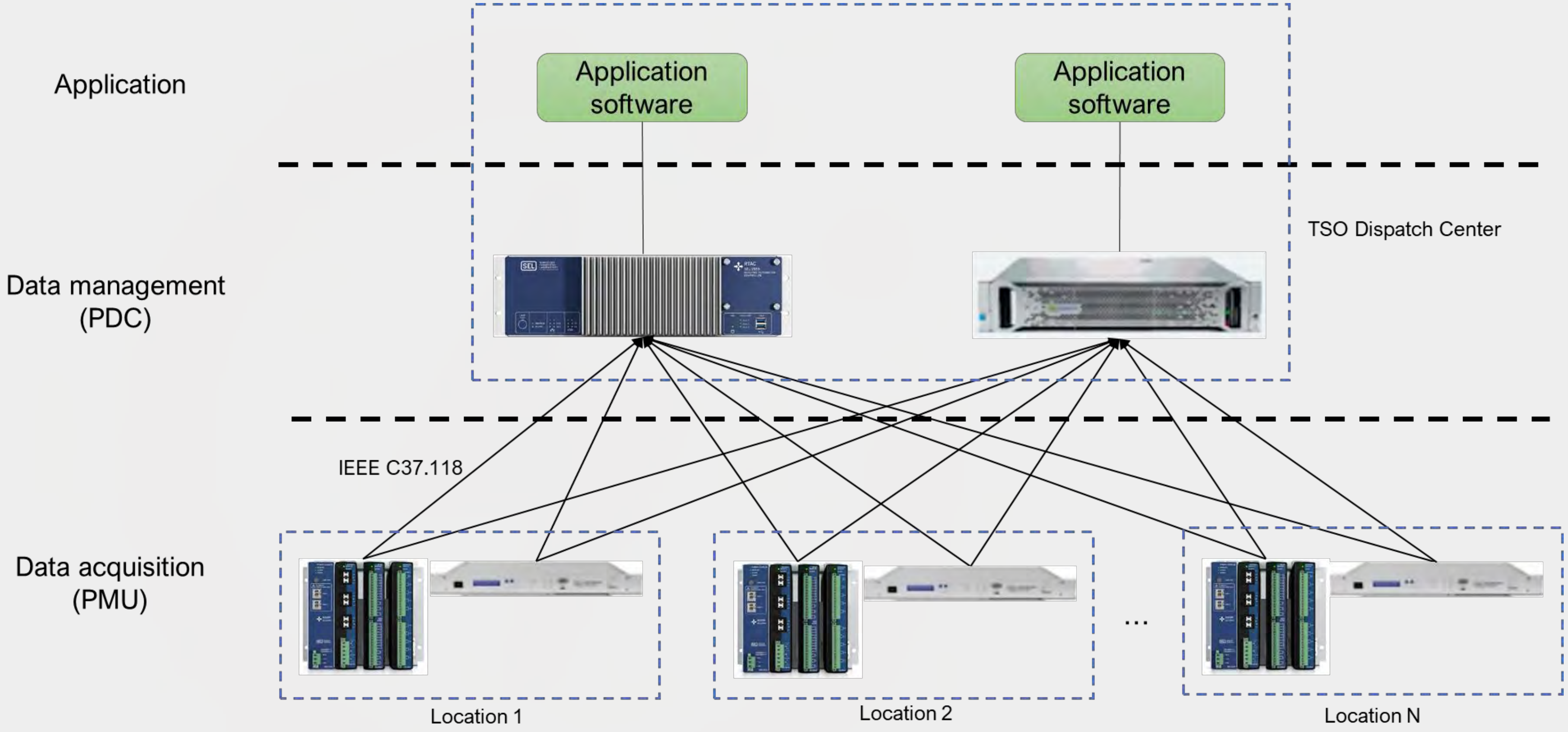
Location of the PMUs of the DEMO



Location of the PMUs of the DEMO



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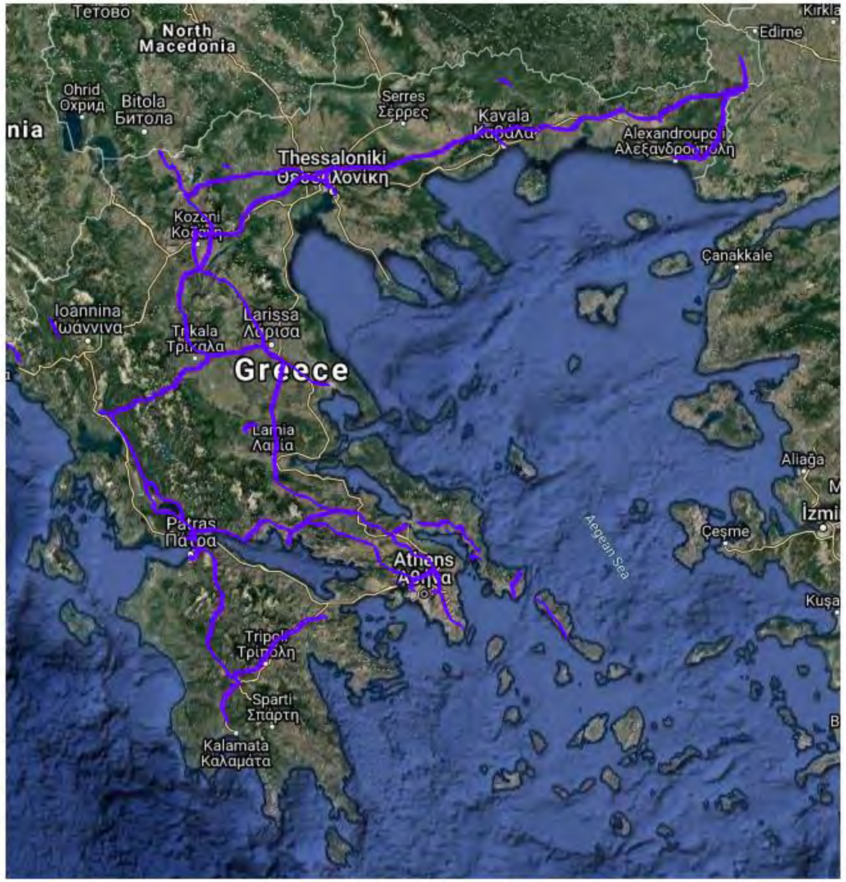
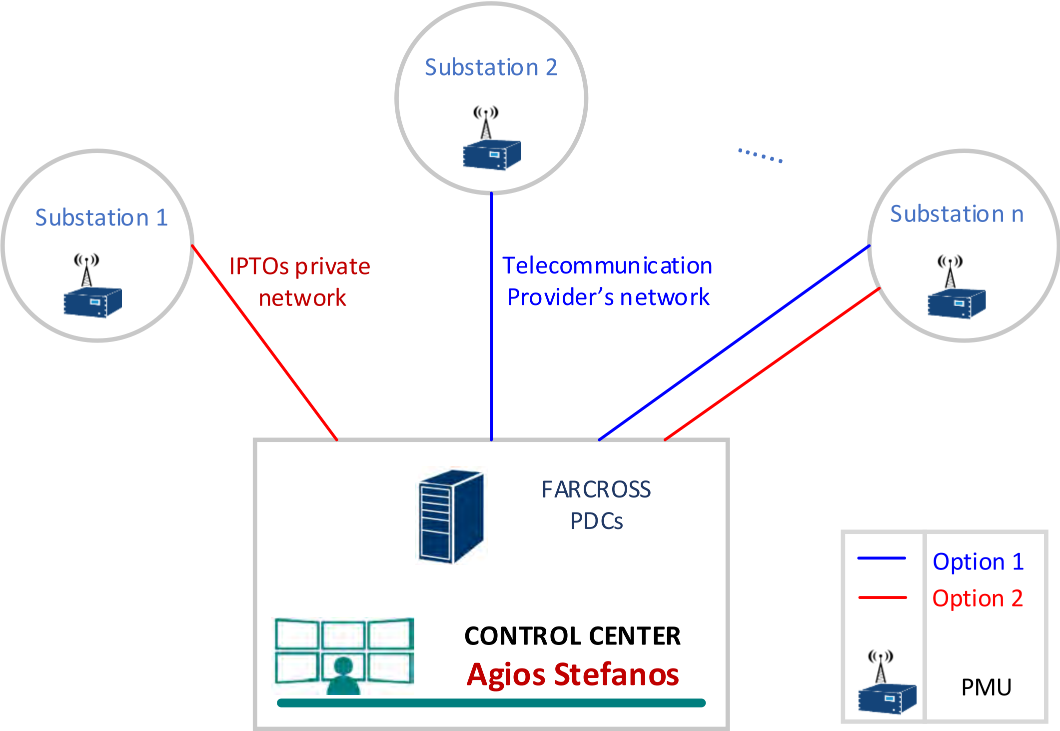
Communication Network





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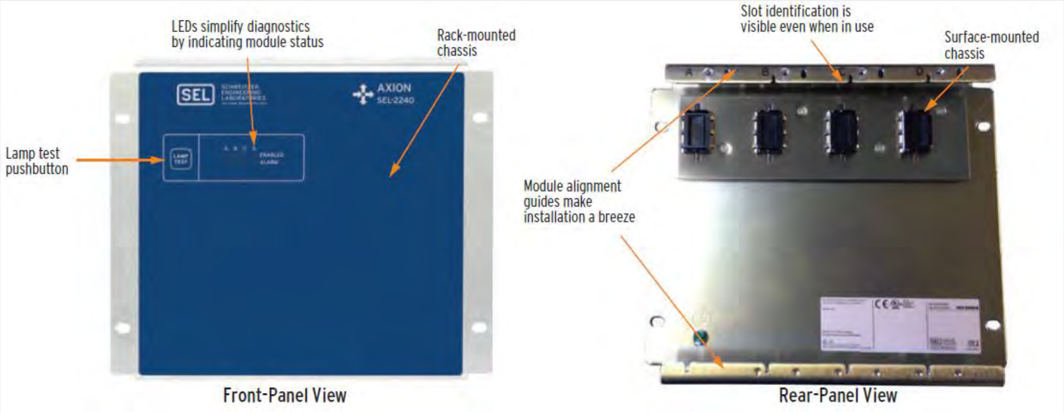
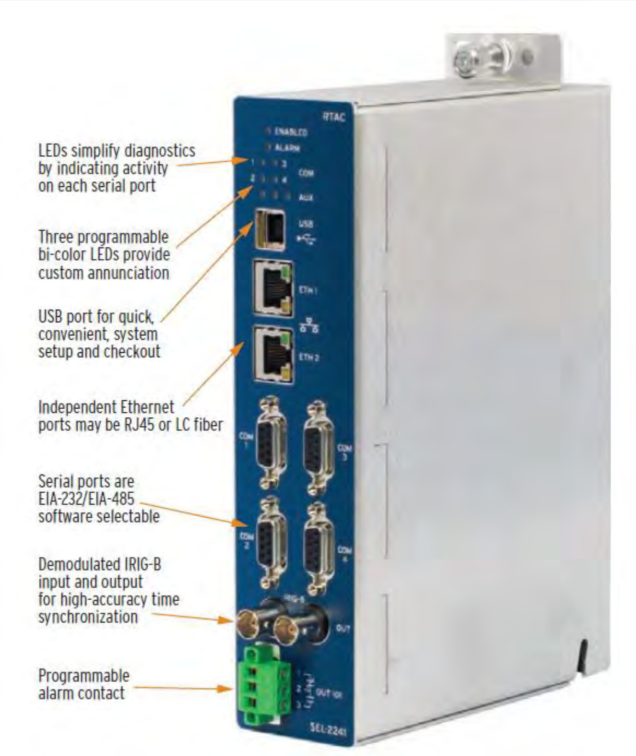
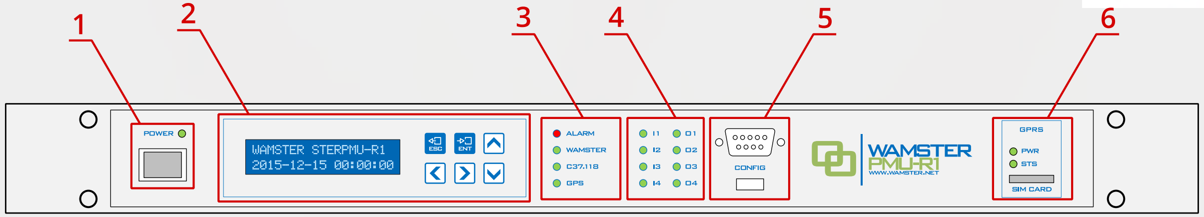
Procurement of control equipment



SEL-2242 4-Slot Chassis/Backplane



SEL-2241 RTAC (Terminal-Side View)



STERPMU-R1 front panel description

Services of the WAMPAC

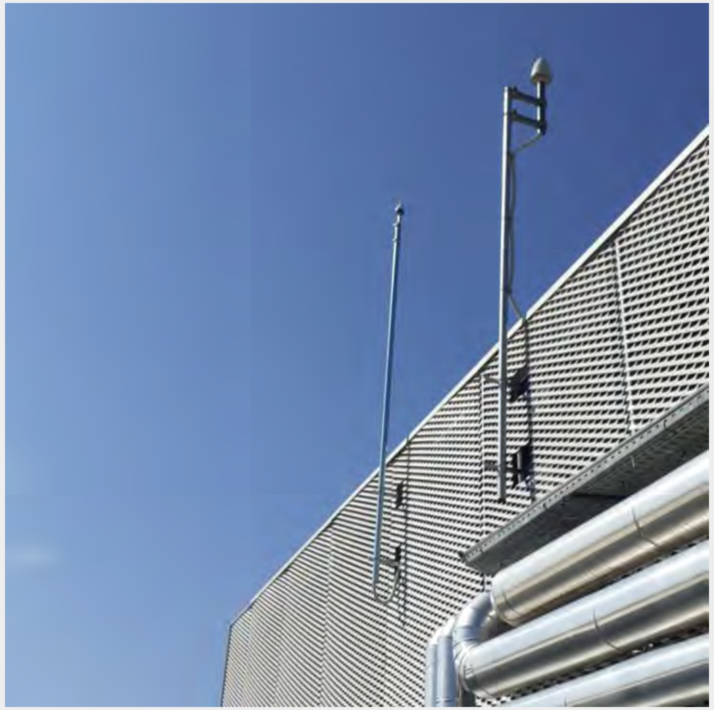
- Dynamic Line Rating
- Voltage Stability
- Short circuit backup protection
- Power oscillation detection
- Loss of synchronism, islanding detection and ROC of Active Power
- Wide area algorithm analysis for damping oscillations
- Feeding the EMS with measurements of the WAMS

WAMPAC LABORATORY SCALED HARDWARE IN THE LOOP DEMO

-Same equipment than in DEMO: PMUs, PDC

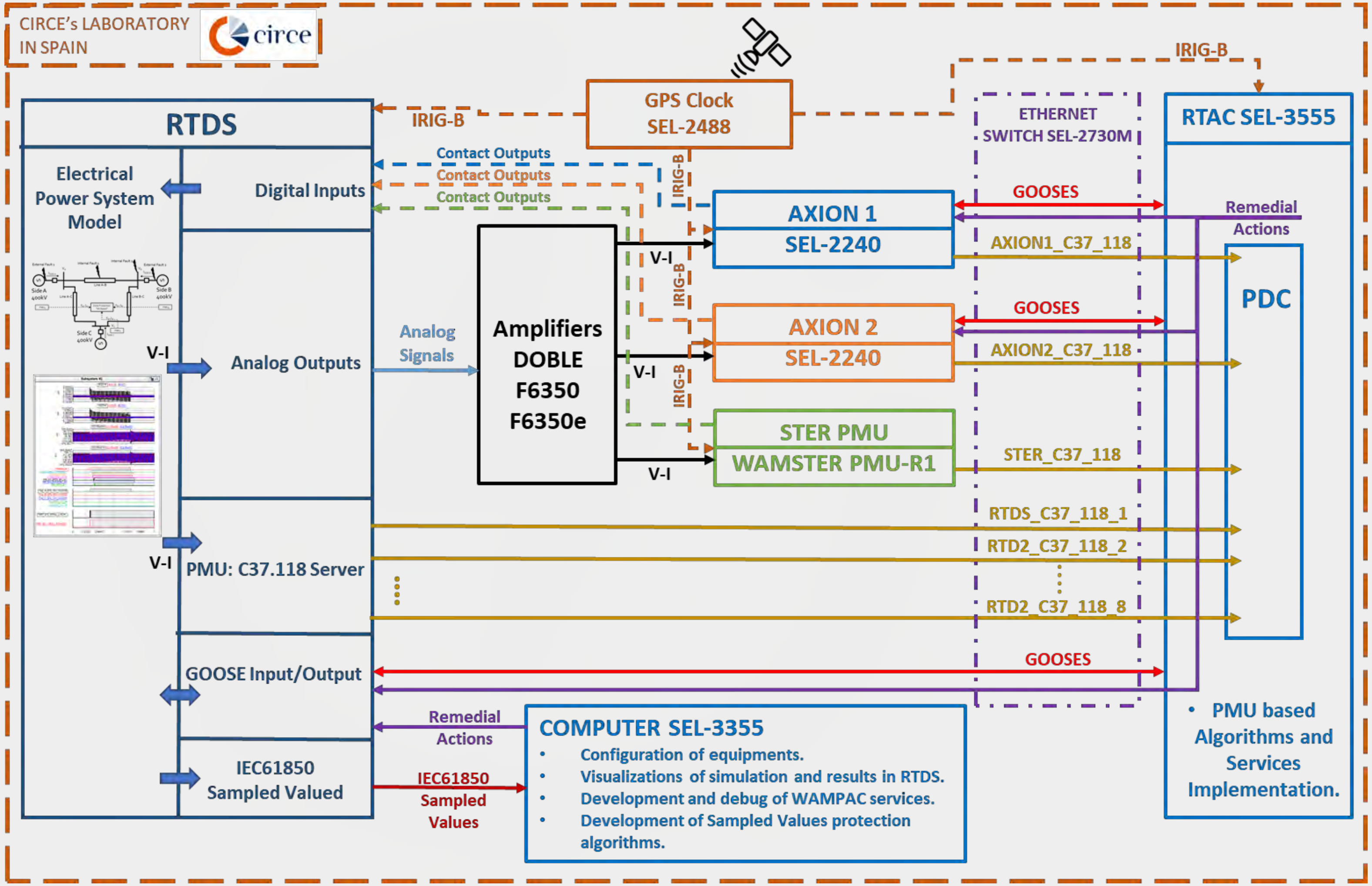
-Programming and testing algorithms before field implementation

Lab-scaled DEMO



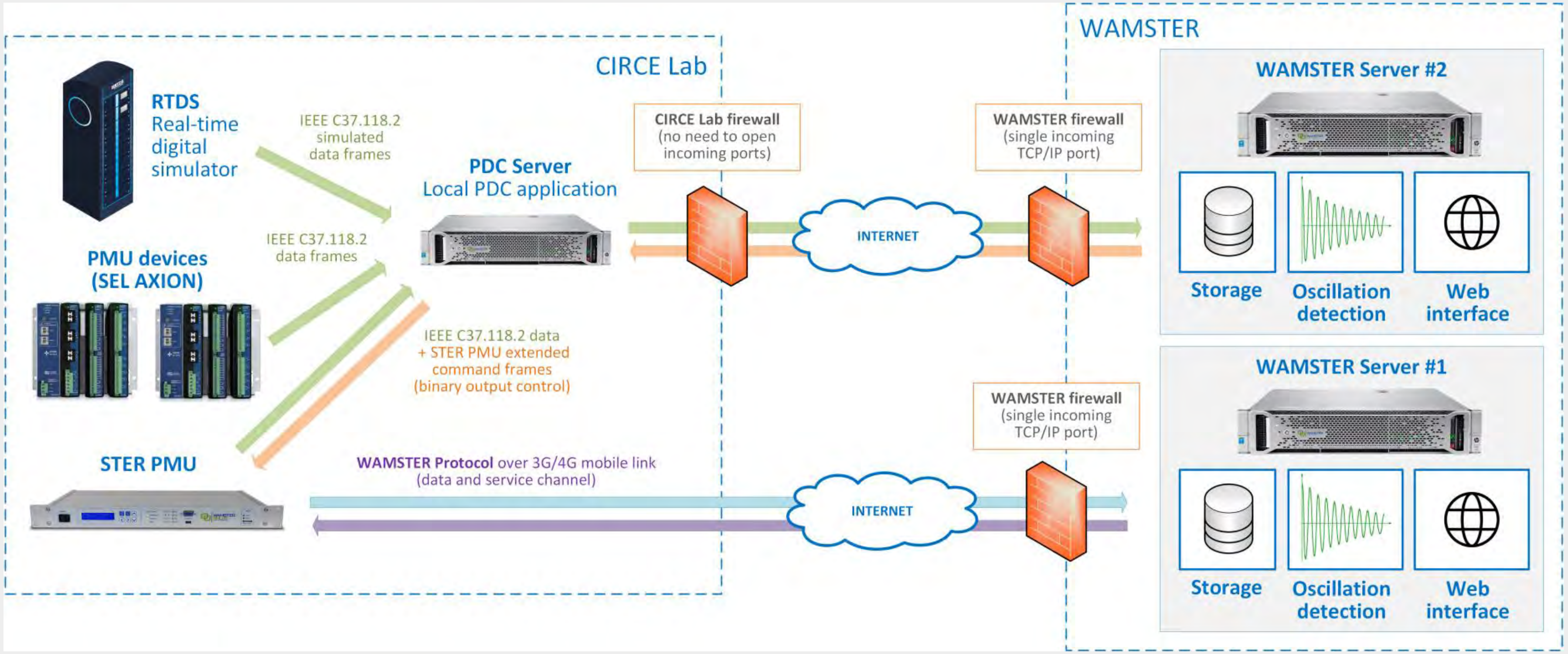
Lab-scaled DEMO

WAMPAC LABORATORY SCALED HARDWARE IN THE LOOP DEMO



Lab-scaled DEMO

- CIRCE PDC application connects locally to all PMU devices using the IEEE C37.118.2 protocol, and concentrates the data into a single outgoing data stream.
- Link between the CIRCE PDC application and WAMSTER is established over a single outgoing TCP/IP connection.
- STER PMU maintains an additional data/service link over the mobile network to a separate WAMSTER server (implemented in the previous phase of the project).



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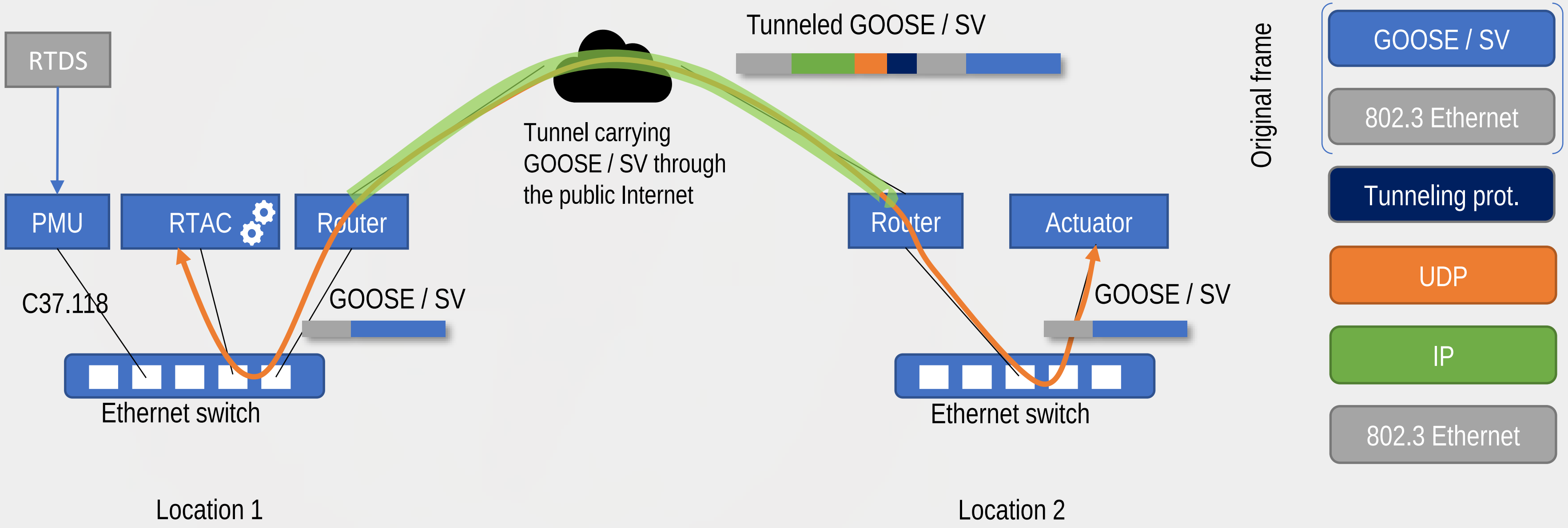
IP tunnel between different locations: scheme and protocol stack

- The setup includes two routers (two Raspberry Pi 3B+) that allow the possibility of sending traffic through public IP networks.
  - The original GOOSE/SV frame (including its Ethernet header) is sent inside a tunnel.



Task 6.1: Definition of the grid, study cases and models' construction in simulation platform (M6-M18, leader: IPTO)

- Oscillatons in eletric power system can be modelled using a linear combination of damped complex exponential functions

$$x[n] = \sum_{k=1}^{p} A_k e^{j\theta_k} \cdot e^{\left(\alpha_k + j2\pi f_k\right)T_s(n-1)}$$

p number of signal components, A_k initial amplitude (same units sa $x[n]$), α_k damping factor (seconds^{-1}), f_k frequency (Hertz), T_s sampling period (in seconds), θ_k initial phase (radians)

- In the Prony, Least Squares and Total Least Squares methods, signal poles (**frequency and damping factors**) are found **as roots of a characteristic polynomial** from the linear prediction coefficicents (non-symmetrical Toeplitz matrix must be previously formed from input data)
- Matrix Pencil method obtains the poles (**frequency and damping factors**) by **finding the eigenvalues from Hankel submatrices** (rectangular Hankel matrix must be previously formed from the input dana for finding eingenvalues)
- Solving the original set of linear equations (roots/eigenvalueas must be known) yields the estimates of initial amplitudes and phase

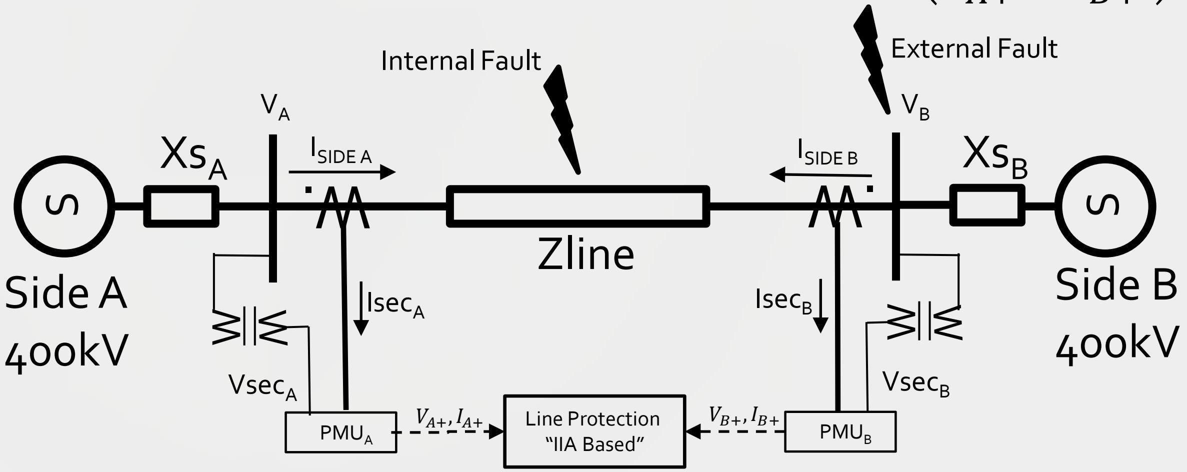
Protection algorithms WAMPAC system including the algorithms for wide area protection

Integrated Impedance Angle (IIA) Line Protection:

- The term integrated impedance is defined as the ratio of the sum of fault components of voltage to the sum of fault component of current across both ends of the line. In this research the positive sequence component of the fault voltage and fault current is extracted from the PMUs placed at both ends of the line. The IIA is calculated from these extracted positive sequence data. [1]

- Let the positive sequence voltage and current at two ends of a line is V_{A1}, I_{A1} and V_{B1}, I_{B1} respectively. The positive sequence integrated impedance (SII) is defined as:

$$\widetilde{SII} = \frac{\widetilde{V_{A+}} + \widetilde{V_{B+}}}{\widetilde{I_{A+}} + \widetilde{I_{B+}}} \Rightarrow IIA = arg\left(\frac{\widetilde{V_{A+}} + \widetilde{V_{B+}}}{\widetilde{I_{A+}} + \widetilde{I_{B+}}}\right)$$



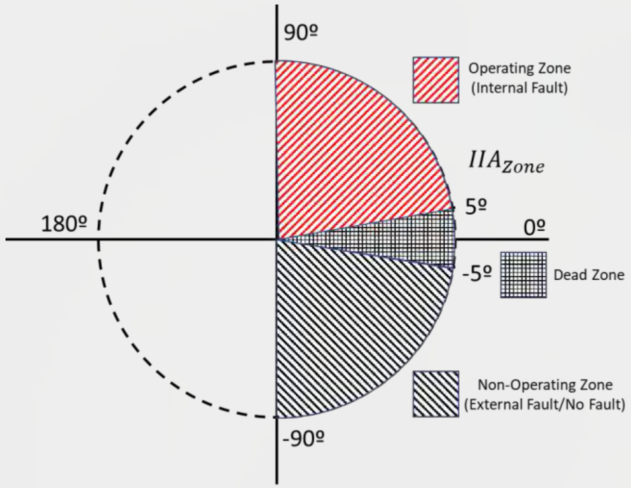
- Trip Line if: 5º <= IIA <= 90º.

Reference [1]: Nikhil Kumar Sharma, Subhransu Ranjan Samantaray, "PMU Assisted Integrated Impedance Angle-Based Microgrid Protection Scheme". IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 35, NO. 1, February 2020

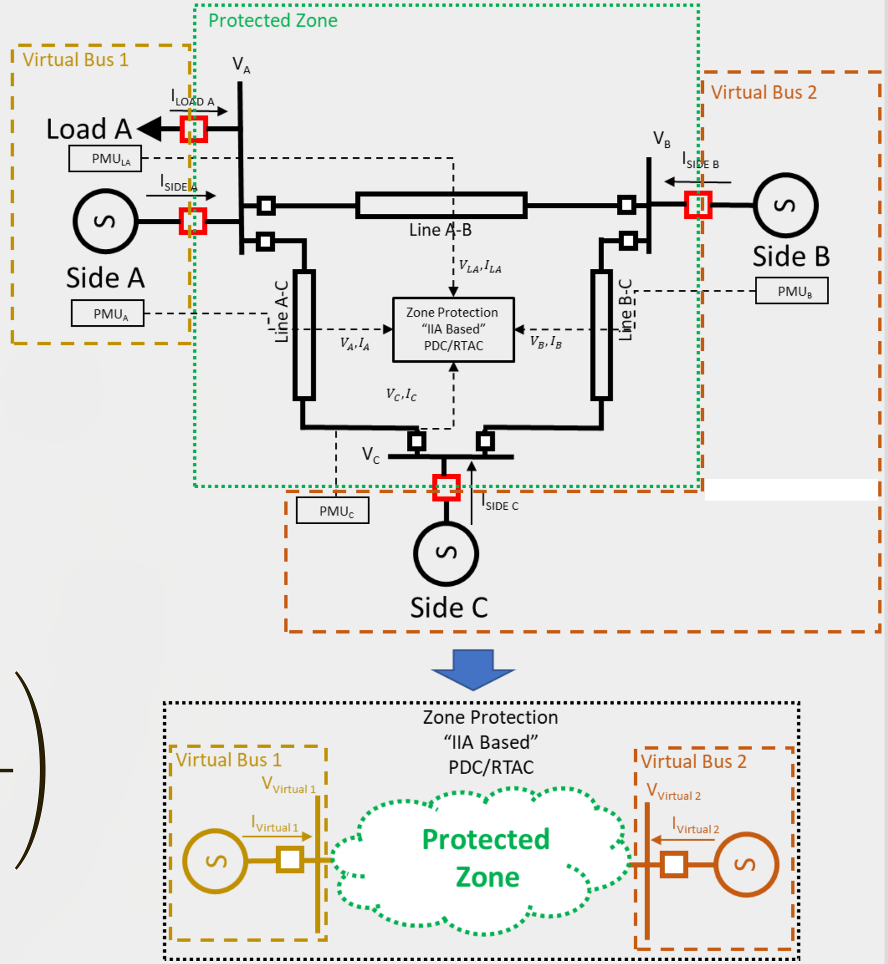
Integrated Impedance Angle (IIA)

Zone Protection:

Protection algorithms WAMPAC system including the algorithms for wide area protection



$$IIA_{Zone} = arg\left(\frac{\widetilde{V^{(+)}_{VIRTUAL\,1}} + \widetilde{V^{(+)}_{VIRTUAL\,2}}}{\widetilde{I^{(+)}_{VIRTUAL\,1}} + \widetilde{I^{(+)}_{VIRTUAL\,2}}}\right)$$



Reference [1]: Nikhil Kumar Sharma, Subhransu Ranjan Samantaray, "PMU Assisted Integrated Impedance Angle-Based Microgrid Protection Scheme". IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 35, NO. 1, February 2020.

Reference [2]: Jaeyeop J., Hwanhee C., Bohyun P., Suchul N., Kyeon H., Byongjun L., "Enhancement of linearity and constancy of PMU-based voltage stability index: application to a Korean wide-area monitoring system". IETGeneration Transmission & Distribution, 2020, Vol. 14 Iss. 17, pp. 3357-3364.

PMU-based Voltage Stability Methods

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Development of the WAMPAC system including the algorithms for wide area protection

- In literature, some PMU-based methods are explained to estimate how far is some location of the system to collapse in voltage.

- The first method was proposed in 1999 by ABB [3] and it work with the theory that the Maximal Power transfer occur when the magnitude of apparent impedance is equal to the magnitude of Thevenin impedance in that location.

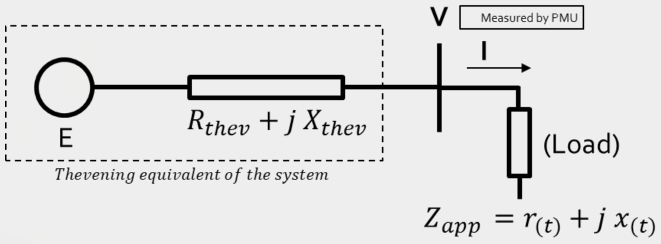
$$Maximal\ power\ transfer \leftrightarrow |\overline{Z_{app}}| = |\overline{Z_{Thev}}|$$

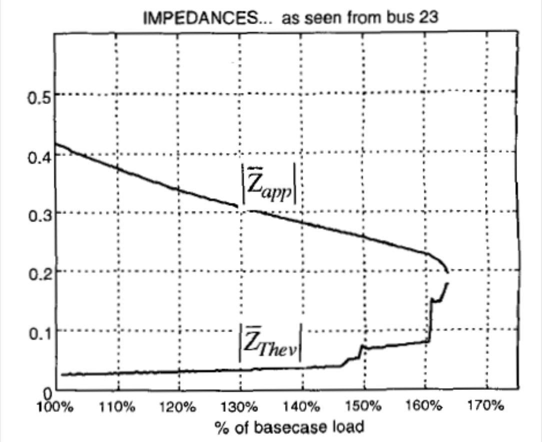
- Tracking the Thevenin equivalent is essential to detection of voltage collapse. There are many methods to track the Thevenin parameters, per example the use of Kalman filter or traditional curve-fitting techniques. In paper [4] a faster method is proposed to estimate the Thevenin parameters.

- An indicator for the proximity of voltage collapse can be calculated using the relation $|\overline{Z_{Thev}}| / |\overline{Z_{app}}|$ in order to alarm the operator of a possible voltage collapse event.

- The advantage of this proposed method is that it use only a single PMU to estimate the voltage stability indicator.

- In FARCROSS project, the methods which use only one PMU will be implemented, in order to detect the proximity to voltage collapse. This service will be implemented in all substation within scope of the project demonstrator.





Reference [3]: Khoi Vu, Miroslav M. Begovic, Damir Novosel, Murari Mohan Saha, "Use of Local Measurements to Estimate Voltage-Stability Margin". IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 14, NO. 3, August 1999.

Reference [4]: Sandro Corsi, Glauco N. Taranto, "A real-time voltaje instability identification algorithm based on local phasor measurements". IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 23, NO. 3, August 2008.

PMU-based Voltage Stability Methods

Development of the WAMPAC system including the algorithms for wide area protection

- To estimate the Thevenin's equivalent (TE) using PMU measurement, the method proposed in [5], use three consecutive voltage and current measurements to determine an exact TE. Phase drifts caused by the slip frequency between the PMU and the system are taken into consideration.

$$E^2 = V_1^2 + Z^2 \cdot I_1^2 + 2 \cdot P_1 \cdot R + 2 \cdot Q_1 \cdot X \quad (1)$$

$$E^2 = V_2^2 + Z^2 \cdot I_2^2 + 2 \cdot P_2 \cdot R + 2 \cdot Q_2 \cdot X \quad (2)$$

- Substracting (1)-(2), we can find the equation of a circle:

$$V_1^2 - V_2^2 + R^2 \cdot (I_1^2 + I_2^2) + X^2 \cdot (I_1^2 + I_2^2) + 2 \cdot (P_1 - P_2) \cdot R + 2 \cdot (Q_1 - Q_2) \cdot X = 0 \ (3)$$

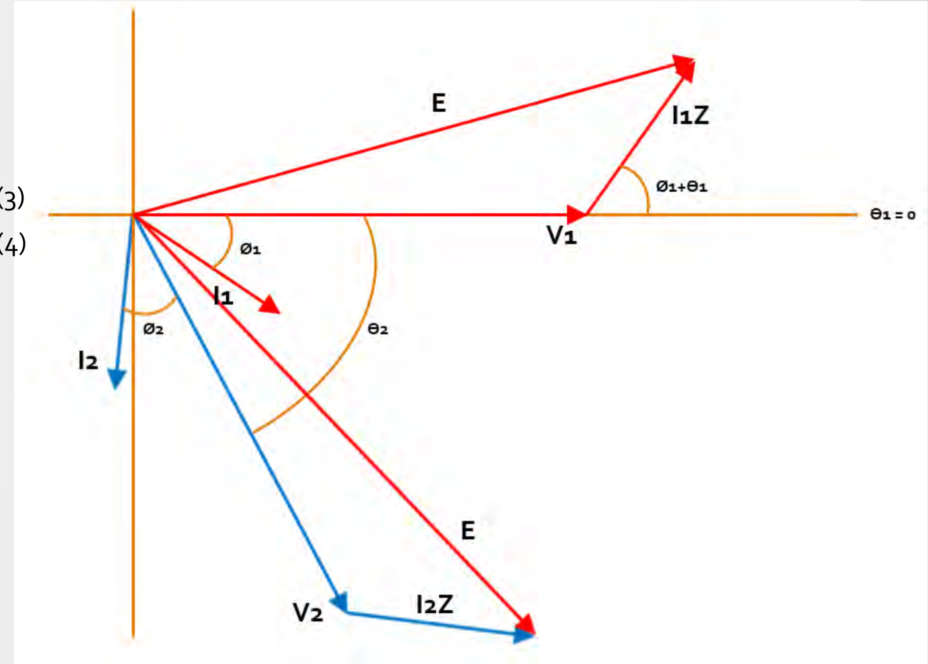
$$V_1^2 - V_3^2 + R^2 \cdot (I_1^2 + I_3^2) + X^2 \cdot (I_1^2 + I_3^2) + 2 \cdot (P_1 - P_3) \cdot R + 2 \cdot (Q_1 - Q_3) \cdot X = 0 \ (4)$$

- One of the intersections between circles (3) and (4) is the Thevenin's Impedance in the point where PMU is located. With the estimated $|\overline{Z_{Thev}}|$ it is possible to define a voltage instability index (VII) where:

$$Maximal\ power\ transfer \leftrightarrow |\overline{Z_{app}}| = |\overline{Z_{Thev}}|$$

$$VII = \frac{|\overline{Z_{Thev}}|}{|\overline{Z_{app}}|}$$

- If VII is between 0,7 and 1, an alarm will be generated to control center. $|\overline{Z_{app}}|$ is the apparent impedance measured by PMU.



Reference [5]: S. Abdelkader , "Online Thevening's Equivalent Using Local PMU Measurement". International Conference on Renewable Energies and Power Quality (ICREPQ'11), Spain, 13th to 15th April, 2011. https://doi.org/10.24084/repqj09.604.

PMU-based Dynamic Line Rating

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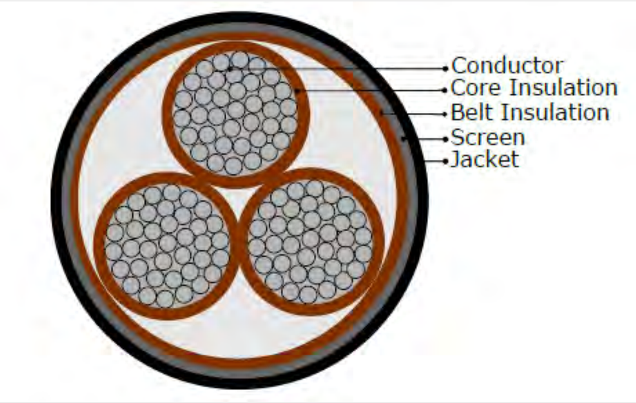
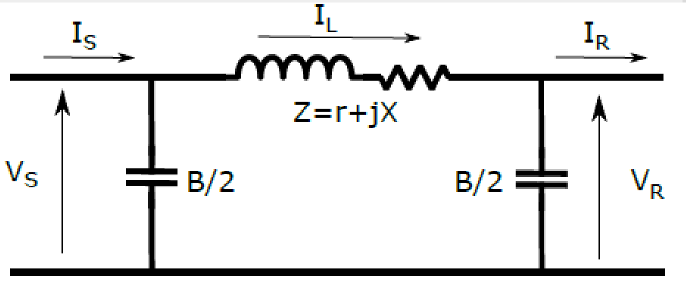
Development of the WAMPAC system including the algorithms for wide area protection

- The main purpose of dynamic line rating is to estimate the real operating conditions of temperature of an OHL or a cable in order to monitor how much power can be transported through the line without generate any damage. Many methods exist to apply dynamic line rating using PMUs.
- In FARCROSS Project, DLR will be applied in 150kV submarine cable between SS Cyclades (Island) and SS Lavrio (Mainland) (near 108Km of length).
- Some methods use PMUs in both extremes of the cable in order to estimate main electrical parameters. With calculated Resistance, the average temperature of the cable between both PMU can be estimated.

$$T = (R/R_{ref} - 1)/\alpha + T_{ref}$$





- The method proposed in [7], follow the next steps:

3 Phase voltages and currents of Sending and Receiving ends of cable. → Estimate the susceptance (B) of the cable. → Estimate the Resistance (R) and Reactance (X). → Estimate the conductor temperature using the equation (1). → For XLPE isolation, 90 ºC is the maximum temperature alow. If Temperature estimated is near 90ºC, an Alarm will be send to control center.

- A time window of 1 hour will be considered, with 5 minutes sample time. Every 5 minutes a cable temperature estimation will be generated after the first hour of data is collected.

Reference [7]: Ravi Shankar Singh, Sjef Cobben, Vladimir Cuk. "PMU-based Cable Temperature Monitoring and Thermal Assessment for Dynamic Line Rating". 2020 DOI 10,1109/TPWRD.2020,3016717, IEEE Transactions on Power Delivery.

Development of the WAMPAC system including the algorithms for wide area protection

Goal: Explore the option to make SmartValve work as active elements to damp oscillations.

A centralized control system will use measurements from PMUs placed in different locations in the Greek transmission system to detect oscillations, select and initiate the appropriate control actions.

Goal: Evaluate the feasibility that the PDC is able to assess the action at SmartValve necessary to mitigate the oscillation by sending the control commands or references to the devices.

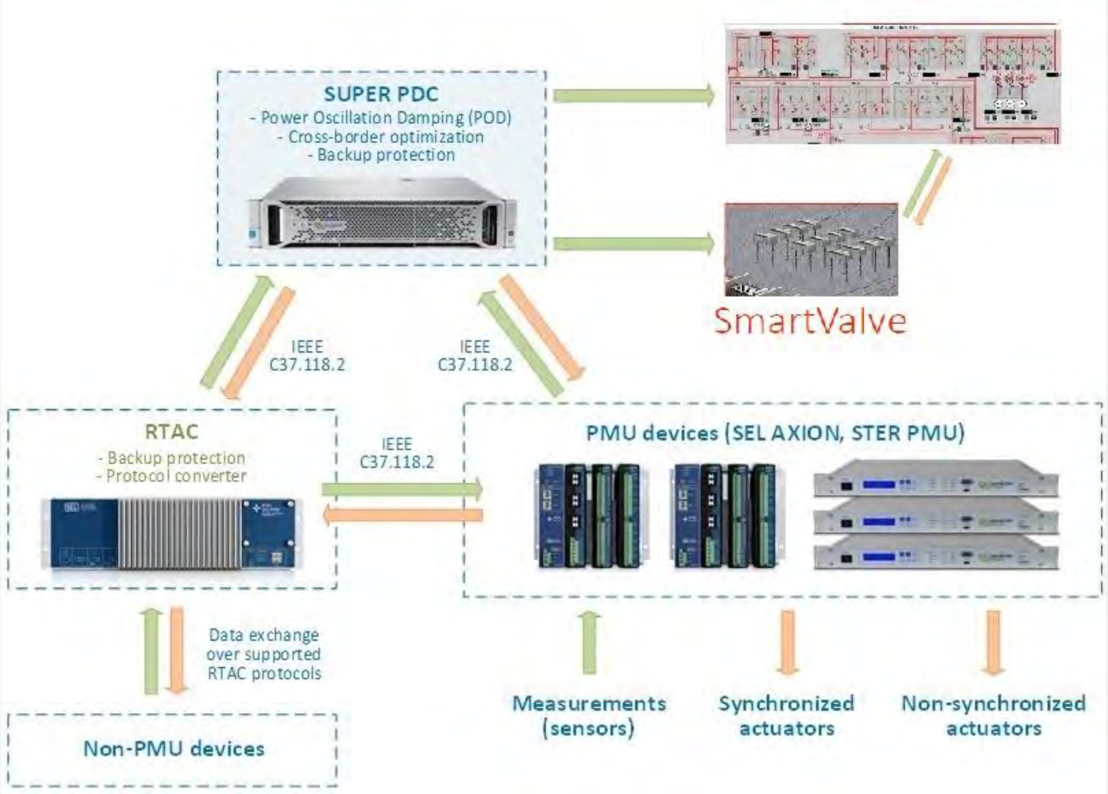


Figure 1. System architecture

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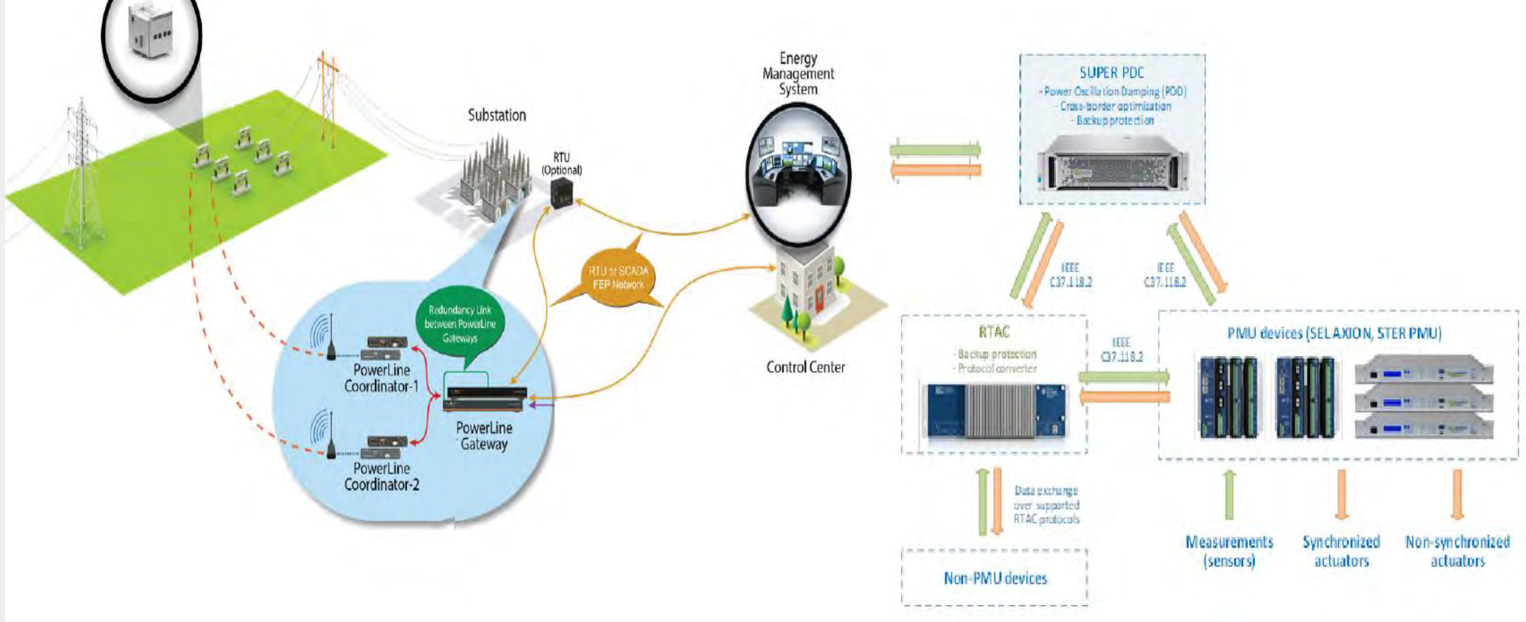
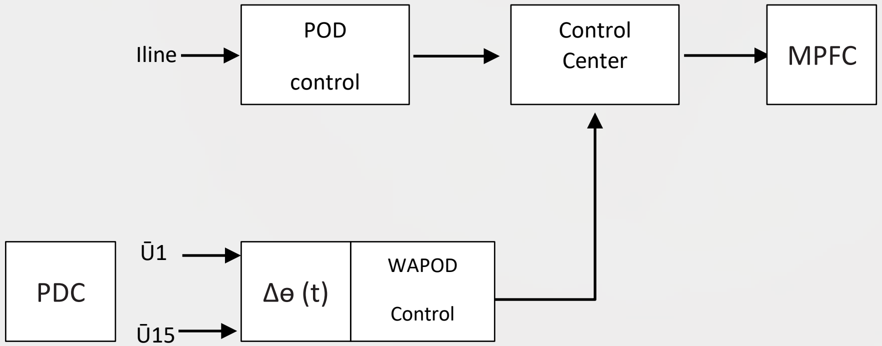
Development of the WAMPAC system including the algorithms for wide area protection

WAPOD Architecture

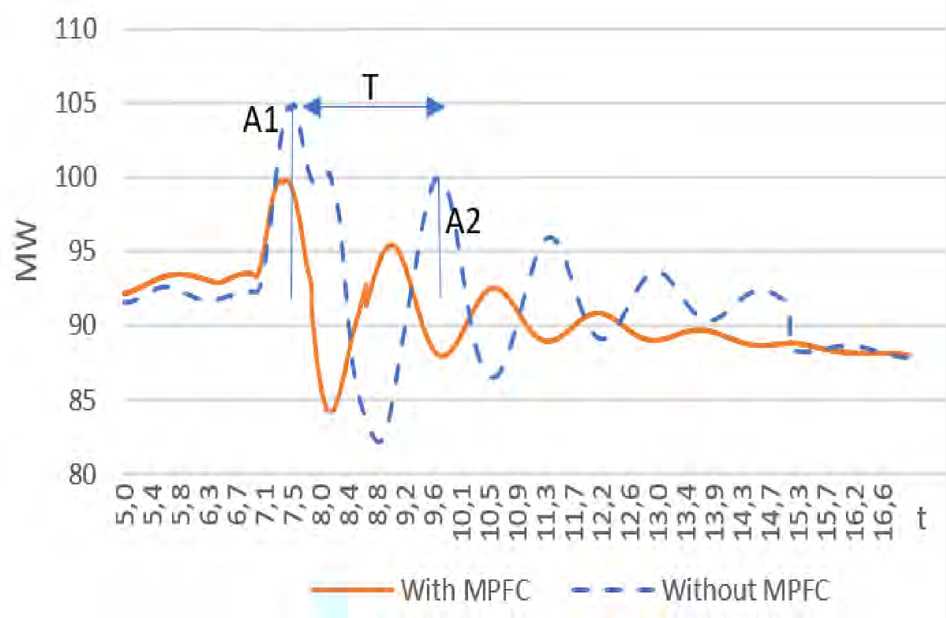




Once the control center receives the alarm from the PDC with the indication of a power oscillation in the network, through the HMI interface the desired control mode for the damping (POD, WAPOD or manual setpoint) will be available. If the operator selects local control mode, the input signals to the POD is the current flowing through the MPFC. When the operator selects the wide area control mode, the input signals to the WAPOD come from the PMUs strategically located at various points in the network in order to interact online and close the control loop with the WAMPAC system.

Local POD Impacts

Development of the WAMPAC system including the algorithms for wide area protection



	Without MPFC	With MPFC
Amplitude A1	12,3	7,41
Amplitude A2	7,26	3,57
Oscillation period T	2,2	1,8
Imaginary part of the mode ω	0,45	0,56
Damping σ	0,24	0,41
Damping factor ζ	-0,47	-0,59