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Laboratory-Scaled DEMO possibilities for testing WAMPAC solutions before field implementation

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***Abstract*—In this paper, the capabilities of a Wide-Area Protection and Control (WAMPAC) lab-scale demonstration (DEMO) is presented. This lab will be used in Work Package 6 of H2020 FARCROSS Project for testing wide-area applications previously to their commissioning in a real DEMO in the Greek Transmission System. The capabilities of this lab-scaled DEMO are presented using the implementation of two different monitoring and protection applications for a *proof of concepts.* The first application is related to detection of inter-area power oscillations using PMU measurements and applying a remedial action. The second application deals with the comparison of the behavior of three line differential protection strategies: classical implementation using two fiber optic communicated relays, a solution based on values received from PMU and an algorithm receiving IEC 61850 Sampled Values and using open-source libraries in a common computer. These applications are tested by closing the loop using real protection and control hardware in the laboratory with an RTDS™ simulator.**

***Index Terms*—WAMPAC, Protection, Inter-area oscillations, Hadware in the loop, Laboratory-scaled DEMO**

I. OVERVIEW OF FARCROSS WP6

FARCROSS WP6 deals with the implementation of a WAMPAC DEMO in the Greek transmission system. Within this DEMO, 14 Phasor Measurement Units (PMUs) are being installed in Independent Power Transmission Operator (IPTO) transmission system with the aim of monitoring key points of the grid and acting in real time to avoid dangerous situations in the grid. Applications to be implemented will be focused on resolving power oscillations and backup protection.

These PMUs will communicate with a central Phasor Data Concentrator (PDC) and with a super-PDC for different applications. This PDC will receive the information via C37.118 protocol from each PMU and will implement algorithms for grid protection:

- Oscillation detection methods: The optimum method for real-time will be implemented based on previous study of the WP6. This study is not included in this paper.
- Oscillation damping: Thanks to the continuous monitoring of key elements in the grid and communications, it is an objective of the project to interact with these elements to improve and damp oscillations in a real-time application.
- Wide-area protection: Backup protection functionalities will be also implemented in this solution.

These objectives will be accomplished by the integration of the elements included in Figure 1.

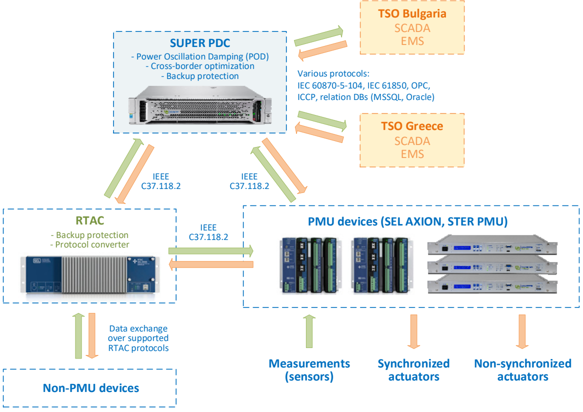

Figure 1. Proposed WAMPAC architecture in WP6

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The PDC receives data from PMUs and provides programming and control capabilities to contain these functionalities.

In addition to the C37.118 protocol, IEC 61850 protocol may be used in this application. This Standard already includes synchro-phasor emulation and remote GOOSE (r-GOOSE) for connection between different substations, what can be used for the real DEMO.

II. HARDWARE IN THE LOOP FACILITIES. LAB-SCALED DEMO

Previous to the DEMO commissioning, it is highly important to test the interoperability between the different elements in the DEMO, to debug the programming of the different solutions implemented in the PDC and to check the effect of the protection and control algorithms on grid stability. For that, a lab-scaled DEMO has been installed, containing:

- Two PMUs SEL-2240 Axion® receiving voltage and current signals from RTDS amplifiers. These PMUs send synchro-phasors to PDC using C37.118 protocol. PDC can also send command orders to the PMU for acting through digital outputs or GOOSE signals.
- One WAMSTER PMU-R1 receiving voltage and current signals from RTDS™ amplifiers and is able to send to PDC using C37.118 protocol. PDC can send command orders to the PMU for acting through digital outputs.
- One GPS SEL-2488 clock providing time reference to the entire system with a GPS antenna installed in the roof of the building.
- One SEL-RTAC-3555 Real Time Controller. This element acts as both a PDC and real-time controller. It communicates with the PMUs using C37.118 protocol and with RTDS using C37.118 and IEC 61850 Sampled Values and GOOSE protocols.
- One Rugged Computer allowing the implementation of user-developed software applications.
- One managed switch.
- Voltage and current amplifiers that provide voltage and currents at secondary level for the PMUs.
- RTDS with 10 PB5 cards, input/output analog and digital cards and communication capabilities using C37.118 protocol and IEC 61850.

The elements of the DEMO can be observed in Figure 2 and Figure 3, mounted in a rack in the laboratory.

For testing the lab-scaled DEMO, RTDS is used for grid modelling and simulating the network conditions and dynamics. In addition, the RTDS provides, through its GTNETx2 card both synchro-phasors using C37.118 protocol and IEC 61850 Sampled Values can be provided to external equipment. In addition, the GTNETx2 card receives and generates IEC 61850 GOOSE signals.

Figure 2. Equipment of the lab-scaled DEMO

The GPS clock provides time synchronization for the whole network using IRIG-B protocol. In this way, the RTDS simulation, PMUs and PDC are precisely synchronized for the tests performed in the laboratory emulating the synchronization needed in the real DEMO.

Figure 3. View of the RTDS connected to the equipment

Figure 4 shows the interconnections between equipment involved in the hardware in the loop lab-scaled DEMO, as far as the information exchanged between all the elements.

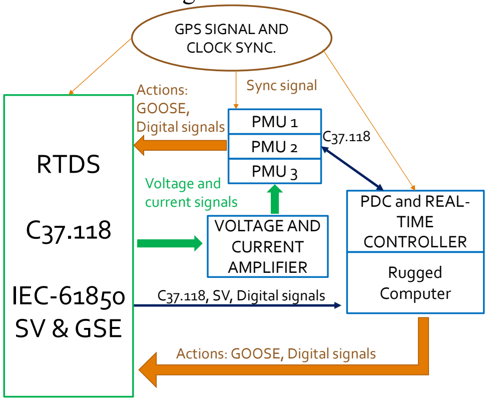

Figure 4. Diagram of the connections between the elements in the grid

III. OBJECTIVES OF THE STUDY

The study presented in this paper aims to present the capabilities of this lab-scaled DEMO through the proof of concept of two different applications using PMUs and IEC 61850.

- Application 1 deals with the detection of power oscillations and protection of the system by shedding a defined protection zone as remedial action, to avoid system collapse due to oscillation spread. This application is implemented in PDC by receiving PMU measurements for online analysis using libraries for applying the Prony method [1] [2].
- Application 2 deals with local protection and is focused on the implementation of line differential protection (87-L) using two alternative designs to traditional solution based on two relays connected via fiber optic at both sides of a line. The two alternatives presented in this paper are line-differential protection based on PMU measurements using PDC for the implementation of the algorithm and an alternative case using Sampled Values measurements received in a Rugged Computer used for programming the protection function using open source libraries.

For testing these applications, two RTDS models have been implemented.

IV. APPLICATION 1: POWER OSCILLATION DETECTION AND REMEDIAL ACTION

Synchro-phasors received from PMUs can be used for backup protection by means of (among other applications) detecting active power oscillations that can be considered dangerous (according to defined criteria in the comparison). For this application, Figure 5 shows a transmission system that contains different elements for the study and is divided into two protection zones. Protection zone 1 contains:

- Two generators modelling the synchronous connection with different countries (interconnections 1 and 2).
- Large loads, representing the most loaded zones of the system.
- Slack bus.
- Generator G1 with Power System Stabilizer (PSS) controller.

These synchronous generators were connected using different impedance values (z1..z5) to provide different short circuit power for each one of those elements connected to the grid.

On the other side, in the protection zone 2, a synchronous generator is connected. This generator represents a weaker grid (protection zone 2) that is connected to the main grid represented in the protection zone 1:

- Generator G2 represents a synchronous connection to a weak network that tends to introduce oscillations in the main system.

These two protection zones are separated by a transmission line (T-line) and can be disconnected if dangerous conditions are detected by the monitoring and protection system.

The decision of disconnecting the protection zones depends on algorithms based on the voltage and current measurements provided by a PMU on the border of the protection zone 1 (Figure 5). The PMU sends voltage and current values to the PDC, where the active power flow in the T-line is monitored. A Prony Analysis library [2] is used in the PDC to detect active power oscillations in the range of 0.05 to 2 Hz. For that, 50 Hz of sampling frequency with a data window of 1000 samples whose solution is updated for every 10 % of the samples has been implemented. These settings provide a window period for analysis of 20 seconds. This window, according to Nyquist Theory, must be valid to detect oscillations that are faster than 0.1 Hz. Within this study, power oscillations in the grid around 1 Hz are expected, so these settings for the modal analysis are correct.

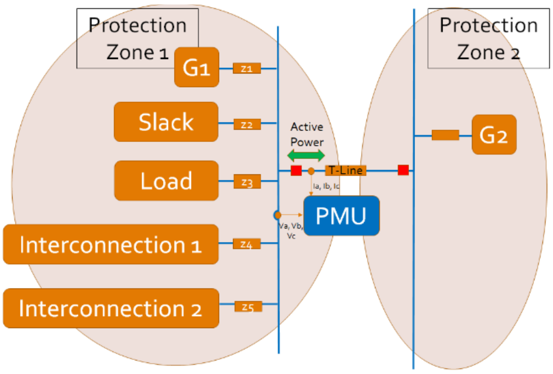

Figure 5. Diagram of protection zones of the model

When an oscillation occurs in the interconnection in the range of the detection window set, conclusions from previous studies suggest that both protection zones must be disconnected by tripping the circuit breakers, as represented in Figure 5, to avoid an unstable situation in the whole grid. The tripping order is communicated to the circuit breaker in the RTDS simulator using a GOOSE signal coming from the PDC.

For checking the behaviour of the designed solution, the generator G2 is forced to oscillate by introducing a 1Hz oscillation in the governor control block at second 0 of the record as shown in Figure 6, aiming to achieve an active power oscillation. Prior to this moment, it can be observed that all elements are working at a balanced operation point. When the G2 starts to oscillate, this oscillation is propagated to the whole system through the T-line that connects both subsystems, affecting all elements of protection zone 1.

The frequency of the detected oscillation was around 1 Hz and the amplitude for each element in the grid was: 51 MW in the T-line, 36 MW in the slack, 7.5 MW in the G1, 51 MW in the G2, 7 MW in the interconnection 1 and 15 MW at interconnection 2.

The oscillation is detected using the Prony Analysis and the trip order is sent 26.54 seconds after the beginning of the oscillation. In this case, the damping of the oscillation was not critical, since the mode detected was highly damped, but the amplitude in the interconnection was greater than the defined threshold of 50 MW, therefore causing the disconnection of the two protection systems.

Due to the disconnection of the system in two different zones both active power oscillations were eliminated, as can be observed in Figure 6, making the protection zone 1 stable again in a new operation point. Active power that was received through the T-line during the pre-incident time coming from G2, about 225 MW, is assumed after the tripping command by the slack connection. G2 with forced oscillation was isolated after the trip of T-line, when the oscillation is detected algorithm. After T-line trip, the protection Zone 1 has a well damped oscillation behaviour.

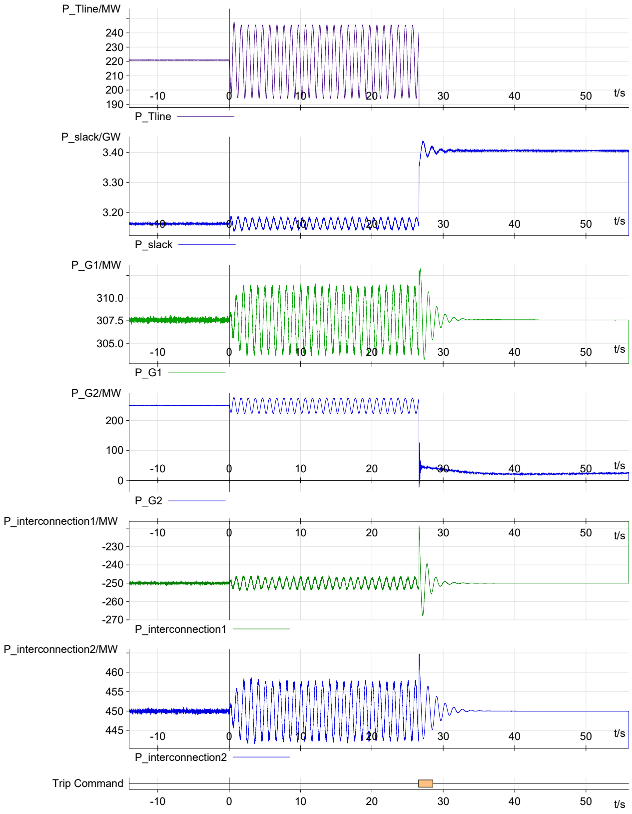

Figure 6. Active power flow in the grid

V. APPLICATION 2: COMPARISON OF DIFFERENT SOLUTIONS FOR LINE DIFFERENTIAL PROTECTION

The goal of this study is to demonstrate the possibility of implementation of line-differential protection using PMU and IEC 61850 Sampled Values, as an alternative to the traditional line differential protection [3] [4] using two protection relays connected by fiber optic at both sides of a protected line [5]. For this application study, an RTDS was also used to model the protected transmission line and the sources. For the use of each application of line differential protection, it can be observed that the source of the current signals is as described in Figure 7:

1. Current amplifiers provide current signal at secondary level for conventional line differential protection. Two protection relays connected by fiber optic were used for this.
2. Current amplifiers also provide current signals at secondary level for PMUs, that send the values via C37.118 protocol to the PDC.
3. RTDS GTNETx2 card sends synchro-phasor current signals via C37.118 protocol to the PDC.
4. RTDS GTNETx2 card also sends IEC 61850 Sampled Values to a computer in the lab.

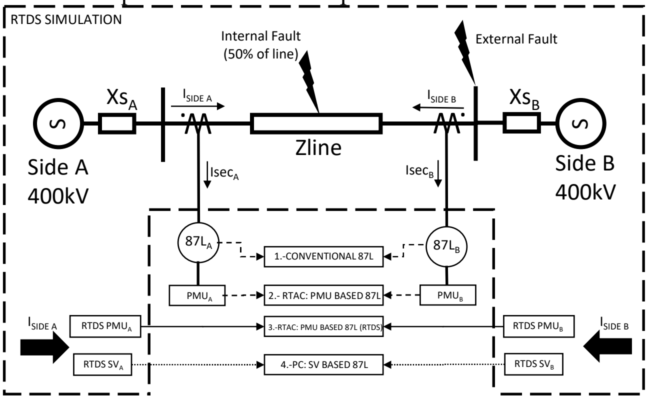

Figure 7. Diagram of protected line

Table I and Table II shows the electrical characteristics of the power system implemented in RTDS.

TABLE I. VOLTAGE SOURCE MODELS

Source Data A and B	
Voltage (kV)	400
Inductance (H)	0.1
Frequency (Hz)	50.0
Phase angle difference between A and B	15 degrees

TABLE II. PHYSICAL DATA OF THE LINE

Line Data	
Model	Bergeron (RLC)
Line Length (km)	70
Positive Sequence Series Resistance (Ohm/km)	0.0293
Positive Sequence Series Ind. Reactance (Ohm/km)	0.3087
*Positive Sequence shunt Cap. Reactance (MOhm*km)*	0.2664
Zero Sequence Series Resistance (Ohm/km)	0.3
Zero Sequence Series Ind. Reactance (Ohm/km)	0.988
*Zero Sequence Shunt Cap. Reactance (MOhm*km)*	0.4369

Table III shows the line differential protection characteristic that has been programmed for trip order in the developed applications based on PMU measurement and with Sampled Values. Equivalent settings were introduced in conventional 87-L relays. The solution based on PMU measurements is implemented in the PDC, programming in IEC 61131-3 language [6] [7] the reception of current values and differential comparison for the emission of a trip command. The solution based on Sampled Values is designed to work on a generic platform, such as a desktop or laptop computer, and was programmed using open-source libraries. In this way, it aims to demonstrate the capability of implementation of protection functions in a generic hardware platform. This implementation is explained in the following lines.

TABLE III. 87-L SETTINGS

Line differential protection settings [3]	
Current base	1000 A
Differential current pick-up	0.15 pu
Restraint current	Maximum current of both sides
Slope 1	15 %
Knee 1	1.0 pu
Slope 2	100 %
Knee 2	3.0 pu

The software stack used for the implementation of line differential protection in a rugged substation computer, consists of a program written in C programming language with the dependency of two widely available open-source libraries: libIEC61850 [6] and FFTW [7]. These dependencies allow running the program in different Operating Systems (i.e. Microsoft Windows or Linux). The results described in this work were collected within a Microsoft Windows 10 operating system.

The program takes the IEC 61850 Sampled Values of two different application IDs (APPIDs) as input, performs the Fast Fourier Transform (FFT) and calculates the first harmonic of both current signals. The differential protection implemented calculates the segregated phase by phase differential current, applies the fault criterium, as defined in Table III, and if the fault appears, then an IEC 61850 GOOSE message is sent to the RTDS to open the line breakers.

The expected input signals are a variation of the IEC 61869-9 [8]. In addition to the three-phase voltages and currents described in that Standard, the optional parameter *RfrTime* was added to the Sampled Values to have the samples timestamped from the origin and thereby avoiding the need for high-accuracy synchronization in the host operating system.

The FFT calculation is performed in a fixed time interval of 20 ms (an expected cycle) and the resultant phasor is tagged with the *RfrTime* timestamp and the APPID of the origin. This tagging allows the calculation of the differential and restraint current immediately before the second input signal FFT is calculated.

The differential phasor is calculated in a straightforward way for every phase so long as the original signal timestamp is synchronized in a sufficiently accurate way, i.e. using IEEE 1588 [9] or IRIG-B.

Once the differential phasor is calculated, the fault criterium is checked in each phase. If the fault status changes, then the system emits an IEC 61850 GOOSE message. Additionally, the GOOSE maxTime parameter (maximum interval between two GOOSE messages) is configured to communicate the global status.

The FFT is performed every 20 ms in the present implementation so that the fault will be detected in 20 ms intervals. This limitation could be avoided by performing the FFT on a half-cycle basis, or within an even shorter interval. The sample buffering would need to be adapted to be used in this strategy. The optimal interval to perform the FFT could be found experimentally through the compromise between the shorter time interval and the increase of CPU time required for such an increase. All FFT computation could be performed in parallel tasks to take advantage of the modern multicore platforms. In this scenario, the optimal interval could be dependent on the number of cores and their performance.

A. *Tested scenarios and results*

For the four different line-differential protection approaches, a combination of different fault conditions was considered:

- Fault resistance: 0.001, 1 and 10 ohms.
- Type of fault: AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, ABC, ABCG.
- Fault position: 50 % of the line and outside of the line.

The tripping times were compared for the different applications and conditions to assess the performance of the solutions. Table IV, Table V and Table VI show the tripping times for each application in the proposed scenarios. It can be observed that the slowest tripping times were obtained for the applications that used PMU values as an input source for the currents. This is due to the combination of filtering needed for receiving these values and that a new solution is provided each 20 ms cycle. This means that, by working on improved filtering, these times could be improved by up to between 20 and 40 ms of tripping time. Between the two line-differential protections using PMU current values (from physical PMU and from RTDS), it can be observed that the physical PMU application provided faster tripping times. These tripping times could be allowed for some wide-area protection applications that do not require a critically fast action time. On the other hand, the protection implemented in a rugged substation computer using Sampled Values as source of current values shows an improved tripping time regarding the PMU solution and is already similar to the tripping time of the conventional solution.

Fault resistance did not seem to affect the tripping time for any of the solutions and external faults did not cause a false trip for any of the solutions, which is considered correct behaviour for all of them.

TABLE IV. TRIPPING TIMES FOR INTERNAL FAULTS WITH 0.001 OHM

Trip time (ms) for 0.001 ohm faults				
Fault type	*Internal fault*			
	Conventional	*PMU Axion+ PDC 87-L*	*PMU RTDS+ PDC 87-L*	*SV RTDS+PC*
AG	19.5	74.0	84.0	30.3
BG	17.8	84.0	84.0	29.8
CG	21.5	84.0	84.0	26.3
AB	17.6	54.1	64.0	30.7
BC	17.9	84.0	84.0	29.7
CA	19.1	74.2	84.0	27.4
ABG	16.3	54.1	64.1	25.0
BCG	18.3	84.0	84.0	25.9
CAG	18.3	74.1	84.1	29.4
ABC	15.9	54.2	64.1	27.3
ABCG	16.3	54.1	64.1	29.6
Mean time	18.0	70.4	76.7	28.3

TABLE V. TRIPPING TIMES FOR INTERNAL FAULT WITH 1.0 OHM

Trip time (ms) for 1.0 ohm faults				
Fault type	*Internal fault*			
	Conventional	*PMU Axion+ PDC 87-L*	*PMU RTDS+PDC 87-L*	*SV RTDS+PC*
AG	18.1	74.3	84.3	30.3
BG	18.4	84.2	84.2	30.3
CG	20.9	84.3	84.3	26.5
AB	17.3	54.4	64.3	57.1
BC	18.7	84.3	84.3	25.7
CA	18.7	74.3	84.3	30.4
ABG	17.3	54.4	64.4	27.9
BCG	19.6	84.2	84.2	27.0
CAG	19.0	74.4	84.3	24.2
ABC	16.8	54.4	64.3	28.9
ABCG	17.8	54.4	64.3	28.8
Mean time	18.4	70.6	77.0	30.6

TABLE VI. TRIPPING TIMES FOR INTERNAL FAULTS WITH 10.0 OHM

Trip time (ms) for 10.0 ohm faults				
Fault type	*Internal fault*			
	Conventional	*PMU Axion+ PDC 87-L*	*PMU RTDS+ PDC*	*SV RTDS+PC*
AG	18.9	74.4	84.4	29.5
BG	17.0	84.3	84.3	27.4
CG	21.6	84.4	84.4	26.9
AB	17.2	74.4	84.4	28.2
BC	17.2	84.4	84.4	28.8
CA	19.8	74.4	84.4	28.7
ABG	17.6	54.4	64.4	28.0
BCG	17.8	84.4	84.4	28.9
CAG	17.8	74.5	84.4	26.3
ABC	17.9	54.4	64.4	29.4
ABCG	18.0	54.4	64.5	26.1
Mean time	18.2	72.5	78.9	28.0

VI. SUMMARY AND CONCLUSIONS

In this paper, the possibilities of the Lab-Scaled DEMO for testing WAMPAC solutions prior to their commissioning are demonstrated. This demonstration was implemented using two different applications in the field of power oscillation damping and remedial actions (wide-area) and in primary or backup protection (local area).

It was demonstrated that PMU-based applications can work as backup protections applied at wide-area and local-area schemes.

In this proof-of-concept, the development and testing of a line differential protection implemented in a generic hardware platform (PC) using open-source libraries promises interesting applications in the future. It was demonstrated that open software can be used to implement protection functionalities combined with IEC 61850, and its performance can be debugged to obtain tripping times similar to those obtained in traditional protection systems. In addition, this type of applications provides the owner of the grid the option to implement flexible solutions in generic platforms for protection, monitoring and supervision, that can be customized for their grids.

In this work, a LAN scenario has been tested, taking advantage of the existing laboratory resources for the project, which include a complete substation automation system network and an RTDS with several digital interfaces. Its natural evolution must incorporate WAN scenarios (e.g. delay and network effects). The presented approach makes it possible to study its migration to remote R-SV (IEC 61850-90-5) with simple modifications. This will introduce an innovative communication stack design when applied to WAMPAC systems and will enable a comparative analysis with IEEE C37.118

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