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System Operation and Control.

Paper ID_11034

TESTING OF POWER OSCILLATION DETECTION ALGORITHM USING A REAL-TIME PMU LABORATORY

Aníbal Prada[1], Eduardo Martinez[1], Jose Saldana[1], Marta Bernal[1], Noemi Galan[1], Dalibor Brnobic[2], Vedran Grudenic[2]

[1]: Fundación CIRCE, Spain, [2]: Studio Elektronike Rijeka d.o.o. (STER), Croatia

Motivation

- Wide Area Monitoring Protection and Control (WAMPAC) applications are difficult to test in power systems that are under operation. Therefore, power systems operators are interested in performing extensive tests of WAMPAC algorithms before their implementation in real environments, because a failure in their functionality could cause a service outage.

WAMPAC LABORATORY

- Wampac Laboratory includes three physical PMUs, a Real Time Automation Controller (RTAC), an industrial PC, a communication switch, a GPS clock and a Real Time Digital Simulator (RTDS). The RTDS can generate up to 8 additional PMUs and simulate power system (PS) behavior in real time.

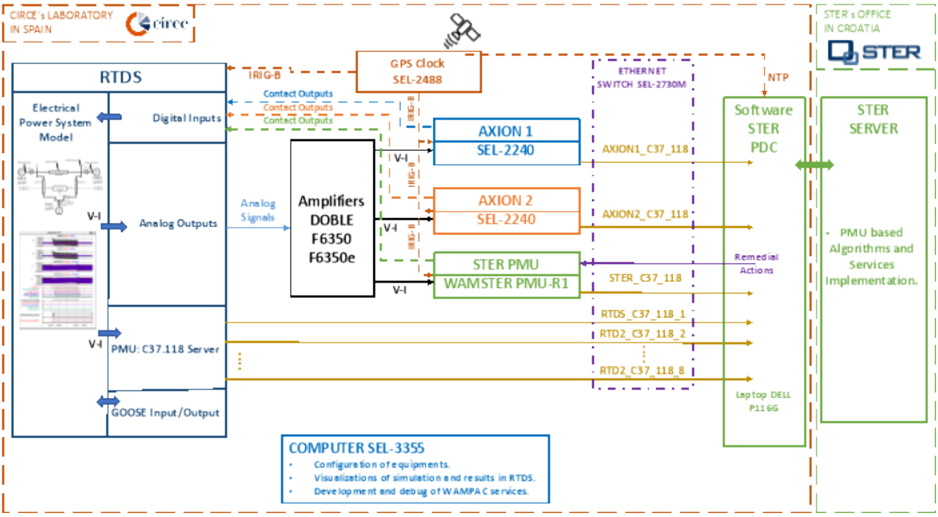

Figure 1. Diagram of Real time PMU laboratory for FARCROSS Project.

- Analog Output (GTAO) cards convert signals, such as voltages and currents, into analog signals to be sent to amplifiers. The amplified voltage and current signals are connected to the analog inputs of physical devices.
- SEL AXIONs and WASTER process their analog inputs and convert them into PMU frames following the C37.118 protocol. The STER PMU can generate a PMU server that can send signals to 4 clients at the same time. In SEL AXION, for each PMU client, a PMU server must be configured.
- GTNETx2_PMU card of the RTDS, can generate up to 8 additional PMU frames, receiving the signals resulting from the real-time power system simulation. Each PMU generated by RTDS can be received by only one client at a time.
- SEL-2488 GPS Clock distributes IRIG-B time synchronization signals to RTDS, PMUs and RTAC. All the elements of the laboratory get synchronization from it.
- RTAC SEL-3555 (phasor data concentrator and a real time controller). It is possible to receive/process PMU signals using different kinds of algorithms and services that will be developed during the project. The algorithms can be generated using IEC 61131-3 code.
- The remedial actions of the algorithms can be executed from the RTAC using IEC-61850 GOOSE messages to close the loop with RTDS, which processes GOOSE messages and executes the actions in real time to PS.
- In order to circumvent communication limitations in the CIRCE laboratory, STER developed PDC forwarder software that groups PMU data in the laboratory and sends it via the Internet to the WAMSTER PDC server in Croatia, where LFO detection algorithms are running. The request for corrective action generated by the server in Croatia is returned to the CIRCE laboratory via the same route and forwarded to a specific device by the PDC forwarder.

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WAMPAC Communication channel

- PMU data streams are sent to the WAMSTER server in C37.118.2 format. WAMSTER runs low-frequency oscillation (LFO) algorithms and triggering. LFOs are detected using the Recursive Least-Squares algorithm. Alarms are activated when LFO results cross selectable thresholds. Once an alarm is triggered, commands for activating binary outputs are sent back to CIRCE laboratory using IEEE C37.118.2 extended frames. The local PDC server forwards the command to the required device (in this stage the STER PMU device), which activates the relay binary outputs wired to RTDS, thus closing the loop.

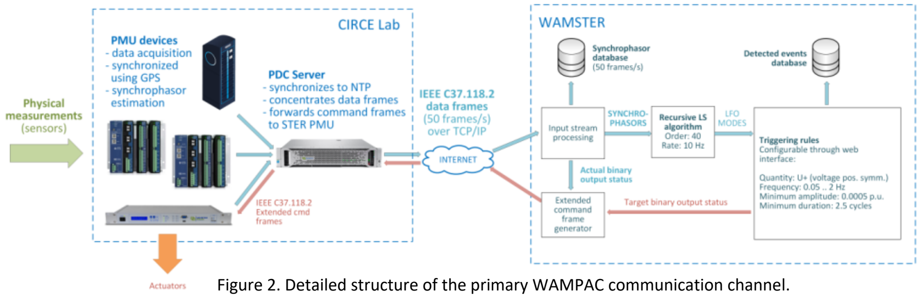


Figure 2. Detailed structure of the primary WAMPAC communication channel.

Low Frequency Oscillation Detection

- Two Methods are implemented in the PDC: Matrix Pencil (MP) method and Recursive Least Squares (RLS) method.

Matrix Pencil Method

- Matrix pencil (MP) method can directly find poles z_i by solving a generalized eigenvalue problem.

$$x(t) = \sum_{i=1}^{p} \frac{1}{2} A_i e^{\sigma_i t} e^{j(\omega_i t + \varphi_i)} = \sum_{i=1}^{p} \frac{1}{2} A_i e^{j\varphi_i} e^{\lambda_i t}$$

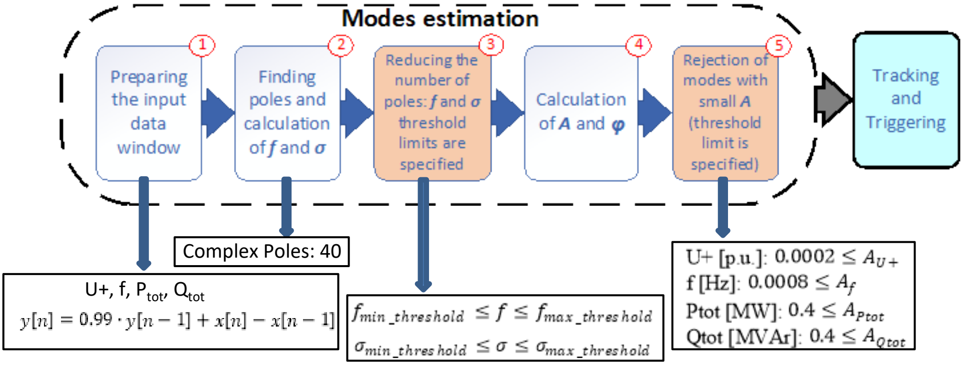
$$x[n] = x(nT_s) = \sum_{i=1}^{p} \frac{1}{2} A_i e^{j\varphi_i} e^{\lambda_i n T_s} = \sum_{i=1}^{p} h_i z_i^{\,n}, \quad n = 0, \dots, N-1$$

Recursive Least Squares method

- It is an adaptive filter algorithm that recursively finds the coefficients $\boldsymbol{\theta} = [a_1 \;\cdots\; a_p]^T$ (p is the number of complex modes) that minimize a weighted linear least squares cost function J relating to the observed signal x.

$$J(\boldsymbol{\theta}[k]) = \frac{1}{2} \sum_{j=1}^{k} \lambda^{(k-j)} \left| x[j] - \boldsymbol{\phi}^T[j-1]\boldsymbol{\theta}[k] \right|^2, \quad 0 < \lambda \le 1$$

Mode Estimation Phases



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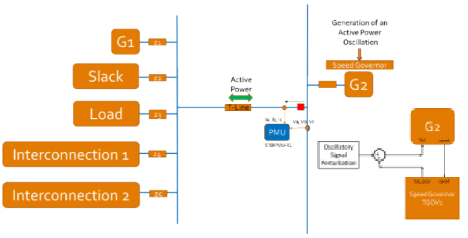
Testing the Algorithms. Event Applied

- Power oscillations generated on February 15th, 2021, between 12:08:00 and 13:59:00 UTC were used to test the LFO algorithms. Active power oscillations were generated introducing an oscillatory perturbation in the mechanical torque of Generator "G2" of the presented power system:



- The oscillatory signal perturbation has a duration of 180 seconds for each test, and it follows the next equation:

$$TM_{pu} = TM_{GOV} + A_{pert} \cdot e^{t \cdot \sigma_{pert}} \cdot \sin 2 \cdot \pi \cdot f_{pert} \cdot t$$

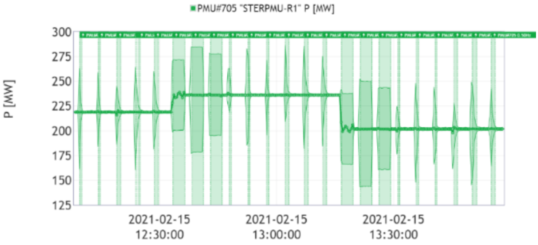
- Voltage and current signals generated in RTDS were measured by the PMU and sent to WAMSTER PDC server in Croatia. Active power signal received from STERPMU-R1 device in CIRCE is processed by the LFO algorithm. The LFO detection results for all other quantities readings are comparable with the ones presented.

Testing the Algorithms. Results Obtained

- LFO detection rule:

QUANTITY	ALGORITHM	MAGNITUDE THRESHOLD	DAMPING THRESHOLD	MIN FREQ.	MAX FREQ.	MIN DURATION	MAX GAP	BINARY OUTPUT
P	RLS	2000000	-0.2	0.05	1.1	2	3	none

- The LFO rule applied to the historical active power records detected 24 events. 24 alarms were detected, one more than the 23 generated by CIRCE. The difference was caused by one extra event, generated due to a loss of packet data during the fourth oscillation generated.



- <u>Comparison of generated and detected oscillations.</u>

Event No.	Power system frequency (Hz)	Generated oscillation frequency (Hz)	Detected oscillation frequency (Hz)	Test result: frequency	Generated damping	Detected damping	Test result: damping
1	50	1	1	PASS	-0.1	-0.1	PASS
2	50	0.5	0.5	PASS	-0.1	-0.1	PASS
3	50	0.1	0.1	PASS	-0.5	-0.5	PASS
4.1	50	1	1	PASS	-0.5	-0.5	PASS
4.2			1	PASS		-0.5	PASS
5	50	0.5	0.5	PASS	-0.5	-0.5	PASS
6	49.9	0.1	0.1	PASS	0	0	PASS
7	49.9	1	1	PASS	0	0	PASS
8	49.9	0.5	0.5	PASS	0	0	PASS
9	49.9	0.1	0.1	PASS	-0.1	-0.1	PASS
10	49.9	1	1	PASS	-0.1	-0.1	PASS
11	49.9	0.5	0.5	PASS	-0.1	-0.1	PASS
12	49.9	0.1	0.1	PASS	-0.5	-0.5	PASS
13	49.9	1	1	PASS	-0.5	-0.5	PASS
14	49.9	0.5	0.5	PASS	-0.5	-0.5	PASS
15	50.1	0.1	0.1	PASS	0	0	PASS
16	50.1	1	1	PASS	0	0	PASS
17	50.1	0.5	0.5	PASS	0	0	PASS
18	50.1	0.1	0.1	PASS	-0.1	-0.1	PASS
19	50.1	1	1	PASS	-0.1	-0.1	PASS
20	50.1	0.5	0.5	PASS	-0.1	-0.1	PASS
21	50.1	0.1	0.1	PASS	-0.5	-0.5	PASS
22	50.1	1	1	PASS	-0.5	-0.5	PASS
23	50.1	0.5	0.5	PASS	-0.5	-0.5	PASS

- <u>Comparison of theoretical event start time with time determined by LFO algorithms.</u>

Event No.	System frequency (Hz)	Generated oscillation frequency (Hz)	Generated damping	t_{start_manual} (UTC)	t_{start_event} (UTC)	Start time difference (s)	Test result
6	49.9	0.1	0.1	12:33:27.900	12:33:30.500	2.600	PASS
7	49.9	1	1	12:38:15.700	12:38:22.100	6.600	PASS
8	49.9	0.5	0.5	12:43:03.300	12:43:09.200	5.900	PASS
9	49.9	0.1	0.1	12:47:51.400	12:47:57.700	6.300	PASS
10	49.9	1	1	12:52:38.800	12:52:44.600	5.800	PASS
11	49.9	0.5	0.5	12:57:26.600	12:57:32.600	6.000	PASS
12	49.9	0.1	0.1	13:02:14.200	13:02:19.900	5.700	PASS
13	49.9	1	1	13:07:02.400	13:07:09.000	6.600	PASS
14	49.9	0.5	0.5	13:11:49.600	13:11:55.900	6.300	PASS

Conclusion

- WAMPAC solutions are usually difficult to test and debug in real environments.
- Network Oscillations are becoming an increasing problem in European transmission networks.
- New algorithms are being developed in the FARCROSS project that are more adapted to support real-time response. The testing of these algorithms with real hardware is also within the scope of FARCROSS.
- In this paper, a lab-scaled laboratory for testing wide-area solutions has been explained. This laboratory is interconnected with a PDC in Croatia, providing realism to the performed tests.
- This infrastructure has been used to validate the low frequency algorithms developed, using RTDS as a model and generating different types of disturbances.
- These tests have been useful to test and debug the algorithms saving a lot of time for the final field implementation.

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