PMU implementation using IEC61850 Sampled Values implemented in a CPC platform

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***Abstract*— This paper presents the implementation of Phasor Measurement Units (PMUs) using IEC61850 Sampled Values (SV) in a Centralized Protection and Control (CPC) platform called EPICS platform. The SV-PMU microservice is developed and implemented via software on an EDGE Server, and its performance is evaluated in laboratory in both steady and transient states according to IEEE/IEC 60255-118-1:2018 standard. The evaluation tests were executed using a Real-Time Digital Simulator (RTDS). Two methods for the evaluation of the behaviour of the PMUs were implemented. The first is an evaluation in real-time using a Real-Time Automation Controller (RTAC) and the second one is an evaluation in offline mode using a Python Script. Two instances of the SV-PMU microservice were evaluated, the first one uses as signal inputs the SV generated in RTDS and the second one uses the signals generated by a Stand-Alone Mergin Unit. The tests results demonstrate the microservice's compliance with the standards, highlighting its potential to enhance the EPICS platform's capabilities as a CPC system in Digital Substations and to contributes to the deployment of Wide Area Monitoring, Protection, and Control (WAMPAC) systems in the power grid. Future work includes comparing the behaviour of SV-PMU microservice with commercial PMUs to validate its real-world applicability.**

Keywords—IEC61850, Sampled Value, PMU, Merging Unit, CPC, WAMPAC, Digital Substations.

I. Introduction

Nowadays, power systems are undergoing rapid changes in terms of grid operation, due to the need to meet greenhouse gas emission reduction targets by the year 2050. To achieve this goal, countries are executing plans for accelerated installation of renewable generation sources, thereby replacing fossil fuel-based generation sources. On the other hand, a digitization plan is also being implemented with the aim of saving construction and maintenance costs, as well as optimizing operation with the processing of large amounts of information using Big Data techniques and Artificial Intelligence that can work in times very close to real time.

The dynamics of the grid have been affected by the transition to renewable energy sources with power electronics interface, as they have a different behavior than that provided by synchronous generators. For example, effects have been observed in the behavior of protections [1-3], and changes in frequency variations due to disturbances caused by the decrease in system inertia [4-7] .

Traditionally, control centres have based their operation on measurements that are refreshed approximately every 1-4 seconds, supervised by a SCADA system. With this time resolution and information, it is not possible to execute algorithms that operate near real time. As an alternative to the above, the WAMPAC systems are presented, which can provide more accurate and time-synchronized information about the state and dynamics of the grid. A WAMPAC system use synchrophasor measurements generated by Phasor Measurement Units, which are capable of generating data up to every 8ms (120fps) or 16 ms (60fps) in a 60 Hz Power System, or every 10 ms (100fps) or 20 ms (50fps) in a 50 Hz Power System (depending of the data rates available in the device), synchronized in time in compliance with IEEE/IEC 60255-118-1:2018 standards [8-11]. More details about the applications of WAMPAC systems can be found in [12-16].

Typically, conventional PMU needs to have secondary voltages and currents wired in order to work properly. In the process of digitalization of the substations, starting the measurements with Stand-Alone Merging Units (SAMU) or digital instrument transformers, it is natural the evolution of PMUs to move towards the use of measurements based on IEC61850 SV [17-18]. The IEEE/IEC 60255-118-1:2018 standard [8], in its Annex E, opens the door to this possibility and generally defines how it should operate and the evaluation criteria. Few commercial devices offers this capability as can be observed in [19] and some SV based distributed solutions as can be observed in [20]. In [21], a comparison of the behaviour between conventional PMU and the combination of commercial SAMU + SV based PMU is shown, concluding that this combination is feasible of its use in synchronized phasor measurements systems like WAMS or WAMPAC.

Some non-commercial implementations of PMUs based on IEC61850 SV, called *SV-PMU*, have been found in the literature. In [22], a preliminary study of measurement of synchrophasors with SAMUs is presented. During that study the *SV-PMU* was not implemented in a hardware, and the comparison of the measurements results between a conventional PMU and the phasor estimation using the SVs collected are performed in a post-processing stage.

In [23-24], the *SV-PMU* is implemented in an embedded industrial controller (NI cRIO-9068) with Linux Real-Time OS and a re-configurable FPGA board. The author explain that they detect some bottlenecks related to the behaviour of the ethernet communication ports when the host computer (NI PXIe 1062Q) is communicating with the controller. It is not possible to have more than one ethernet port active at a time. The scalability of the solution is not represented, the paper is focussed on the implementation of a single *SV-PMU*.

As novelty, the present paper includes the following items:

- Proposes and develops a *SV-PMU microservice* (IEEE/IEC 60255-118-1:2018 performance – P-class), implemented via software in a generic hardware platform like an EDGE Server. The implementation was done using Docker containers [25] and microservices, following the instructions defined in the standards [8-11].
- Two methods were implemented for the evaluation of the PMUs' behaviour. The first is a real-time evaluation using a Real-Time Automation Controller, and the second is an offline evaluation using a Python Script. The evaluation was conducted according to the limits defined in [8].

This work is part of the EPICS project (Edge Protection and Intelligent Control in Substations) [26]. This implementation enhances the number of microservices provided by the EPICS platform, which final goal is to operate as a Centralized Protection and Control system in the Digital Substations, with the capability to feed with accurate measurements a WAMS or WAMPAC system associated with a Transmission or Distribution electrical system.

The paper is structured as follows. Section II presents a general description of the EPICS platform. Section III describes the implementation of the *SV-PMU microservice*. Section IV outlines the laboratory infrastructure used during this work. Section V details the tests executed and the evaluation criteria for the *SV-PMU microservice*. Section VI presents the test results. Finally, Section VII presents the conclusions.

II. EPICS Platform Description

EPICS is a software-based CPC platform, designed to execute protection, control and automation algorithms in digital substations in a centralized way. EPICS separates hardware and software in protection and control systems and implements an architecture based on containerized microservices executed on generic hardware such as a conventional server. Then, EPICS platform is not built using vendor-specific software nor hardware. It is worth noting that EPICS is implemented over a server Lenovo ThinkSystem SE350 with 16 Intel Xeon D-2183IT (16 cores) at 2.2 Ghz with 64 GB of memory. The server has an ''Edge Computing'' design with significant smaller dimensions than traditional servers giving enough flexibility for its installation in field. The operating system used in that server was Rocky Linux 9.0. It has to be noted that the kernel used in this work is the default of the Linux distribution and hence the use of a real-time scheduler does not guarantee deterministic temporal behaviour. Deeper information about developments of EPICS platform can be found in [27-29].

III. Implementation of SV-PMU microservice

The implementation described and tested in this work is based on the transcription of the reference signal processing models, specifically P-class, described in both IEEE C37.118.1-2011 Annex C [9] [10] and IEEE/IEC 60255-118-1:2018 Annex D [8]. These reference models describe the algorithms and filters to obtain phasors from timestamped sampled signals. In that way, the Sampled Values fulfilling the time requirements of the IEC 61869-9 [30] standard are an example of those kind of sampled signals.

In particular, the Annexes describe the low pass filter for both P-class and M-class phasors, the quadrature oscillator used to calculate the complex value of the phasor for each single phase, the timestamp compensation for low pass filter group delay, and the estimation of frequency and ROCOF with the positive sequence. The FRACSEC and SOC of the timestamping of the computed phasors, frequency and ROCOF values are performed by considering the SV *smpCnt* counter synchronized as stated in IEC 61869-9 (synchornized by PTP protocol) and the absolute timestamping of the server system time (synchronized by NTP protocol). It should be noted that the NTP client reported a maximum time error < 300 µs and the offset < 10µs.

A general diagram of the implementation of the *SV-PMU microservice* in the EPICS platform can be observed in Fig. 1.

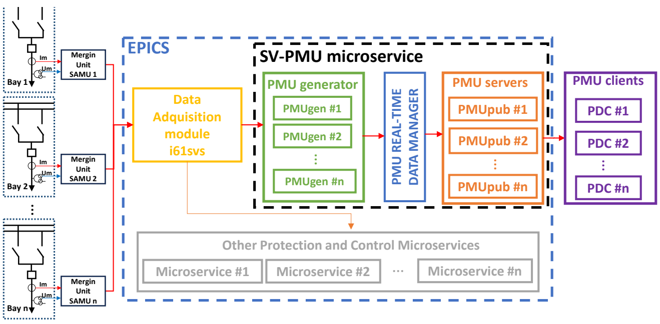

Fig. 1. General diagram of *SV-PMU microservice* in EPICS Platform.

The platform can manage and process multiple 61850 Sampled Values (SV) frames published by the SAMUs installed in field using the *i61svs* microservice. The outputs of the *i61svs* microservice are available to be used by multiple protection an control microservices as described in [27-29]. For this implementation, the outputs of the *i61svs* microservice are used by the *SV-PMU microservice* to calculate and generate the PMU servers needed for each implementation. The *SV-PMU microservice* is composed of three layers. The first layer, called the *PMU generator,* uses the outputs of the *i61svs* microservice to calculate the synchrophasors. The resulting synchrophasors are managed by the second layer, called *PMU REAL-TIME DATA MANAGER,* where all the information is available to be taken by the third layer responsible for creating all the *PMU servers* needed by the specific application that will be subscribed by the *PMU clients* (Typically Phasor Data Concentrators PDCs) externally to the EPICS Platform.

IV. Laboratory Infrastructure

In Fig. 2 is represented a general diagram of the laboratory testbed used during this work. As it is shown in the figure, the laboratory testbed mainly includes the following components:

- A Real-Time digital simulator: It is used to generate any type of synthetic signals needed for the evaluation of the "*SV-PMU microservice".*
- A GTNETx2_SV module of the RTDS: Publishes IEC61850 SV stream ("*RTDS IEC61850 SV*") at 4000 Hz, equivalent to 80 samples per cycle.

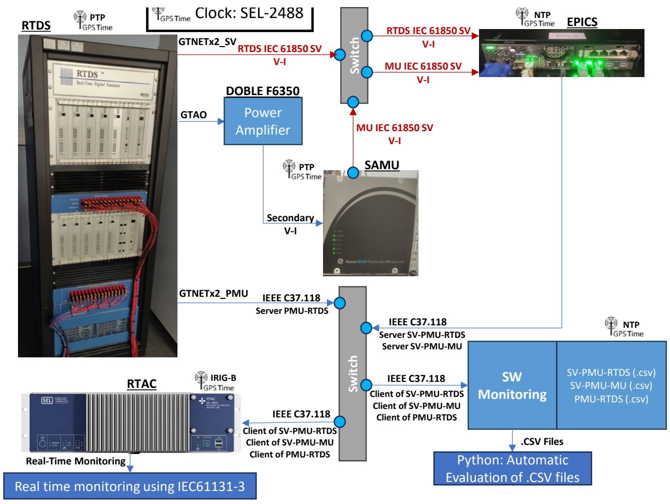

Fig. 2. General diagram of Laboratory testbed.

- A GTNETx2_PMU module of the RTDS: It works as a PMU server ("*Server PMU-RTDS"*) and can generate a synchrophasor frame compliant with standards [9-10]. The RTDS is time synchronized with PTP protocol. During this work, a P-class synchrophasor was used.
- The GTAO card of the RTDS and power amplifiers (*Doble F6350*): Converts the current and voltage signals providing by the simulation, which are low level analog signals (+/- 10V), into suitable secondary values to be wired to a conventional PMU or SAMU.
- A commercial SAMU ("*Reason MU320*"): Converts the secondary voltages and current values provided by the power amplifiers in IEC 61850 SV frames ("*MU IEC61850 SV*") according to [17].
- EPICS platform: In the platform the *SV-PMU microservice* and auxiliary services are implemented. The EPICS platform subscribes to the "*RTDS IEC61850 SV*" and "*MU IEC61850 SV*", and it is responsible to generate the PMU servers called "*SV-PMU-RTDS*" and "*SV-PMU-MU*" using two instances of the *SV-PMU microservice*.
- Real-Time Automation Controller (RTAC) SEL-3555: [31]. This equipment is used during *SV-PMU microservice* validation stage in real-time. It will manage the PMU information published by EPICS platform (*"SV-PMU-RTDS"* and *"SV-PMU-MU"*).
- Synchrowave monitoring [32] This tool is used during *SV-PMU microservice* validation during offline stage. It will manage the PMU information published by EPICS platform (*"SV-PMU-RTDS"* and *"SV-PMU-MU"*).

All the RTDS modules (GTNETx2_SV, GTNETx2_PMU and GTAO) use the same voltages and currents generated by the real-time digital simulation as input signals, ensuring that any comparison between PMUs "*SV-PMU-RTDS"*, "*PMU-RTDS"* and "*SV-PMU-MU*" will be valid. Furthermore, all the devices are time synchronized using a GPS Clock (SEL-2488), and the time synchronization protocol used by each device during this work is specified in Fig. 2. The GPS clock has a peak time stamp accuracy for PTP, demodulated IRIG-B and NTP protocols equal to ± 100 ns, ± 100 ns and <100 µs respectively. A PTP-compliant Ethernet switch (Hirshmann Greyhound) was used to distribute the PTP frames. Both, the RTDS and the SAMU reported that are time synchronized (Clock Locked) with PTP with a time quality accuracy < 1 µs.

An evolution of the laboratory testbed will include in the future a commercial PMU, measuring the same voltages and currents of the SAMU, to compare the behaviour of the *SV-PMU-MU* with a commercial device.

V. Test description and Evaluation criteria

This section includes a description of the tests carried out to check *SV-PMU microservice* operation (subsection A). Furthermore, the tolerances selected during tests are summarized in subsection B. Finally, a detailed description of the methodology used to check the *SV-PMU* operation is described in subsection C.

A. *Test description.*

To check the *SV-PMU microservice* outputs (*SV-PMU-RTDS* and *SV-PMU-MU)* operation, several steady state and transient state tests were carried out. These tests were selected from the IEEE/IEC 60255-118-1:20218 standard [8]. Following, the tests included during the study are listed:

a) Steady state tests.

- Signal frequency tests: The *SV-PMU microservice* operation is tested when the frequency of the voltage and current sources is 48, 50 and 52 Hz.
- Signal magnitude voltage tests: The *SV-PMU* operation is checked when the magnitude of the voltage sources is 80 %, 100 % and 120 % rated voltage.
- Signal magnitude current tests: The *SV-PMU* operation is evaluated when the magnitude of the current sources is 10 %, 100 % and 200 % rated current.
- Harmonic distortion tests.

Each steady state tests have a time duration of 10 minutes.

b) Transient state tests.

- Frequency ramp tests: The *SV-PMU microservice* operation is tested when the frequency of the voltage and current sources vary periodically from 48 to 52 Hz (Triangular behaviour), with a ramp rate of ±1 Hz/s. This test has a time duration of 10 minutes.
- Step Change in Magnitude: The tests consist of generating a voltage and current step of 1.1 p.u. and 0.9 p.u.
- Step Change in Angle. +10° steps in Current Angle.

B. *Test tolerances definition*

The evaluation of a PMU is executed, as defined in [8], calculating the Total Vector Error (TVE), Frequency Error (FE) and Rate of change of Frequency Error (RFE). The tolerances defined to evaluate the behaviour of the *SV-PMU microservice* outputs can be observed in TABLE I.

The threshold limits defined in TABLE I. are reduced by the standard [8] when it works in steady state at nominal frequency and it is only considered the operation of the synchrophasor estimation algorithm, i.e., without consider AC analog signals provided by instrument transformer. In these scenarios, the new thresholds are TVE=0.01 %, FE= 0.004975 Hz and RFE=0.398 Hz/s. This particular case applies during the *SV-PMU-RTDS* performance evaluation.

TABLE I. CONTROL VARIABLES THRESHOLDS TO CHECK SV-PMU MICROSERVICE OUTPUTS

Control Variables	Steady State Tolerances	Transient State Tolerances
Max TVE (%)	1	1
Max FE (Hz)	0.005	0.01
Max RFE (Hz/s)	0.4	0.4

For frequency ramp tests, the exclusion intervals defined in [8] were considered. The TVE, FE and RFE were ignored when the frequency exceeded 51.92 Hz or was below 48.04 Hz. The exclusion intervals are used to disregard transitory transitions when the frequency slope changes during the test.

For Step test, the standard [8] stablished a maximum overshoot/undershoot equal to 5 % of the step, a response time in TVE of less than 60 ms (3 reporting intervals), a response time in frequency of less than 0.09 s and a response time in ROCOF of less than 0.12 s.

C. *Evaluation criteria*

The signal provided by *PMU-RTDS* server is used as reference during the evaluation process, for the calculation of the TVE, FE and RFE. The standard [8] specifies that a traceable synchronized signal generator shall be used to verify the performance. In absence of that generator, the PMU-RTDS is used as reference. In [33] extensive tests were done to the GTNETx2_PMU module obtaining good results. In [34-35] is expressed that the GTNETx2_PMU module has a TVE<0.01 % at their test facilities which trace back to metrological authority. This value enables the possibility to use the *PMU-RTDS* as a valid reference for PMU evaluations in the 1 % TVE limit.

The laboratory testbed described in section IV is used to check the *SV-PMU* operation. Two methods of evaluation of have been used during this study. The first one is focused on to check *SV-PMU* performance in real-time and, the second one, uses an offline mode evaluation. Following, a detailed description of these methods is carried out.

a) Real time evaluation method

To do this task, the RTAC SEL-3555 described in section IV is used. The evaluation criteria previously described (TVE, FE and RFE) are programmed in the RTAC, using the IEC 61131-3 language [36-38]. The evaluation consists of the monitoring and comparing the *SV-PMU microservice* outputs (*SV-PMU-RTDS* and *SV-PMU-MU*) with the values provided by *PMU-RTDS*. If the monitored values are outside of the tolerances defined in [8], a COMTRADE file is generated for post-mortem analysis.

a) Offline mode evaluation method

This method is executed in offline mode and uses a Python script to process the .CSV files stored by the Synchrowave Monitoring software (SWM) [32], to calculate the TVE, RFE and FE of the *SV-PMU microservice* outputs (*SV-PMU-RTDS* and *SV-PMU-MU*) using as pattern the values provided by "*PMU-RTDS*". The outputs of the script include the maximum, average, deviation and tolerance evaluation of the TVE, RFE and FE.

VI. Test Results.

This section summarizes the most representative results obtained from tests described in section III. The figures show the control variables performance (TVE, FE and RFE) when the EPICS' input signal comes from RTDS (*SV-PMU-RTDS*) and from SAMU (*SV-PMU-MU*). The evaluation of the PMUs performance is carried out according to the values shown in section III.

A. SV-PMU-RTDS Results

a) Steady state Test Results.

The TABLE II. presents the test results obtained during steady-state tests. Based on these results, is concluded that in all study cases, the TVE, FE and RFE values fall within the defined limits.

TABLE II. Steady state test results

Type test	Max TVE (%)	Max FE (Hz)	Max RFE (Hz/s)	Inside limits
Magnitude Voltage	8.73E-05	0	2.64E-07	☑
Magnitude Current	0.00045	0	2.12E-07	☑
Harmonic distortion	0.02047	0	2.29E-07	☑
Frequency	0.206	0	2.86E-06	☑

As an example, the TVE results in average obtained by the *SV-PMU-RTDS* in the frequency tests can be observed in Fig. 3. It can be observed that the TVE of voltages and currents are inside the TVE limit. The maximum obtained TVE was 0.206% in 52Hz test.

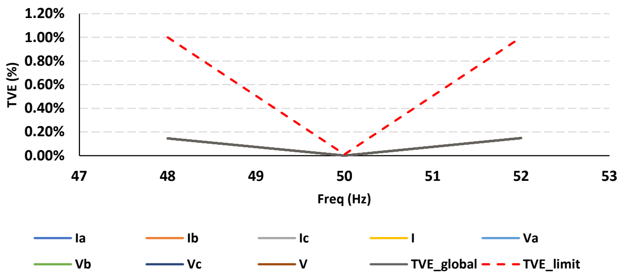

Fig. 3. SV-PMU-RTDS, Signal Frequency test, TVE, average.

b) Transient state

These tests are divided into Frequency ramp test and Step Change in magnitude and angle. In case of frequency ramp test, the maximum TVE, FE and RFE values obtained during the test are 0.188 %, 0.00135 Hz and 0.0086 Hz/s respectively. Those values are inside the limits defined by [8].

On the other hand, test results from Step Change in magnitude and voltage are detailed TABLE III. The results are inside the limits defined by [8].

TABLE III. Step Change in Magnitude, SV-PMU-RTDS

Test	**Step Magnitude**	**Response time (ms)**	**Max Overshoot/undershoot (%)**
Step in Voltage Magnitude	1 p.u. to 1.1 p.u.	< 60 ms	0 %
	1 p.u to 0.9 p.u.	< 60 ms	0 %
Step in Current Magnitude	1 p.u. to 1.1 p.u.	< 60 ms	0 %
	1 p.u to 0.9 p.u.	< 60 ms	0 %
Step in Angle	+10°	< 60 ms	0 %

As can be seen in the test results of the *SV-PMU-RTDS*, the obtained values are very similar to the reference values provided by "*PMU-RTDS*". This suggests that the implementation of the *SV-PMU microservice* in the EPICS platform is correct. However, this scenario is highly idealized and unlikely to occur in the real world. This is because the *SV-PMU-RTDS* is obtaining the measurements directly from RTDS, without any perturbation or real measurement element like a SAMU.

To extrapolate the use of the *SV-PMU microservice* to the real world, a SAMU was used to measure the secondary voltages and currents generated by the RTDS. This scenario is more applicable, and the results can be compared with a commercial PMU in future studies. The test results of the *SV-PMU-MU* can be observed next.

B. *SV-PMU-MU Results*

a) Steady state Tests

The TABLE IV. presents the test results obtained during steady-state tests. Based on these results, it can be concluded that in all study cases, the values obtained for TVE, FE and RFE fall within the defined limits.

TABLE IV. STEADY STATE TEST RESULTS

Type test	Max TVE (%)	Max FE (Hz)	Max RFE (Hz/s)	Inside limits
Magnitude Voltage	0.588	0.000473	0.037	☑
Magnitude Current	9.40	0.000446	0.036	☑
Harmonic distortion	0.554	0.00134	0.1017	☑
Frequency	0.691	0.00048	0.038	☑

In case of magnitude current tests, it is observed that the maximum TVE value exceed the preset limit. This happens in the test with 10 % of rated current where the current magnitude is lower and any deviation in current magnitude will be traduced in big deviations in the TVE of the currents. In the tests with 100 % and 200 % of nominal currents the TVE is inside the limits defined by [8]. The average values of TVE can be observed in Fig. 4.

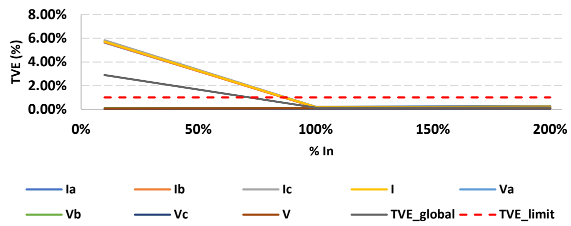

Fig. 4. SV-PMU-MU, Signal magnitude current test, TVE, Average.

As an example, the TVE results obtained in average by the *SV-PMU-MU* in the frequency tests can be observed in Fig. 5. It shows that the TVE of voltages and currents are inside the TVE limit. The maximum TVE obtained was 0.691 % in 48 Hz.

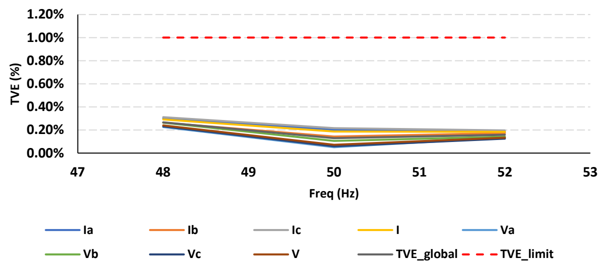

Fig. 5. SV-PMU-MU, Signal Frequency test, TVE, Average.

b) Transient state

These tests are divided into Frequency ramp test and Step Change in magnitude and angle. In case of frequency ramp test, the maximum TVE, FE and RFE values obtained during the test are 0.638 %, 0.001732 Hz and 0.0351 Hz/s respectively. Those values are inside the limits defined by [8].

On the other hand, test results from Step Change in magnitude and voltage are detailed in TABLE V. The results are inside the limits defined by [8].

TABLE V. STEP CHANGE IN MAGNITUDE, SV-PMU-MU

Test	**Step Magnitude**	**Response time (ms)**	**Max Overshoot/undershoot (%)**
Step in Voltage Magnitude	1 p.u. to 1.1 p.u.	0 ms	0.93 %
	1 p.u to 0.9 p.u.	0 ms	0.69 %
Step in Current Magnitude	1 p.u. to 1.1 p.u.	0 ms	2.01 %
	1 p.u to 0.9 p.u.	0 ms	3.53 %
Step in Angle	+10°	< 60 ms	0.58 %

VII. CONCLUSIONS.

During this work was successfully developed and implemented a *SV-PMU microservice* (Performance – P class), implemented via software in a generic hardware platform like an EDGE Server, called EPICS Platform. The implementation was done using Docker containers and microservices, following the instructions defined in the standards [8-11].

The *SV-PMU microservice* was evaluated in laboratory using an RTDS. Two methods for the evaluation of the behaviour of the PMUs were implemented. The first is an evaluation in real-time using a Real-Time Automation Controller (RTAC) and the second one is an evaluation in offline mode using a Python Script. The obtained test results indicate that the *SV-PMU microservice* implemented in the EPICS platform has good results during the executed steady state and transient state tests, fulfilling in all of them the requirements defined in [8].

This implementation enhances the capabilities of the EPICS platform to operate as a Centralized Protection and Control system in Digital Substations, enabling it use as a vital part of WAMPAC systems.

As part of future work, a commercial PMU will be incorporated into the laboratory testbed. This device will measure the same voltages and currents as the SAMU, and its performance will be evaluated and compared with the results obtained by the *SV-PMU-MU*. The complete test set listed in [8] will be executed to ensure compliance with the standard specifications in all technical aspects. These tests will be performed with real-time schedulers in the EPICS Operating System in order to measure worst case latencies of the system as a whole including additional protection and control microservices. Additionally, following the laboratory validation stage, the EPICS platform will be installed in a substation owned by the Spanish Transmission System Operator (REE).

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