

RTDS-Based HiL Validation of Virtualized Protection, Monitoring and AI algorithms for Digital Substations.

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- u CIRCE Technology Centre



Table of contents



01 Who are we?
CIRCE presentation

02 Virtualized Platforms
General Overview

03 Testing Case
1. Analog Processing Module
2. Multicriteria FPS
3. Virtual PMU

04 AI applications
Datasets and Testing.

05 Other experiences

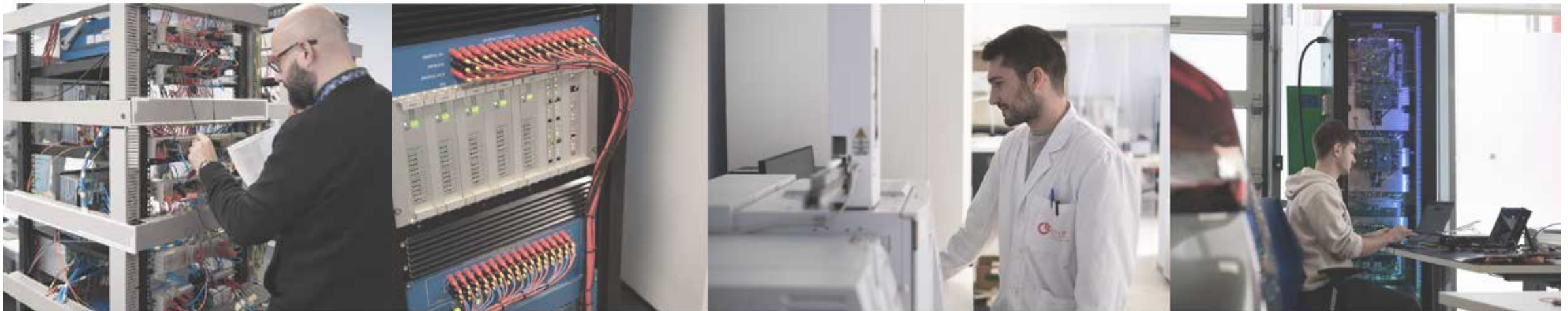
01

Who are we?

Who are we?

- We are a **private non-profit foundation**

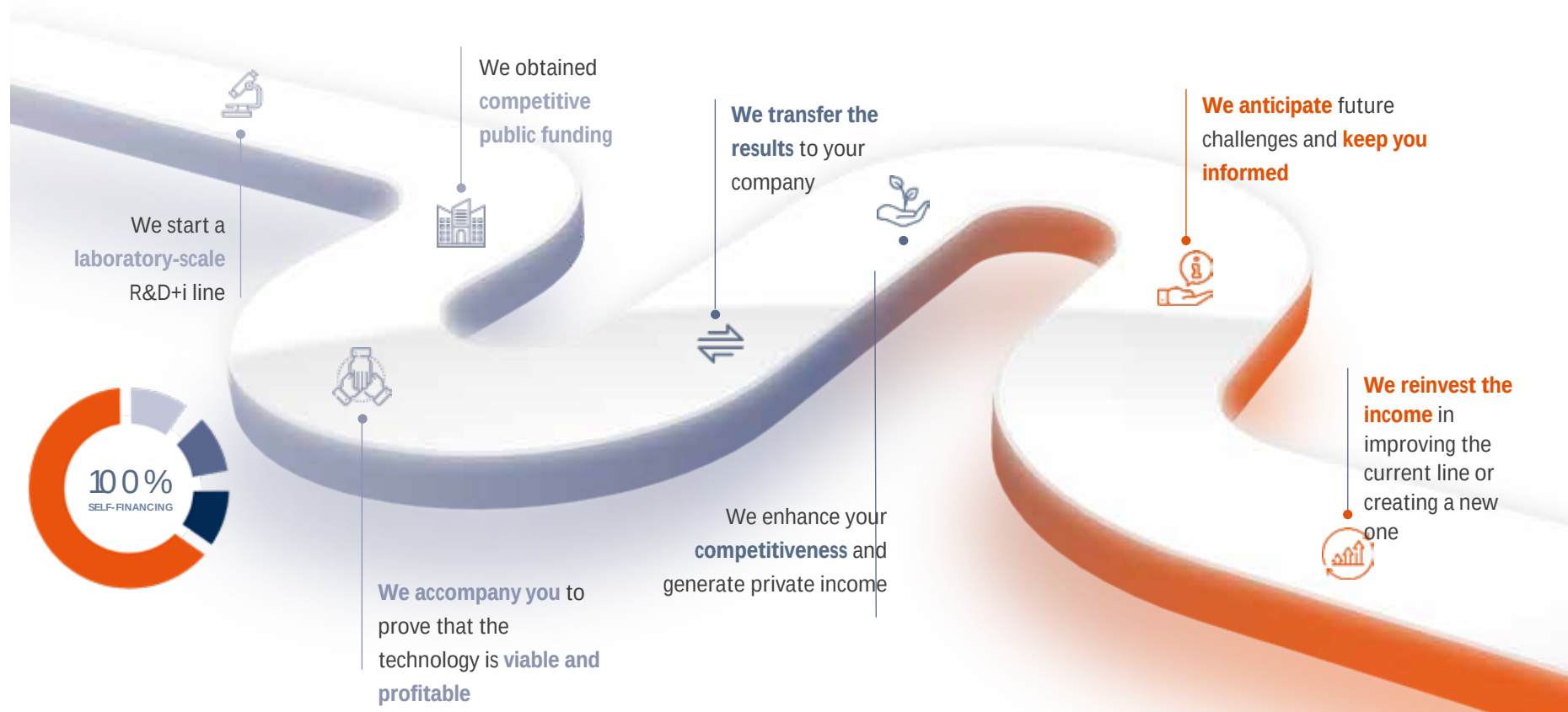
- We helps you improve your competitiveness in the fields of **energy, sustainability and digitalisation**

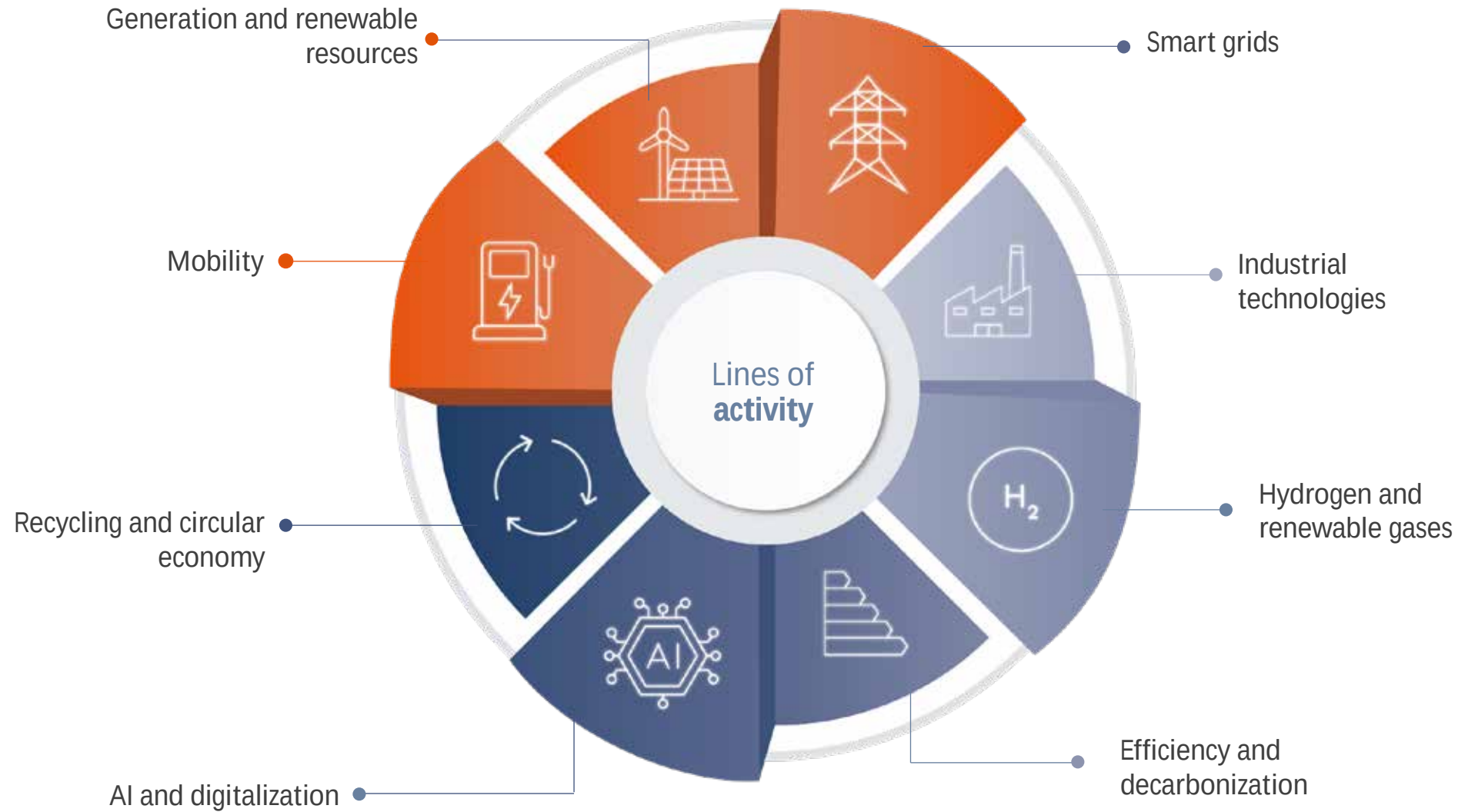


- We are the gap between research and the **needs of the business sector**

+300
PEOPLE

Our model





Horizon Europe Experience

2021-2025 CALLS

90

Projects funded
2021-2025

25

Projects directly coordinated
by CIRCE

55

M€
Return secured
by CIRCE

100

M€
Return or national
partners

Proposal success rate last 6 years

Proposals written entirely by CIRCE

CIRCE



>40%

EU avg.



<10%



+10

Multidisciplinary experts
Dedicated to proposal writing



Top 10 in Spain

For total Horizon Europe return



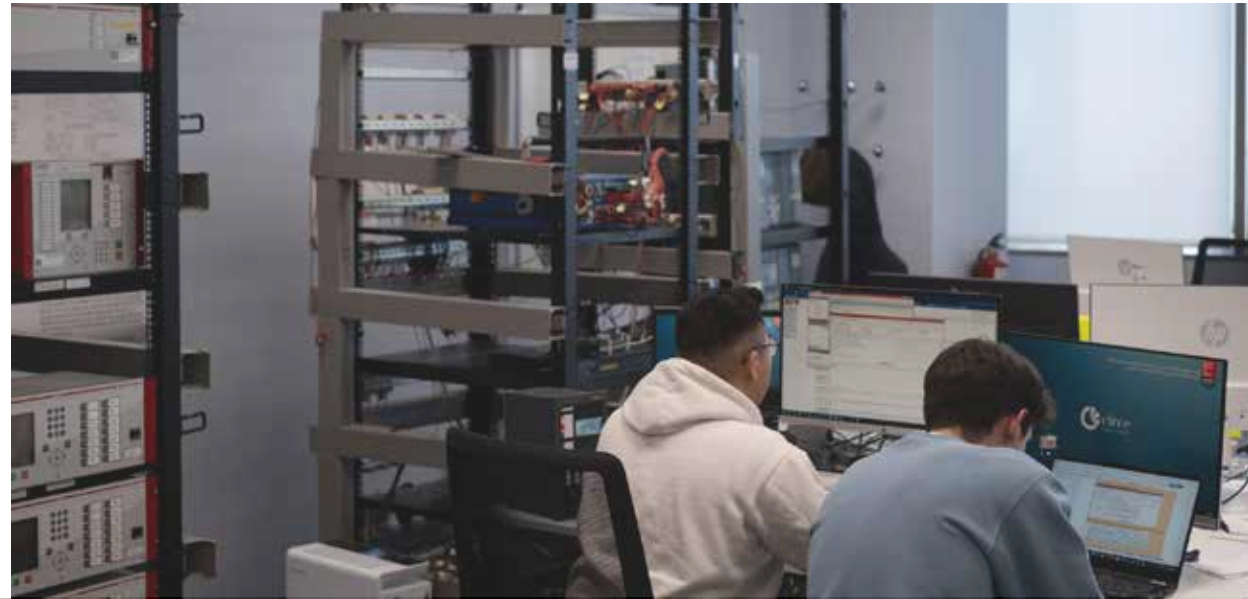
**4th in Spain
for coordination**



Top 50 in Europe

Real-time laboratory tests are conducted to study the interaction of smart equipment with the electrical grid. Equipped with test cases, communication infrastructure, wiring replicas, and GPS network.

Control, protection, remote control, and telecommunications equipment, along with automation tools for 61850 testing developed by CIRCE, are utilized.



Validation and homologation laboratory for IEDs and communication protocols

We also have a laboratory that allows the development and testing of wide area protection systems (WAMPAC), virtualized systems and algorithms based on neural networks that contemplate the necessary adaptations for the operation of the electricity grid of the future.





NOVACOR 2.0

1 chassis with 4 cores

Additional Cards

1 GTFPGA, 1 GTDI, 2 GTAO, 2 GTNETx2, 1 GTNET,
1 GTDO, 1 GTSYNC, 1 GTFPI, 2 power amplifiers
(12 voltaje and 12 currents), 1 Power Amplifier EGSTON.



PB5

2 racks, the first with 2 PB5 cards and the
second with 5 PB5 cards)

GTFPGA card with EGSTON amplifier



RTDS



GTFPGA

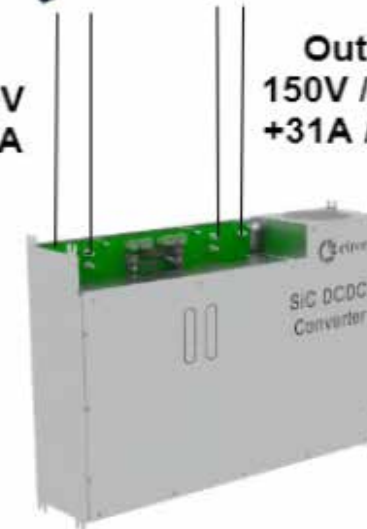


EGSTON

Power Amplifier

Input
500V / 700V
+28A / -28A

Output
150V / 500V
+31A / -31A

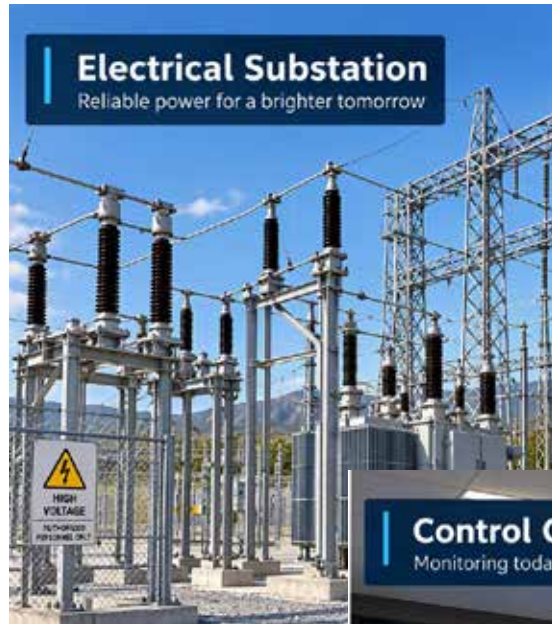
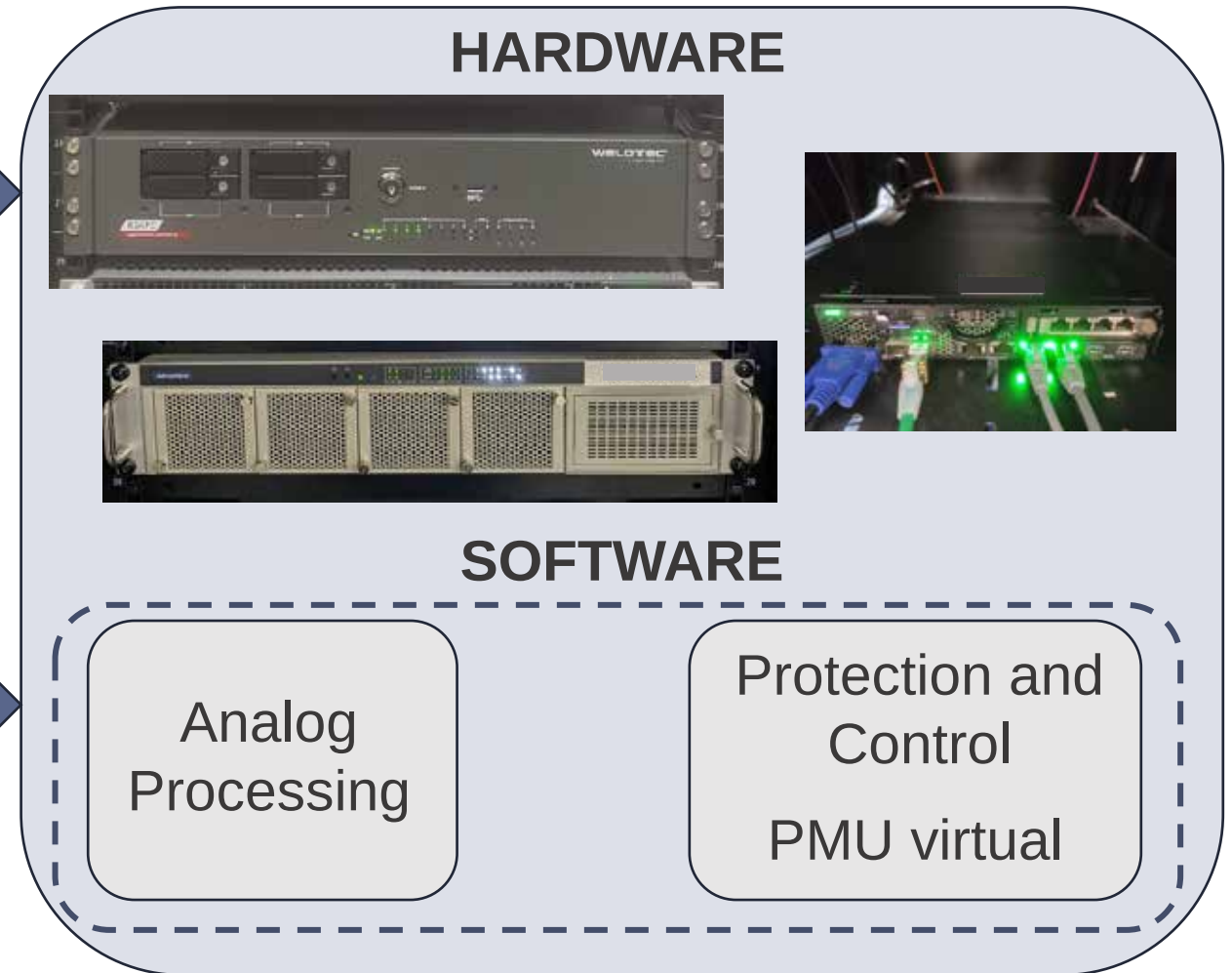


**Power Electronic
Device**

02

Virtualized Platforms General Overview

Virtualized platforms. General Overview



03

Test Cases using HiL

03.1

Test Case 1: Analog Processing Module

Test case 1: Analog Processing Module validation

OBJECTIVE

Provide **MU data** to the control services running on the platform.

Ensure the information is delivered **accurately** and **within the required time constraints**.

MAIN FUNCTIONS TO BE EVALUATED

Merging Units

V / I sampled values

IEC 61850-9-2



1

Signal reconstruction

Missing samples, incorrect quality bits and loss of synchronization (SRM)



2

Grid frequency estimation

Based on voltage measurements



3

Resampling

According to the actual system frequency



4

Fourier, RMS & harmonics

Calculation of Fourier components, RMS values and harmonics



Control services

Protection & control apps

VMs / containers

■ Data flow

■ Processing on the virtualized host

Test case 1: Analog Processing Module validation

Tests performed to verify the behaviour

Functional tests

NUMBER OF TESTS

1,915 tests

EVALUATION

Comparison of the theoretical values published by RTDS with the values calculated by the Analog Processing Module

Performance tests

TEST DURATION

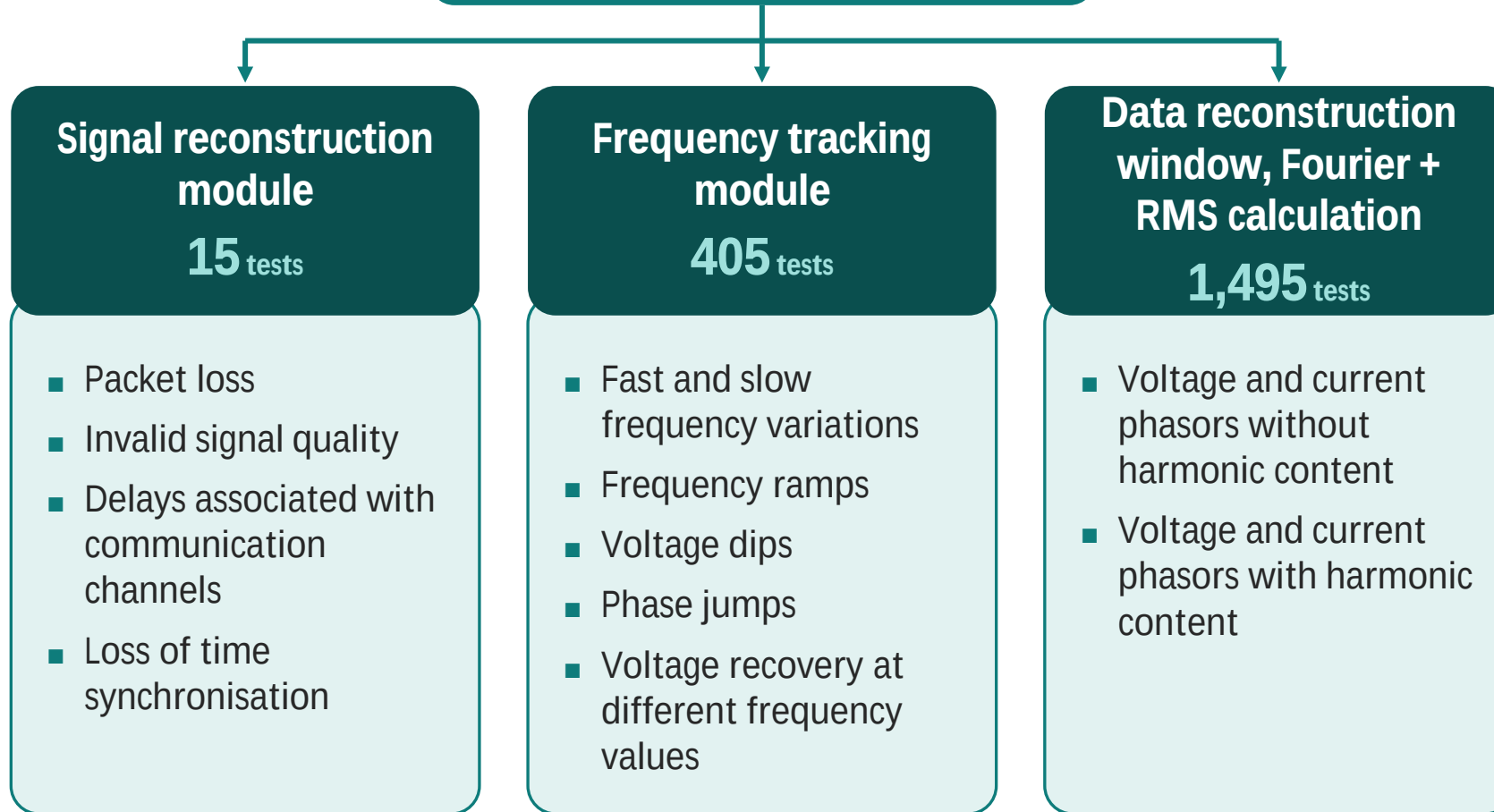
3 days

EVALUATION

Verify that the measured average latency is below the requirements defined in the IEC 61850 standard

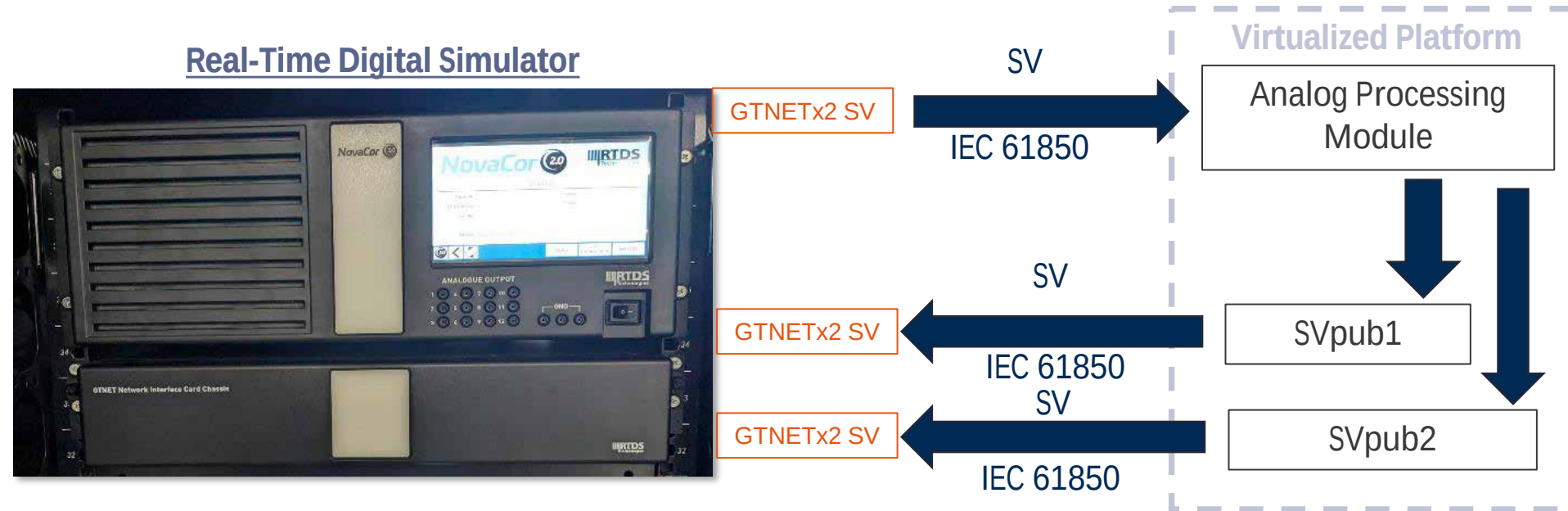
Test case 1: Analog Processing Module validation

Functional tests



Test case 1: Analog Processing Module validation

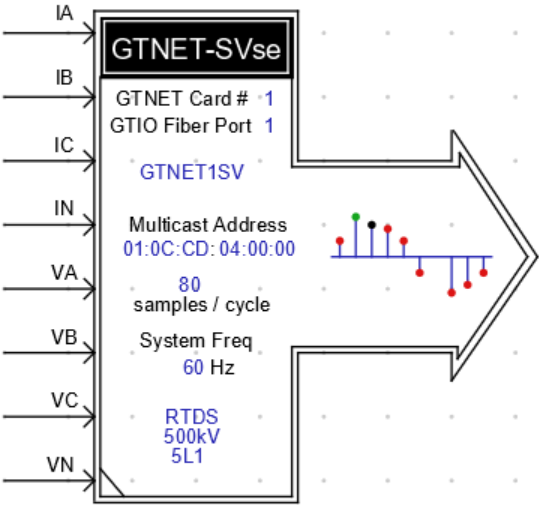
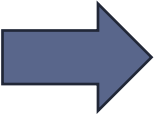
q Signal reconstruction testbed



- SVpub1: Publishes the current and voltage signals generated by RTDS.
- SVpub2 : Publishes the current and voltage signals reconstructed by the analog processing module.

Test case 1: Analog Processing Module validation

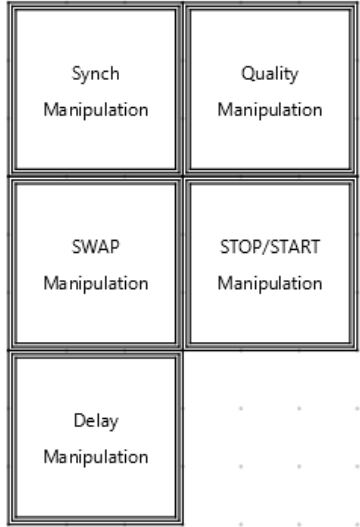
q SV Manipulation scenarios



Component Parameters for _rtds_ctl_GTNET_SV_SE2.def

	Name	Description	Value	Unit	Min	Max
CONFIGURATION	NsprsMsg	Input Name for Suppressing Message	Stop2_REM			
CHANNEL SCALING	NchgOrdr	Input Name for Changing Packet Order	Swap2			
SV-1 OUTPUT IEC 61850 CONFIG	NdlyDt	Input Name for Delay Time (in Number of DT)	real_delay_REM			
SV-1 OUTPUT CHANNEL QUALITY ENABLES	NOTE	The delay is limited to 3 sample-period.				
CONTROL INPUT/OUTPUT SIGNAL NAMES	NsmpCnter	Output Name for Sample Counter	SmpCnter_out2_RTDS			
	NpcktTrnsmtInd	Output Name for Packet Transmit Indicator	PcktTrnsmt_out2_RTDS			
AUTO-NAMING SETTINGS						

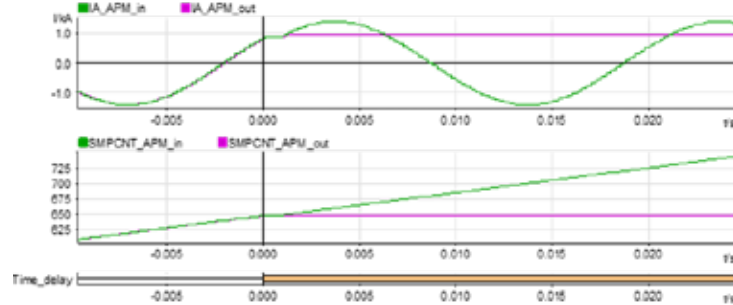
OK Cancel Cancel All



Test case 1: Analog Processing Module validation

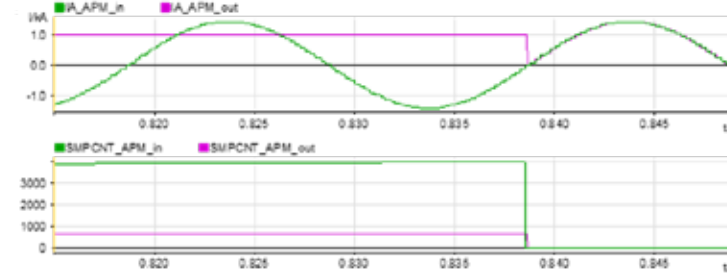
- q Signal Reconstruction Module.
- q Operational test results: Communication channel delay

1 Start of the delay



When the delay starts ($t = 0$ s), the output holds the last received value: the current stays constant and the sample counter freezes at 650, while the input keeps evolving.

2 System recovery

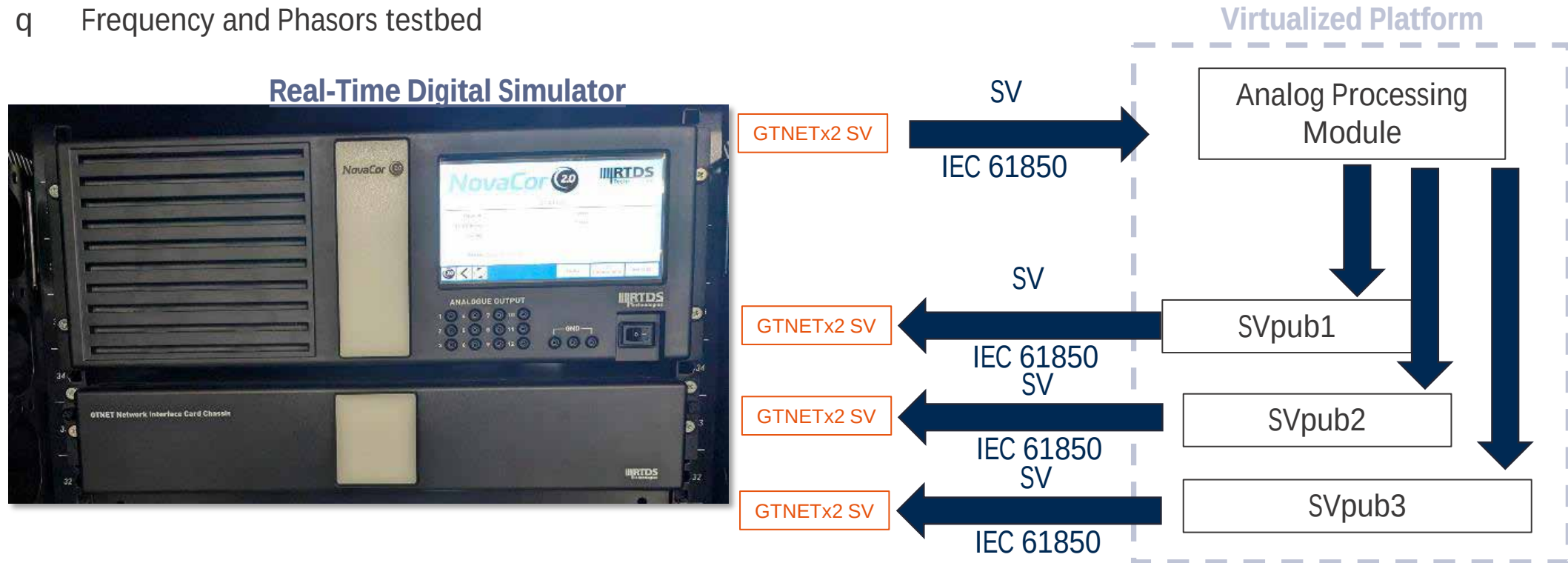


The output resynchronises with the input as soon as the sample counter resets to zero ($t \approx 0.839$ s).

■ $_in$: signal received by the APM ■ $_out$: signal delivered by the APM

Test case 1: Analog Processing Module validation

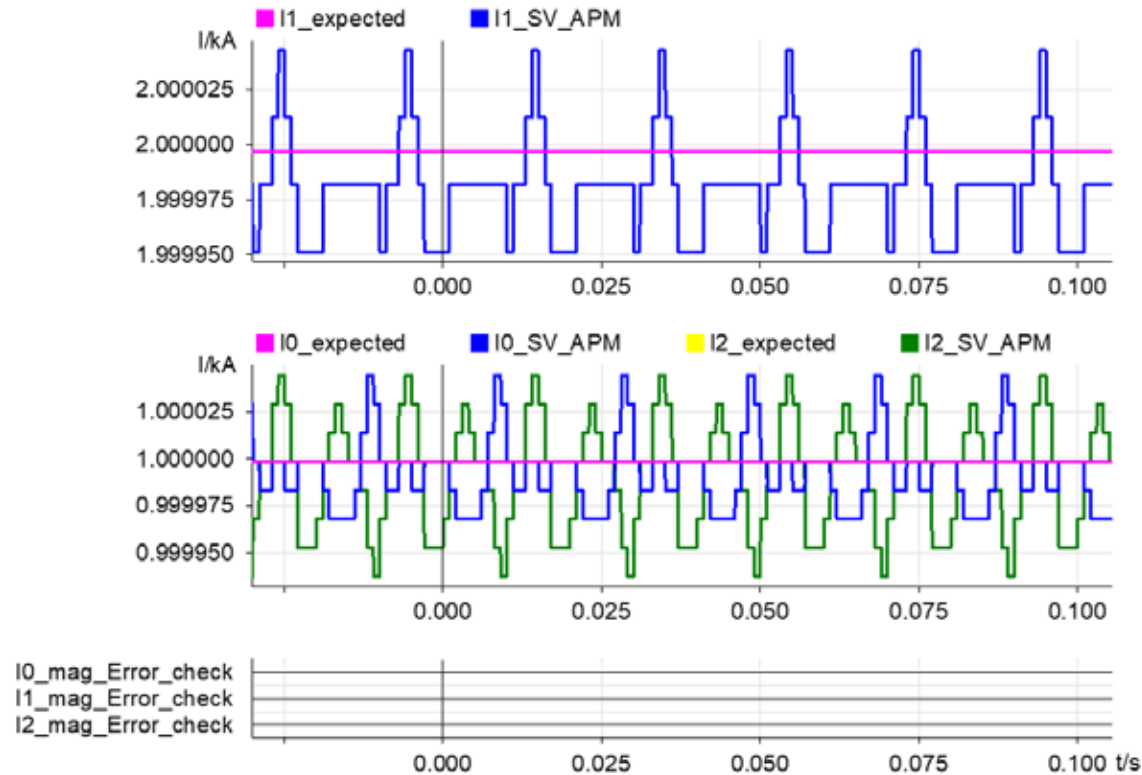
q Frequency and Phasors testbed



- SVpub1 : Publishes the frequency, and the current and voltage phasors (magnitude, RMS value and phase angle)
- SVpub2 : Publishes the current and voltage harmonic components up to 4th harmonic
- SVpub3 : Publishes the current and voltage symmetrical components and 5th harmonic component

Test case 1: Analog Processing Module validation

q Fourier calculation



■ _expected: reference magnitude

■ _SV_APM: magnitude computed by the APM from the SV stream

< 0.01 %

Maximum deviation of the computed magnitudes from the expected values (< 0.1 A)

2.0 / 1.0 kA

Expected values: I1 = 2.0 kA, I0 = I2 = 1.0 kA

No errors

Magnitude error checks for I0, I1 and I2 stay inactive over the whole test window
(Tolerance considered < 0.2% in magnitude)

IEEE POWER & ENERGY SOCIETY SECTION

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Received 20 November 2023, accepted 8 January 2024, date of publication 15 January 2024, date of current version 25 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3354718



RESEARCH ARTICLE

Software-Defined Analog Processing Based on IEC 61850 Implemented in an Edge Hardware Platform to be Used in Digital Substations

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AND CARLOS RODRIGUEZ DEL CASTILLO⁴

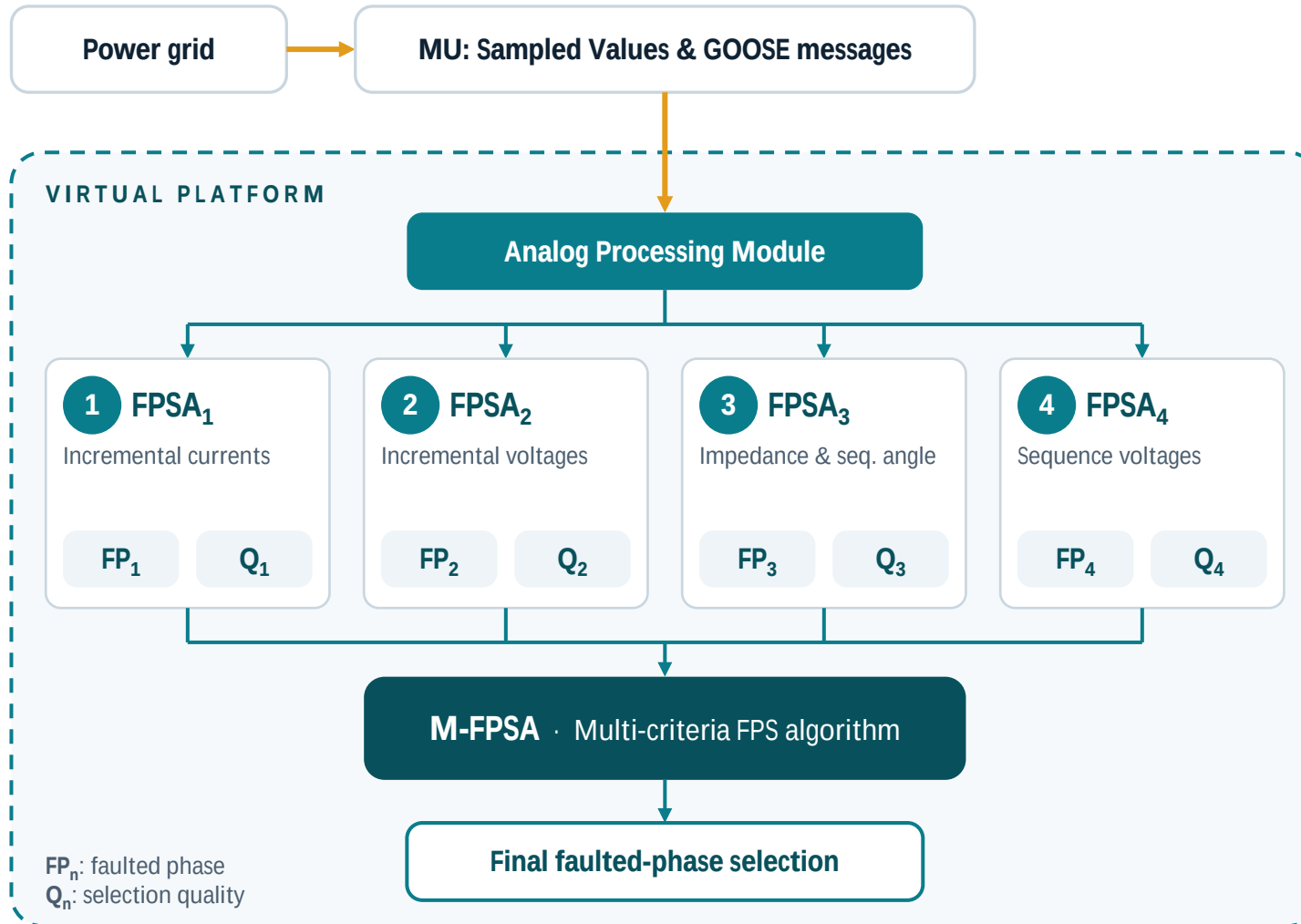
elewit

Villén, M.T.; Comech, M.P.; Prada Hurtado, A.A.; Oliván, M.A.; Cortón, D. L. and Castillo, C.R.D. "Software-Defined Analog Processing Based on IEC 61850 Implemented in an Edge Hardware Platform to be Used in Digital Substations", IEEE Access, vol. 12, pp. 11549-11560, 2024, doi: <https://doi.org/10.1109/ACCESS.2024.3354718>.

03.2

Test Case 2: Multicriteria FPS Algorithm

Test case 2: Multicriterio FPS algorithm

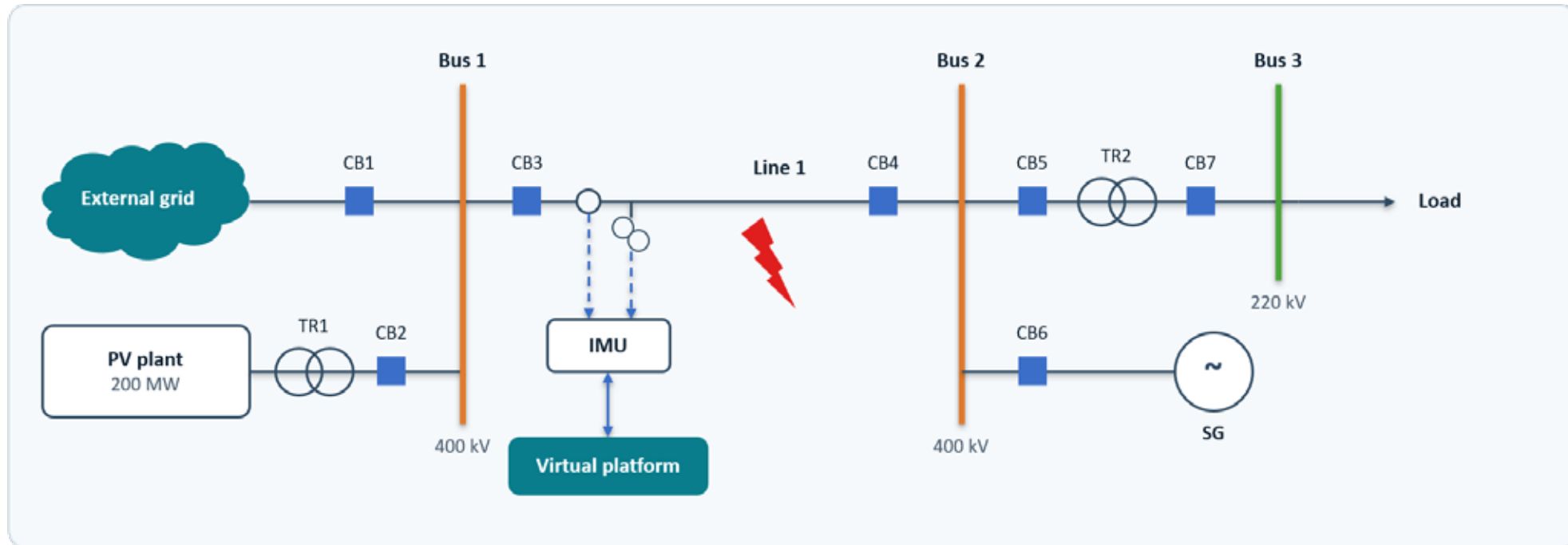


M-FPSA COMBINES 4 FPS ALGORITHMS

- 1 Incremental currents**
Faulted-phase selector based on incremental currents
- 2 Incremental voltages**
Faulted-phase selector based on incremental voltages
- 3 Impedance & sequence currents**
Faulted-phase selector based on impedance calculation and the angular displacement between sequence currents
- 4 Sequence voltages**
Faulted-phase selector based on sequence voltages

Test case 2: Multicriterio FPS algorithm

q Test network



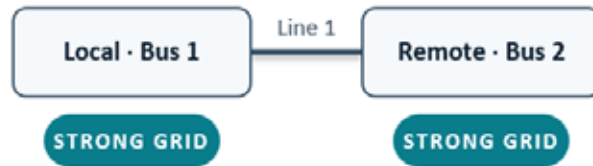
270 test cases in total

 400 kV bus  220 kV bus  Circuit breaker (CB)  Fault on Line 1  SG: synchronous generator

Test case 2: Multicriterio FPS algorithm

q Test scenarios

1 Scenario 1

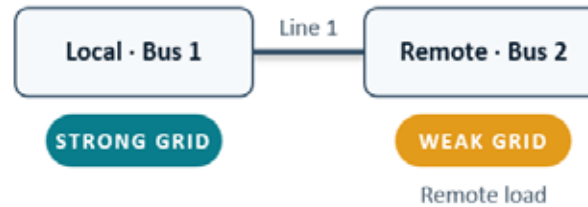


Long line · SIR = 0.5

Short line · SIR = 5

Strong grid at both the local (Bus 1) and remote (Bus 2) terminals. Two line lengths: long line (SIR = 0.5) and short line (SIR = 5).

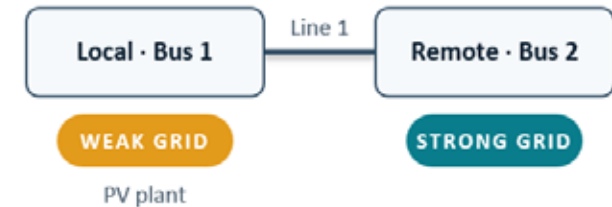
2 Scenario 2



Long line · SIR = 0.5

Strong grid at the local terminal and weak grid at the remote terminal. A load at the remote terminal simulates weak-end conditions.

3 Scenario 3



Long line · SIR = 0.5

Weak grid at the local terminal and strong grid at the remote terminal. The weak grid is simulated by connecting a PV plant.

STRONG GRID

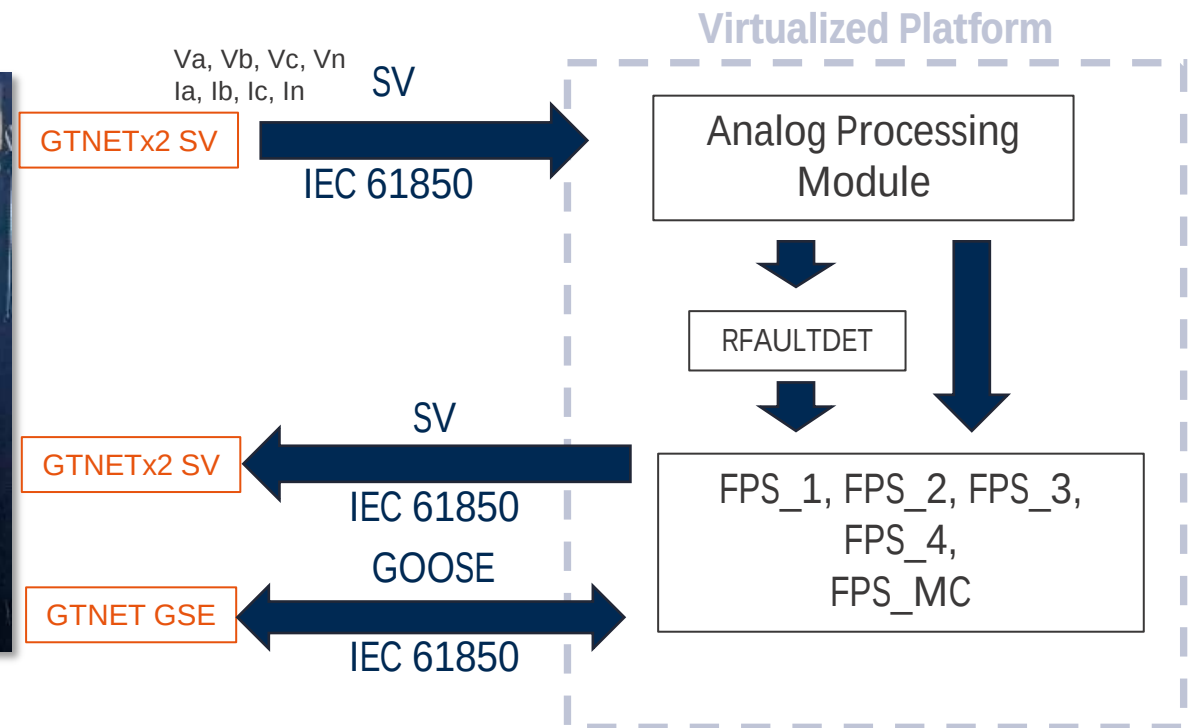
WEAK GRID

SIR: source-to-line impedance ratio

Test case 2: FPS Module validation

q FPS Testbed

Real-Time Digital Simulator

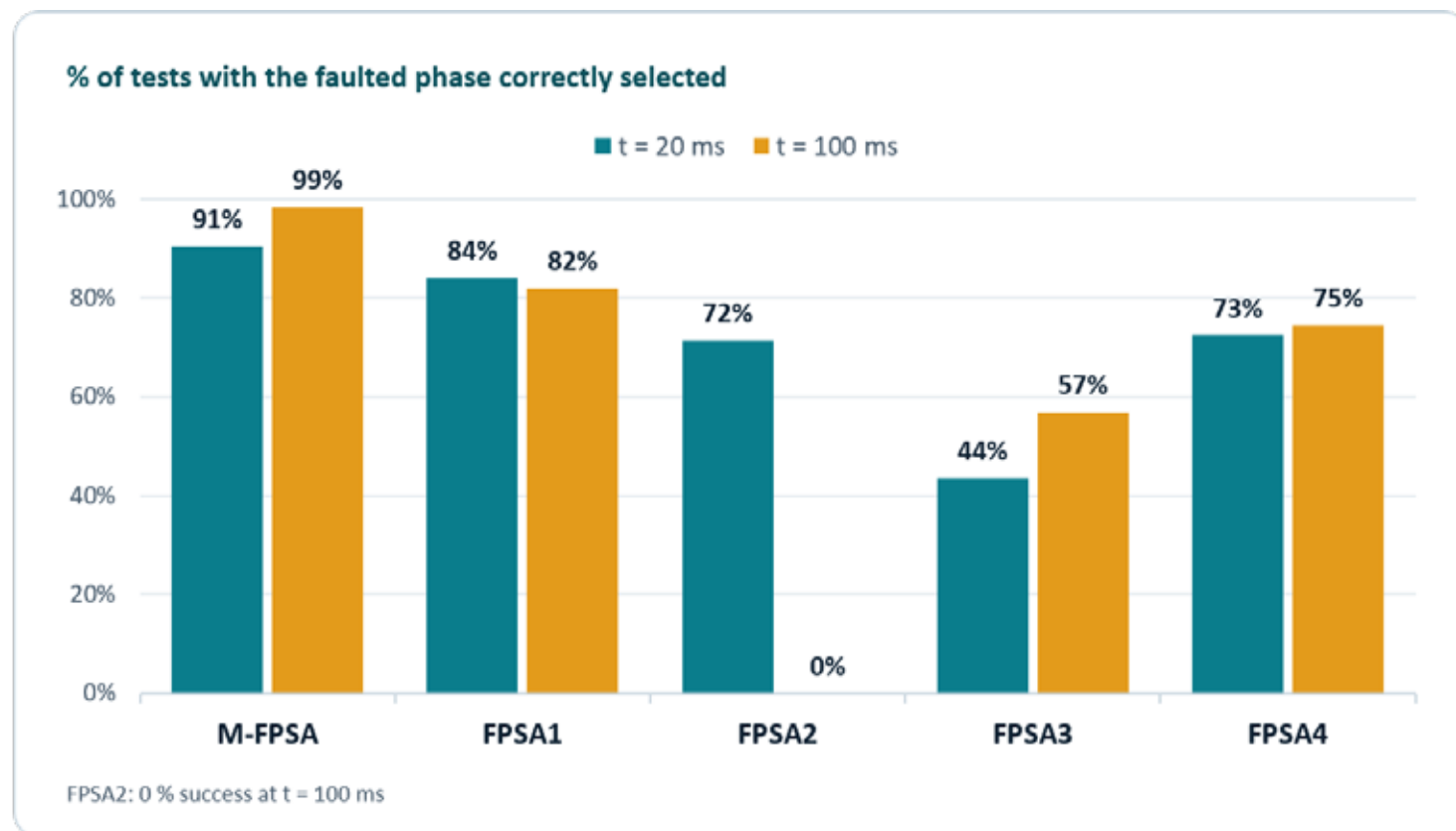


- FPS_1, FPS_2, FPS_3, FPS_4 : Relevant outputs of each method, using IEC61850 SV and GOOSE messages.
- FPS_MC : Relevant outputs of Multicriteria method, using IEC61850 SV and GOOSE messages.

[illegible]

Test case 2: Multicriterio FPS algorithm

q Test results



91 %

M-FPSA success rate at t = 20 ms

99 %

M-FPSA success rate at t = 100 ms

+7 / +17 pp

Margin of M-FPSA over the best single algorithm (FPSA1) at 20 / 100 ms

Combining the four FPS algorithms makes M-FPSA the most reliable selector in both time windows.

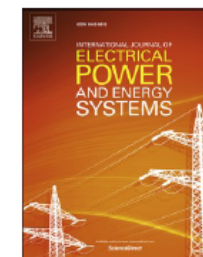
Electrical Power and Energy Systems 155 (2024) 109541



Contents lists available at [ScienceDirect](#)

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes



Faulted phase selection multicriteria algorithm implemented in generic hardware for centralized P&C in smart grids



María Teresa Villén Martínez^{a,*}, Maria Paz Comech^b, Anibal Antonio Prada Hurtado^a, Miguel Angel Olivan^a, Carlos Rodriguez del Castillo^c, David López Cortón^d, Rubén Andrino Gallego^d

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Villén, M.T.; Comech, M.P.; Prada Hurtado, A.A.; Oliván, M.A.; Castillo, C.R.D.; Cortón, D. L. and Andrino, R. "Faulted phase selection multicriteria algorithm implemented in generic hardware for centralized P&C in Smart Grids". International Journal of Electrical Power & Energy Systems, vol. 155, pp. 109541, 2024, doi: <https://doi.org/10.1016/j.ijepes.2023.109541>.

03.3

Test Case 3: Virtual PMU

Test case 3: Virtual PMU

q What is a WAMPAC system?

WAMPAC SYSTEM

APPLICATION

- SCADA FOR WAMPAC
- INTEGRATION FOR EXTERNAL TOOLS

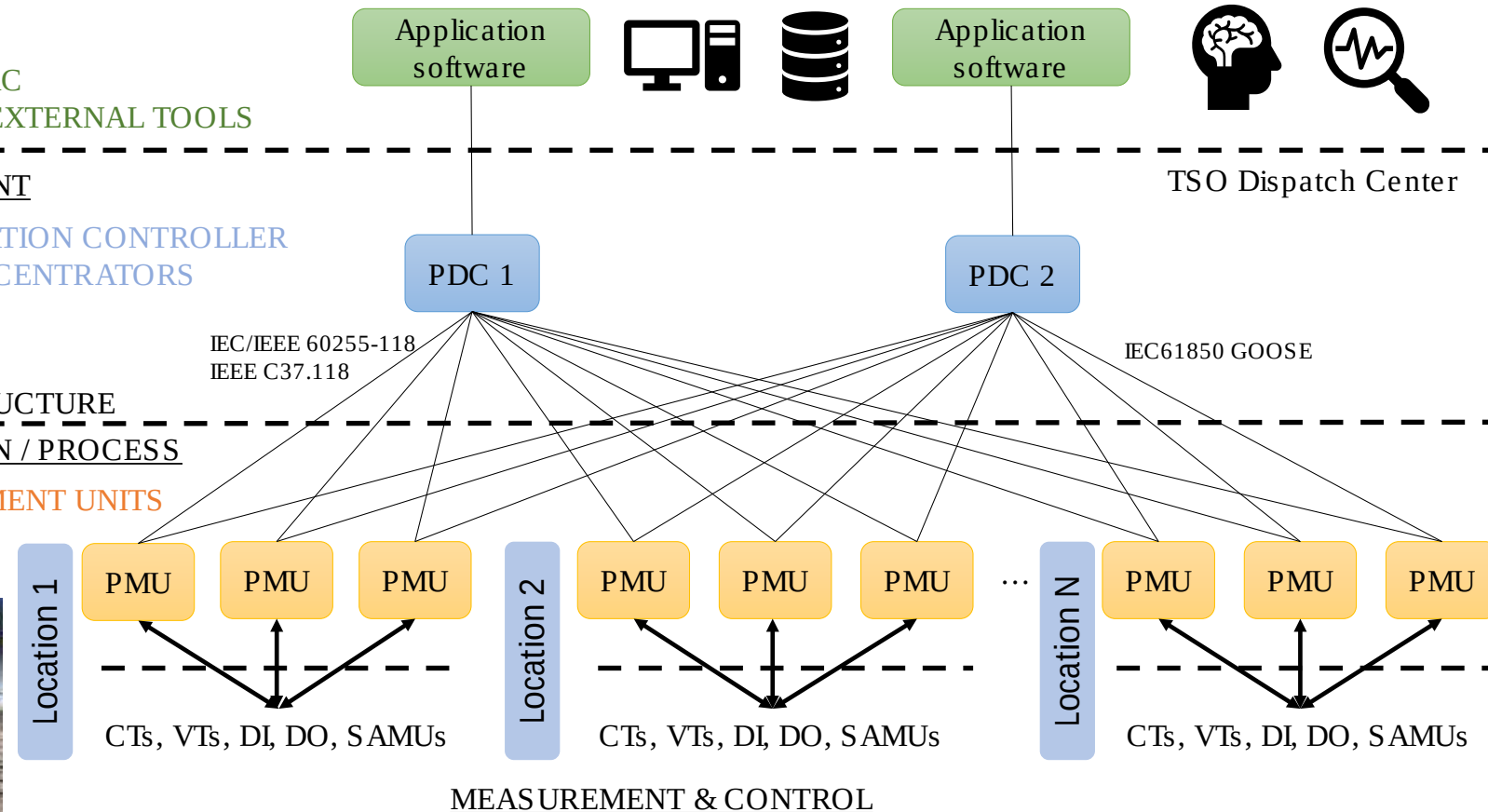
DATA MANAGEMENT

- REAL TIME AUTOMATION CONTROLLER
- PHASOR DATA CONCENTRATORS
- WAMPAC SERVICES

COMM. INFRASTRUCTURE

DATA ACQUISITION / PROCESS

- PHASOR MEASUREMENT UNITS
- ACTUATORS
- GPS SIGNALS



Test case 3: Virtual PMU

q How does it work?

- Conventional PMU

- Needs to have secondary voltages and currents wired.



SEL-AXION 2240

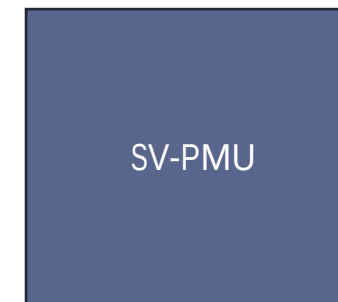
- PMUs in digital substations

- Must work with digital measurements, based on IEC61850 SV standard.



SAMU

+



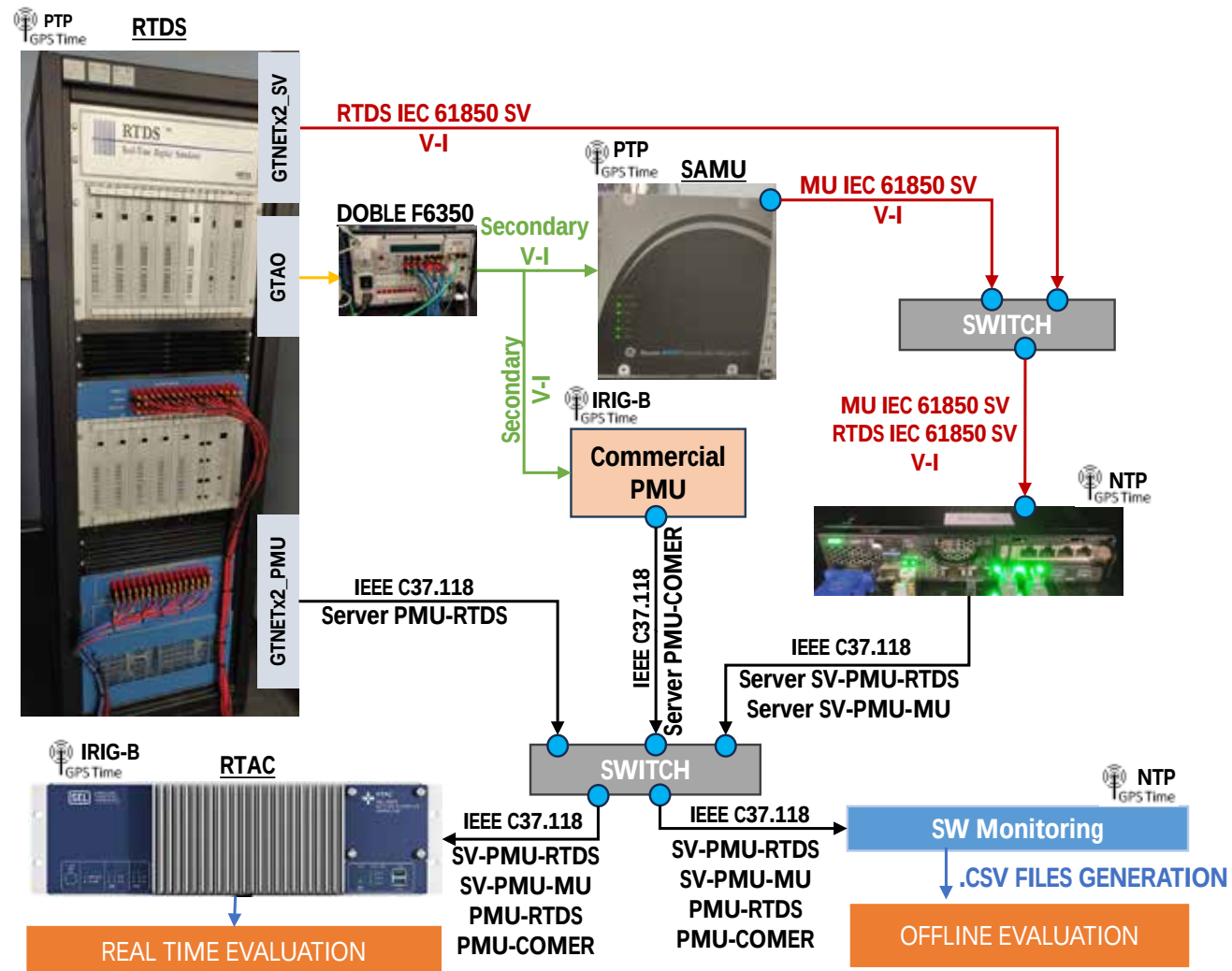
SV-PMU

WAMPAC Systems

Usefull to be deployed in digital substations on a Generic hardware server using the information provided by the SAMUs.

Test case 3: Virtual PMU

q How was tested?



Test case 3: Virtual PMU

q How was tested?

Tested in accordance with IEEE/IEC 60255-118-1:2018 standard

TVE, FE AND RFE VALUES, FREQUENCY TEST

PMU	Value	Max	Mean	σ	Inside limits
SV-PMU-MU	TVE (%)	0.781	0.5358	0.0958	p
	FE (Hz)	0.00126	0.000295	0.000206	p
	RFE (Hz/s)	0.071	0.015103	0.011874	p
PMU-COMER	TVE (%)	0.982	0.72	0.02369	p
	FE (Hz)	0.00088	0.000301	0.00016	p
	RFE (Hz/s)	0.102	0.036028	0.01951	p

TVE VALUES, MAGNITUDE CURRENT TEST: 10%

Current magnitude	Signal	Max TVE (%)	Mean TVE (%)	TVE σ (%)	Inside limits
SV-PMU-MU	Ia	1.126	0.347	0.1664	x
	Ib	1.518	0.628	0.2391	x
	Ic	0.864	0.247	0.1262	p
	Va	0.409	0.389	0.0056	p
	Vb	0.535	0.511	0.0061	p
	Vc	0.350	0.328	0.0059	p
PMU-COMER	Ia	0.973	0.395	0.1487	p
	Ib	0.899	0.305	0.1406	p
	Ic	0.778	0.250	0.1281	p
	Va	0.509	0.503	0.0017	p
	Vb	0.545	0.539	0.0016	p
	Vc	0.506	0.499	0.0017	p

All the TVE values related with 100 % and 200% current magnitude tests fulfil the standard requirements

LIMITS

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

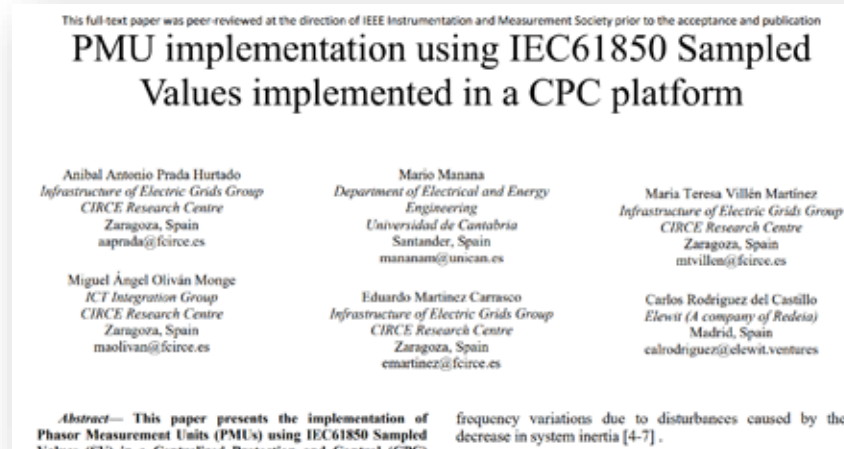
TVE, FE AND RFE VALUES, VOLTAGE MAGNITUDE TEST

PMU	Value	Max	Mean	σ	Inside limits
SV-PMU-MU	TVE (%)	0.546	0.52155	0.00638	p
	FE (Hz)	0.001003	0.000201	0.000155	p
	RFE (Hz/s)	0.069	0.014339	0.011474	p
PMU-COMER	TVE (%)	0.674	0.60104	0.01838	p
	FE (Hz)	0.00085	0.000304	0.000165	p
	RFE (Hz/s)	0.09559	0.035741	0.019148	p

TVE, FE AND RFE VALUES, HARMONIC TEST

PMU	Value	Max	Mean	σ	Inside limits
SV-PMU-MU	TVE (%)	0.823	0.792	0.0085	p
	FE (Hz)	0.003300	0.000722	0.000530	p
	RFE (Hz/s)	0.23384	0.05233	0.03983	p
PMU-COMER	TVE (%)	0.538	0.533	0.0016	p
	FE (Hz)	0.001026	0.000317	0.0001869	p
	RFE (Hz/s)	0.1286	0.0375	0.0223	p

Related Publications



2024 IEEE 14th International Workshop on Applied Measurements for Power Systems (AMPS):
PMU Implementation Using IEC61850 Sampled Values Implemented in a CPC Platform.
Link: <https://ieeexplore.ieee.org/document/10706693>



elewit

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 74, 2025

9514413

Implementation of a Virtualized PMU in a CPC Platform Based on IEC61850 Sampled Values

Anibal Antonio Prada Hurtado¹, Mario Manana², Senior Member, IEEE, Maria Teresa Villén Martínez¹, Miguel Ángel Oliván Monge¹, Eduardo Martínez Carrasco¹, and Carlos Rodríguez del Castillo¹

Abstract— This article presents the implementation of phasor measurement units (PMUs) using IEC61850 sampled values (SVs) in a centralized protection and control (CPC) platform called Elewit. The implementation allows for frequency variations due to disturbances caused by the decrease in system inertia [4-7]. 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.

IEEE Transaction on Instrumentation and MEasurement: Implementation of a Virtualized PMU in a CPC Platform Based on IEC61850 Sampled Values.

Link: <https://ieeexplore.ieee.org/document/10945521>

04

AI applications Datasets and Testing

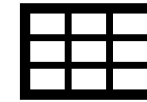
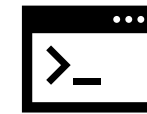
q Generation of Datasets



Power system in RSCAD
AC or DC grids

1. Generate the testing scenarios.
2. Format definition to store the datasets.
3. Script to generate automatically the testing scenarios and results.

Dataset used for Training and testing of the AI model



AI applications: Datasets

q Example of Datasets

.CSV file format:

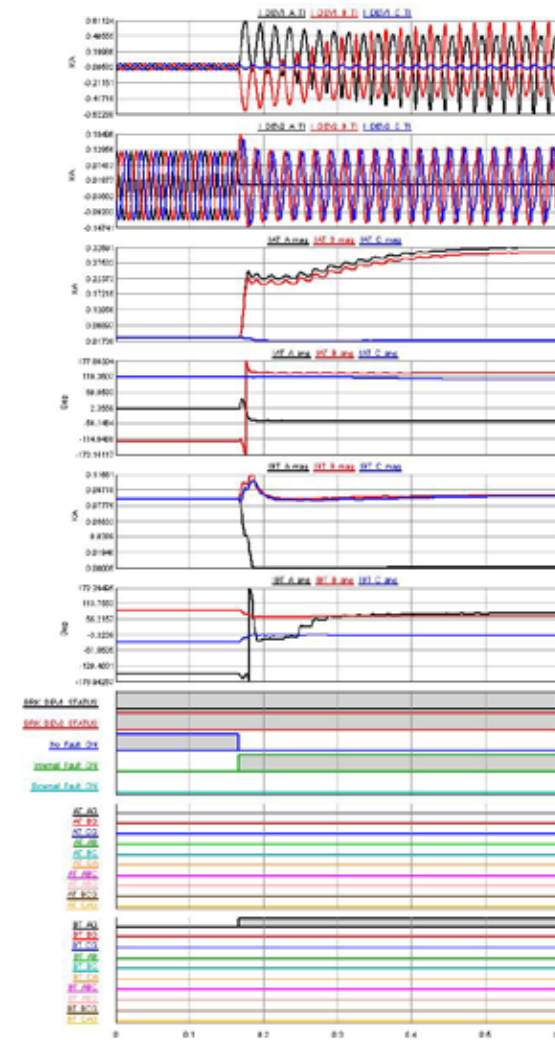
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Time	DEV1_A_T	DEV1_B_T	DEV1_C_T	DEV1_D_T	DEV1_E_T	DEV1_F_T	DEV1_G_T	DEV1_H_T	DEV1_I_T	DEV1_J_T	DEV1_K_T	DEV1_L_T	DEV1_M_T	DEV1_N_T	DEV1_O_T	DEV1_P_T
662	0.305	-0.007509	-0.0004273	0.006144	0.0438030	0.0788038	0.3297864	0	0	0	0	0	0	0	0	0	0
663	0.30525	-0.0077959	-0.0003206	0.0061285	0.025481121	0.0804630	-0.3179383	0	0	0	0	0	0	0	0	0	0
664	0.3055	-0.0079829	-0.0111041	0.0060871	0.0255790	0.0897290	-0.3133444	0	0	0	0	0	0	0	0	0	0
665	0.30575	-0.0054493	-0.013067	0.0074159	0.01619136	0.0803385	-0.3129524	0	0	0	0	0	0	0	0	0	0
666	0.306	-0.002846	-0.0160006	0.0077126	0.00679791	0.10133441	-0.3089754	0	0	0	0	0	0	0	0	0	0
667	0.30625	-0.003216	-0.02256	0.007776	0.00727172	0.1145946	-0.3082137	0	0	0	0	0	0	0	0	0	0
668	0.3065	-0.0062435	-0.0313029	0.0070664	0.00726921	0.12267273	-0.3057500	0	0	0	0	0	0	0	0	0	0
669	0.30675	-0.0045882	-0.0417729	0.0070643	0.0077309	0.13547796	-0.2783967	0	0	0	0	0	0	0	0	0	0
670	0.307	-0.00752343	-0.0538256	0.006764	0.0077795	0.14535554	-0.2583341	0	0	0	0	0	0	0	0	0	0
671	0.30725	-0.0065791	-0.0673925	0.0070594	0.00717890	0.15523660	-0.2433397	0	0	0	0	0	0	0	0	0	0
672	0.3075	-0.0072694	-0.0833393	0.0068118	0.00718380	0.1663883	-0.2307596	0	0	0	0	0	0	0	0	0	0
673	0.30775	-0.00504411	-0.0980966	0.0052935	0.00780186	0.18743359	-0.2165543	0	0	0	0	0	0	0	0	0	0
674	0.308	-0.00458356	-0.1161363	0.0051533	0.00667389	0.2156474	-0.2019009	0	0	0	0	0	0	0	0	0	0

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1	DEV1_STATUS	DEV2_STATUS	BT_AB	BT_BC	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB	BT_AB
662	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
663	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
664	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
665	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
666	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
667	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
668	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
669	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
670	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
671	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
672	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
673	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
674	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

	AK	AL	AM	AN	AO	AP	AQ	AR
1	IBT_A_ang	IBT_A_mag	IBT_B_ang	IBT_B_mag	IBT_C_ang	IBT_C_mag	Internal_Fault_ON	No_Fault_ON
662	-152.2033	0.0858234	87.79683	0.0858232	-32.2032	0.0858235	0	1
663	-152.2033	0.0858234	87.79683	0.0858232	-32.2032	0.0858235	0	1
664	-152.2033	0.0858234	87.79683	0.0858232	-32.2032	0.0858235	0	1
665	-152.2033	0.0858234	87.79683	0.0858232	-32.2032	0.0858235	0	1
666	-152.2033	0.0858234	87.79683	0.0858232	-32.2032	0.0858235	0	1
667	-152.2033	0.0858234	87.79684	0.0858232	-32.2032	0.0858235	1	0
668	-152.2033	0.0858234	87.79684	0.0858232	-32.2032	0.0858235	1	0
669	-152.2033	0.0858234	87.79684	0.0858232	-32.2032	0.0858235	1	0
670	-153.5363	0.0853953	88.0681	0.087157	-31.56218	0.0846041	1	0
671	-153.5363	0.0853953	88.0681	0.087157	-31.56218	0.0846041	1	0
672	-153.5363	0.0853953	88.0681	0.087157	-31.56218	0.0846041	1	0
673	-153.5363	0.0836095	88.0681	0.0898173	-31.56218	0.08343	1	0
674	-155.805	0.0836095	88.12534	0.0898173	-29.99067	0.08343	1	0

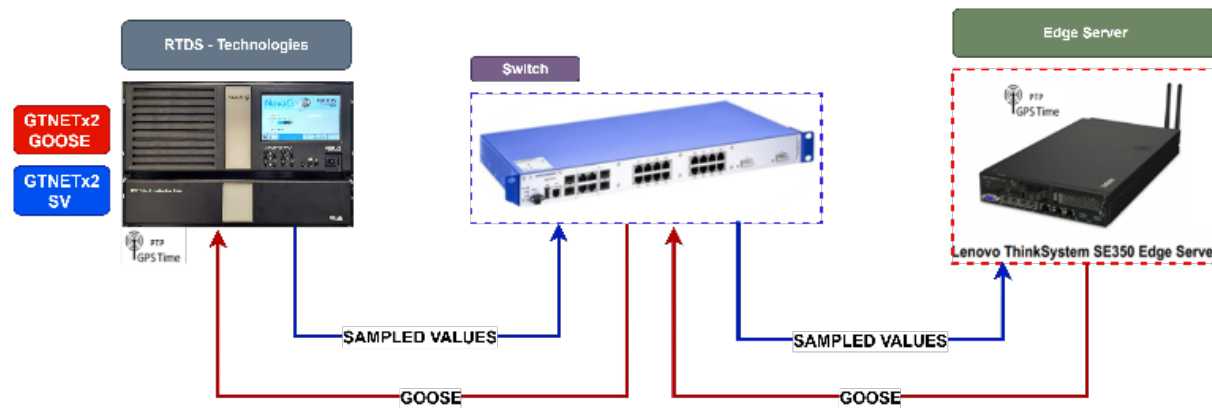
Each CSV file stores
time window
simulations

Each CSV file store a specific time window of the simmulation



AI applications: Testing

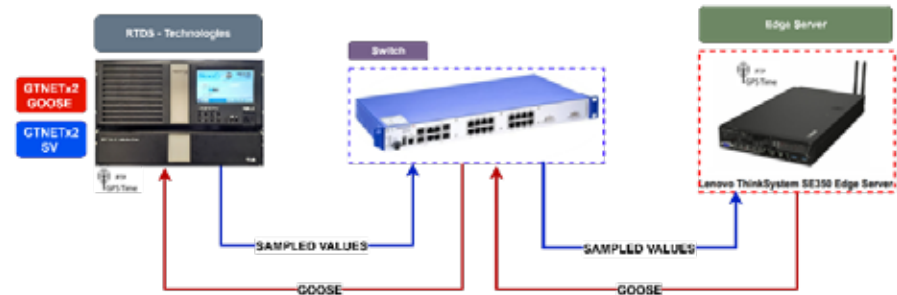
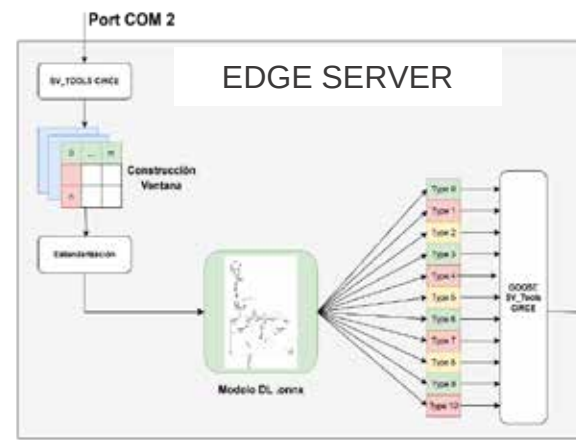
- q Testbed to evaluate the AI model behaviour after deployment in EDGE server



HIL chain: real-time EMT simulator, IEC 61850-9-2LE Sampled Values, edge inference and GOOSE output



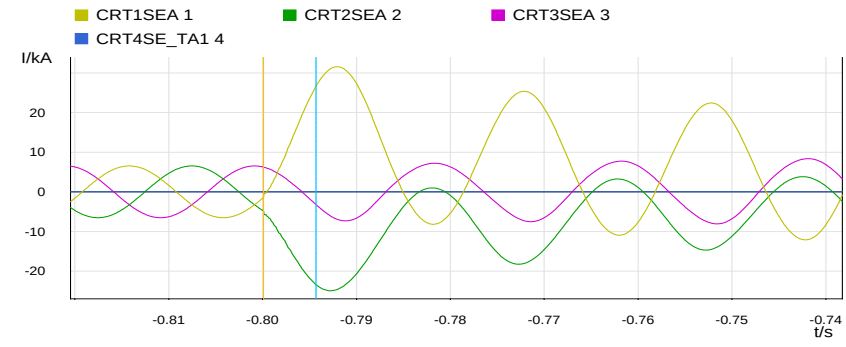
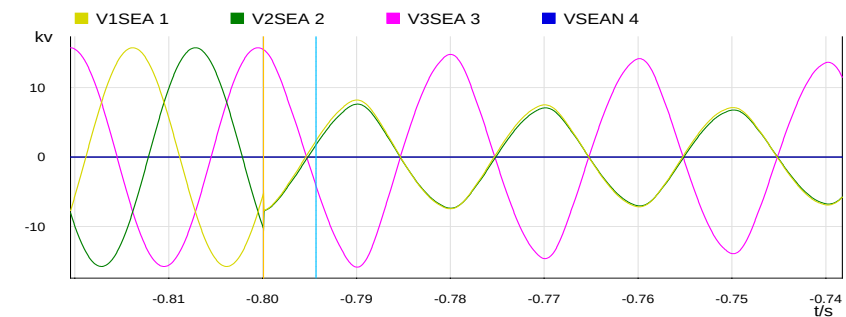
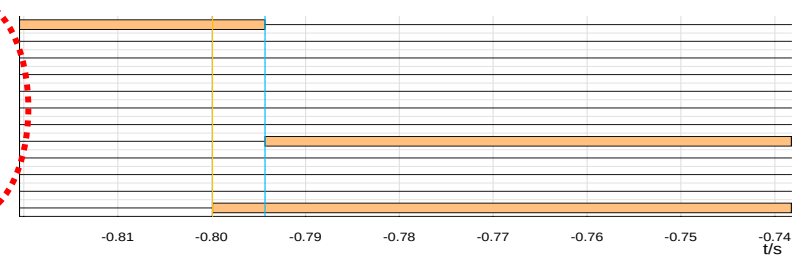
q Test results



Port COM 2
FPS - SLAG

- NOF
- SLAG
- SLBG
- SLCG
- DLABG
- DLBCG
- DLCAG
- LLAB
- LLBC
- LLCA
- LLL
- CIEFAL3

Resistive AB fault (R= 5Ω)





Paris Session 2026
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Palais des Congrès, Paris, France

11488

B5 PROTECTION & AUTOMATION

PS2 Protection and Control in Networks with Unconventional Sources Electrical

Deep Learning-Based Faulted-Phase Selector for Transmission Networks with High Renewable Penetration Level

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Guillermo Rios Gómez; Maria Teresa Villen Martínez; Anibal Antonio Prada Hurtado; Eduardo Martínez Carrasco. CIGRE Paris Session 2026. Deep Learning-Based Faulted-Phase Selector for Transmission Networks with High Renewable Penetration Level.

Link: <https://www.e-cigre.org/publications/detail/b5-11488-2026-deep-learning-based-faulted-phase-selector-for-transmission-networks-with-high-renewable-penetration-level.html>

Engineering Applications of Artificial Intelligence 168 (2026) 114093



Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai



Research paper

Hybrid Inception-Transformer model for signals classification: The case of electrical faults in power transformers

Elías Herrero Jaraba ^{a,b,*}, Eduardo Martínez Carrasco ^b, Anibal Antonio Prada Hurtado ^b,
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ARTICLE INFO

Keywords:
Deep neural networks

ABSTRACT

This paper presents a hybrid deep learning model for fault detection in power transformers, addressing the limitations of conventional protection schemes under transient operating conditions. The proposed model

Elías Herrero Jaraba, Eduardo Martínez Carrasco, Anibal Antonio Prada Hurtado, María Teresa Villen Martínez, Guillermo Rios Gómez, David Hernando Polo, Julio David Buldain Pérez, Hybrid Inception-Transformer model for signals classification: The case of electrical faults in power transformers, Engineering Applications of Artificial Intelligence, Volume 168, 2026, 114093, ISSN 0952-1976, <https://doi.org/10.1016/j.engappai.2026.114093>.

05

Other experiences

CIRCE' Services

Zone IIA protection.

Inertia estimation.

3Ph Shortcircuit MVAs estimation.

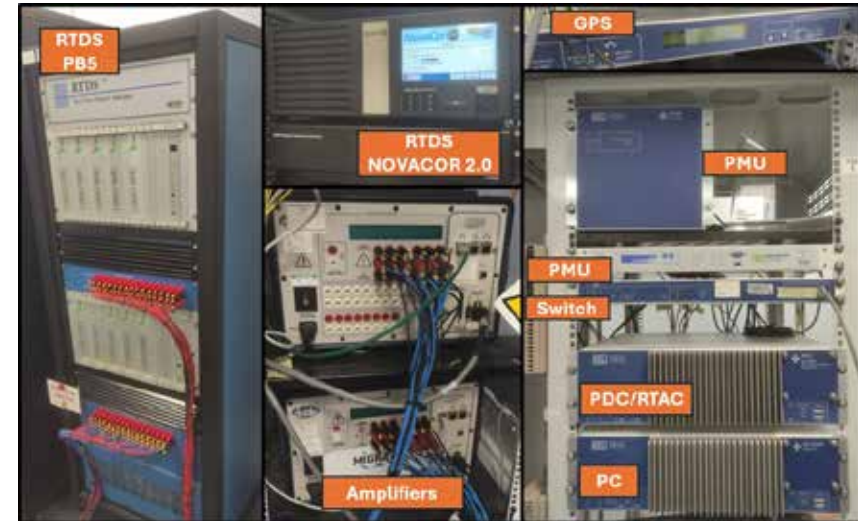
Voltage Instability detection.

Electrical Parameter Estimation Method.

Virtual PMU

CIRCE Marshal

New Developments





Thank you

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