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Secondary Injection Testing in Merging Units Considering Low Power Instrument Transformer Technology

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SUMMARY

All technological evolution in Protection, Automation, and Control Systems (PACS), driven by the advent of the IEC 61850 standard, has led to the implementation of several digital substations around the world. In this context, all information exchanges between IEDs (Intelligent Electronic Devices) from different manufacturers using the communication protocols defined by IEC 61850 demonstrate the importance of interoperability.

Furthermore, the relevance and criticality of the data transmitted on the Process Bus network are emphasized, with particular focus on time synchronization, achieved through the Precision Time Protocol (PTP), an essential feature in this context. In this scenario, the method of transmitting current and voltage information is modified through the use of Sampled Values (SV), whose implementation can be performed, for instance, using Low Power Instrument Transformers (LPITs), which provide low-voltage outputs and are inherently safer, connected to their respective Merging Units (MUs).

Thus, to contribute to the advancement and dissemination of IEC 61850-based protection systems, this paper aims to demonstrate the effectiveness of using LPITs and Merging Units.

Several closed-loop tests will be presented, in which low-voltage signals were injected into the Merging Unit inputs to simulate the outputs of LPITs based on Rogowski coils and capacitive dividers. The response of the Merging Unit was monitored through the Sampled Values output via optical fiber connection directly to the test set. The test results will be discussed in terms of linearity verification, SV frame interval, message integrity, sample loss or duplication, digitization time, amplitude and angle accuracy, and time synchronization.

KEYWORDS

Sampled Values, Process Bus, IEC 61850, Test Set, LPIT, Test Interfaces.

1 Introduction

Since its release more than two decades ago, the IEC 61850 standard has broken paradigms and explored new horizons, making the implementation of digital substations a reality today. The exchange of information between IEDs from different manufacturers using standardized communication protocols and mechanisms such as Sampled Values, GOOSE, PTP, and Client/Server (MMS), ensuring system interoperability, is one of the greatest contributions (if not the greatest) of the IEC 61850 standard to the power system.

In this context, the Process Bus stands out due to the critical nature of the protocols it carries: current and voltage information through SV messages, Trip commands and horizontal communication through GOOSE messages, and time synchronization through PTP messages.

Synchronization plays a fundamental role in this scenario due to the need for current and voltage signal sampling by the Merging Unit to be time-aligned, so that when reconstructing the waveform, the subscribing IED can ensure accurate phase angle measurement.

The advantages of implementing protection systems based on the IEC 61850 standard are related to safety, cost-effectiveness, simplicity, and interoperability. Safety, because data and not electrical quantities are handled in this context; cost-effectiveness, due to the replacement of copper cables with network cables and reduced infrastructure requirements in the substation's civil design; simplicity in wiring; and interoperability through standardized communications.

However, despite these advantages, adopting the standard also poses challenges, mainly because it represents a radical shift in traditionally adopted concepts and practices. For example, the Process Bus changes how current and voltage signals are read: what used to be measured from the secondary of conventional instrument transformers is now information published as SV messages on the network. This fact generates additional uncertainties and concerns regarding the adoption of the new technology.

The implementation of Sampled Values on the Process Bus can be done in two ways: by connecting the secondary of conventional instrument transformers to Stand-Alone Merging Units (SAMUs), typically installed in the switchyard near current transformers (CTs) and voltage transformers (VTs), or through LPITs and their respective Merging Units. The technology used for electrical measurement in these LPITs may vary, as well as the signal output format.

For current measurement, it is common to use low-power current transformers with Rogowski coils or optical measurement using the Faraday effect. For voltage measurement, resistive, capacitive, or resistive-capacitive dividers are usually employed. The signal output from these LPITs can be analog, with low-amplitude signals, or digital, using standardized or proprietary protocols. Once these signals are connected to the respective Merging Unit, the output is always standardized in the IEC 61850 Sampled Values format.

In this context of new technologies being applied to PACS based on the IEC 61850 standard, it is vitally important to structure testing procedures to ensure that the devices will perform their functions correctly in the event of a fault in the power system. Thus, even if the protection, automation, and control system consists of devices from multiple manufacturers, the reliability required for interoperability as defined by the standard can be guaranteed. Therefore, test equipment must keep up with technological advances and be capable of performing all required tests with accuracy and result reliability.

This paper addresses the different technologies used for current and voltage measurement in protection systems within the context of the IEC 61850 standard, using LPITs. The focus is to explore the use of LPITs and demonstrate their effectiveness. For this purpose, closed-loop testing methodologies will be presented, with low-voltage signal injection into the MU simulating the LPIT output, and SV message subscription in a test set via optical fiber connection. The secondary signal injection into the MU at Low Level was conducted in two ways: first, using an adapter that allows compatibility with test sets that do not natively implement LPIT output simulation, and second, using modern test sets with this functionality built in. The tests performed include verification of linearity, SV frame interval, MU digitization time, sample loss, duplicated or corrupted samples, and time synchronization, as well as accuracy in the amplitude and phase angle values of current and voltage data.

2 Low Power Instrument Transformers

Originally, power system protection was implemented using electromechanical relays, which required a relatively high amount of power for the mechanisms, that were connected to the secondaries of VTs (Voltage Transformers) and CTs (Current Transformers), to operate. The power needed to generate torque in an overcurrent relay disk, to pull the spring of a distance relay, etc., came directly from the secondaries of instrument transformers installed in the switchyard. In this context, having a current transformer secondary rated at 5A made perfect sense, as this nominal current level already provided enough power for all relay polarizations. In fault conditions, where current typically increases, the power available in the CT secondary for electromechanical relays would be even greater.

With the evolution of protection devices, especially from the advent of numerical relays, this power requirement at the CT and VT secondary is no longer necessary, since modern relays only need to measure a signal proportional to the voltage and/or current magnitude. The CT and VT secondaries no longer need to power magnetic circuits with springs, rotating disks, torque, etc., only the low-level signals are sufficient. However, due to previously established standardization, compatibility issues, retrofitting, and modernization of older systems, the 1A / 5A and 115V / 66.7V secondary standards have remained consolidated.

In Brazil, where the 5A CT secondary standard has historically dominated, many new installations are now adopting 1A secondaries, already showing progress in this regard. A 1A nominal secondary current requires less iron in the core for the same application. This also results in lighter CTs and potentially lowers the cost throughout the supply chain.

Conventional instrument transformers, which have iron cores, exhibit nonlinear responses under saturation conditions, potentially causing serious issues in the protection system. Modern saturation detection algorithms are employed in IEDs to mitigate problems such as improper operation or failure to operate. Another limiting factor of conventional CTs and VTs relates to their size and weight. Additionally, conventional CTs pose safety risks due to potential explosions. Figure 1 below illustrates an explosion caused by moisture ingress.

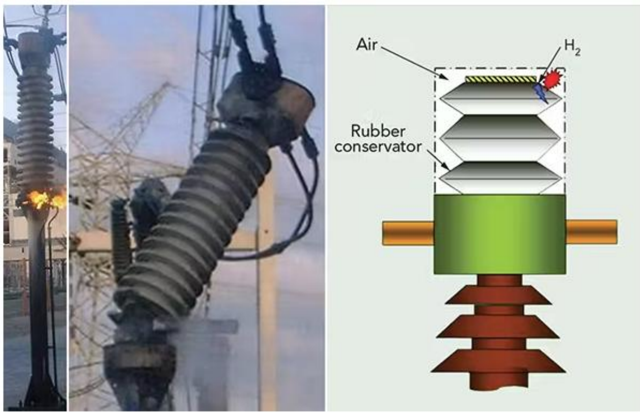

Figure 1 - Explosion of a CT due to Moisture Ingress

Non-conventional instrument transformers, among them Low Power Instrument Transformers (LPITs), offer optimized solutions compatible with the operational requirements of digital substations based on the IEC 61850 standard. These devices feature linear performance characteristics due to their coreless design, and they are more compact and lighter than conventional instrument transformers.

The operational and financial benefits of implementing LPITs are significant when compared to conventional CTs and VTs. Some of these benefits include:

- Infrastructure costs: Due to their smaller size and lighter weight, LPITs require smaller or even no foundations, as they can be mounted on existing structures. This leads to savings in civil construction costs. Additionally, optical fibers in these systems occupy less space than copper cables, freeing up the space formerly used for cable trenches in substations. Compact options for GIS (Gas Insulated Substations) are also available and already in use, reducing transportation costs and optimizing space.
- Operational flexibility: LPITs facilitate maintenance since the primary device can remain energized while the secondary device, such as a protection IED, is being repaired or inspected. This benefit increases availability in digital substations.
- Safety: Explosions of conventional CTs are not isolated incidents, they pose a real risk. However, LPITs do not present this explosion risk due to moisture ingress or overheating, as they do not contain oil or insulating gas. Furthermore, since they operate at low voltage, they do not require the secondary short circuit like conventional CTs, which greatly enhances substation safety and personnel protection.

For voltage measurement in a non-conventional VT, it is common to use resistive, capacitive, or resistive-capacitive dividers. For current measurement in a non-conventional CT, two technologies are typically used: Rogowski coils and optical measurement using the Faraday effect. One advantage of using Rogowski coil-based low-power CTs is their lower cost compared to optical measurement. However, the latter may offer greater immunity to noise and electromagnetic interference since it uses light. Depending on the shielding of the

Rogowski-based non-conventional CT, its geometry, and the physical arrangement of the elements, interference from adjacent circuit signals may occur.

LPITs can also be housed in the same enclosure, forming what is known as a combined instrument transformer. Figure 2 below illustrates a simple schematic: voltage measurement using a resistive divider (R1 and R2) and current measurement using a magnetic Low Power Current Transformer (LPCT) combined with a shunt resistor; where P1 is the primary current input and P2 is the primary current output.

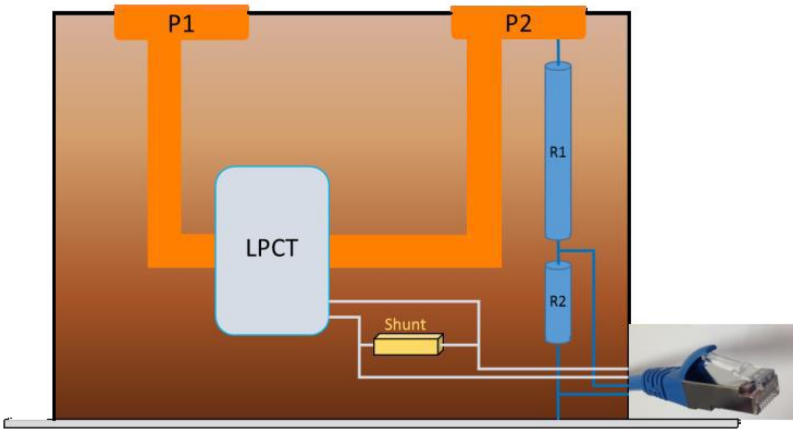

Figure 2 - Simplified Schematic of a Combined Instrument Transformer

IEC 61869 establishes that, for nominal current, the secondary voltage for measurement should be 22.5 mV / 150 mV / 225 mV, with the latter two values being more commonly found in Brazil. For nominal voltage, the measurement voltage should be 3.25/√3 V or 100/√3 V (1.88 V / 57.7 V, respectively), with the former being more commonly used.

3 Testing Tools in the Context of IEC 61850 Standard

Protection system devices can fail for various reasons, including hardware failures due to natural wear of electronic or mechanical components, as well as accidental damage. Failures may also originate from embedded software containing logical errors, or from incorrect parameter settings. Therefore, since devices are subject to failure, they must be tested periodically and after any update or maintenance procedure.

In traditional testing, it is common to use test sets that, through test interfaces, inject controlled secondary values corresponding to the conventional CTs and VTs characteristics, as well as primary values into the transformers, in that specific order. These tests allow for a comprehensive assessment of the protection system's performance, covering everything from wiring to logic and signals originating from the transformers, helping to reduce failures during normal operation.

In the context of digital substations, test tools must be capable of evaluating the entire protection chain, including instrument transformers, Merging Units, IEDs, and circuit breakers. Therefore, the test tool used must include analog functionalities, with current and voltage amplifiers, binary outputs, binary/analog inputs, low-power outputs, transducer measurements, among others. It must also implement the IEC 61850 communication protocols with GOOSE and SV publishing and subscription, PTP synchronization, as well as network monitoring and diagnostics.

Specifically for testing involving LPITs and MUs, even if a particular test tool does not have low-power outputs, it is still possible to use adapter tools that, in addition to providing convenient access to the Merging Unit's analog input terminals, simulate a three-phase LPIT. These adapter tools consist of calibration switches for panel mounting, test plugs, and a device that simulates the three-phase LPIT, referred to here as the LPA (Low Power Adapter). In this way, within the digital substation context, it is possible to perform all the well-established traditional operation tests with greater reliability and compliance with the standard.

Figure 3 illustrates a traditional power chain, in a simplified manner, the various testing combinations in which the test tool is essential to validate the system, involving both analog injections (primary level – P An; and secondary level – S An), and GOOSE and SV publishing/subscription. It is worth noting that the analog injections of primary values by the test set are linked to its hardware limits.

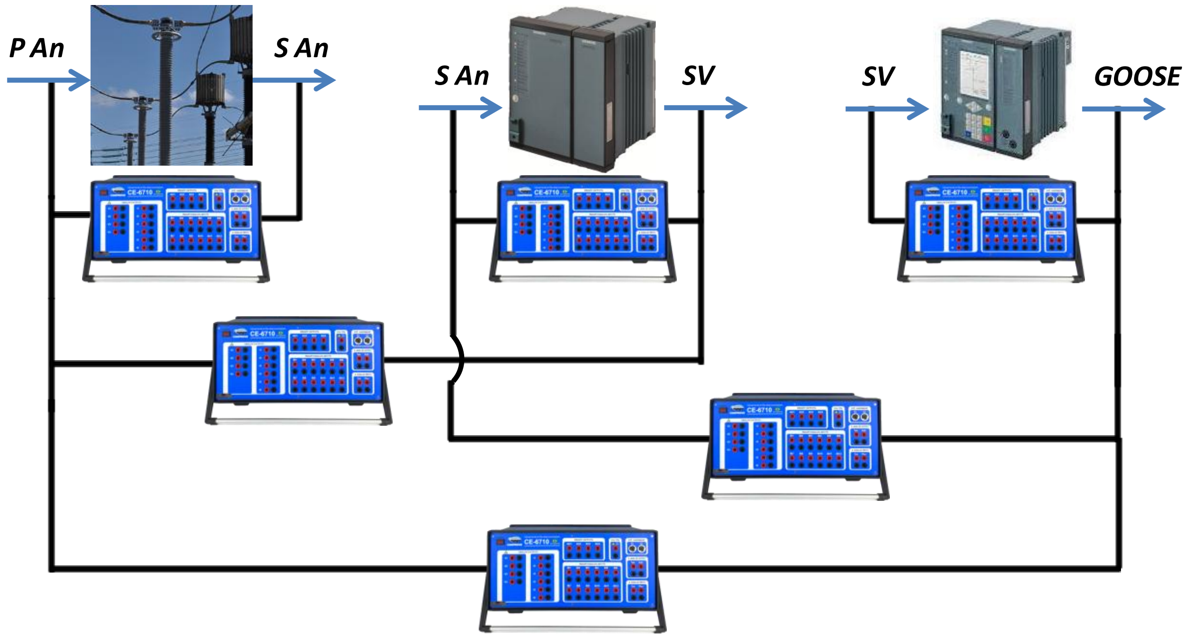

Figure 3 - Importance of Testing Tool in Various Test Combinations

On the other hand, when testing MUs with low-level inputs, Figure 4 shows a test setup in which the low-level outputs of the test set are connected directly to the MU. Figure 5 presents a test setup using an adapter tool with test devices that do not have low-level outputs, in a test scenario involving LPITs (simulated by the adapter tool – LPA) and Merging Units. The LPA adapts the voltage and current values injected by the test set on the primary side into low-power values on the secondary side. These values are then injected into the MU, which publishes the SVs to the IED.

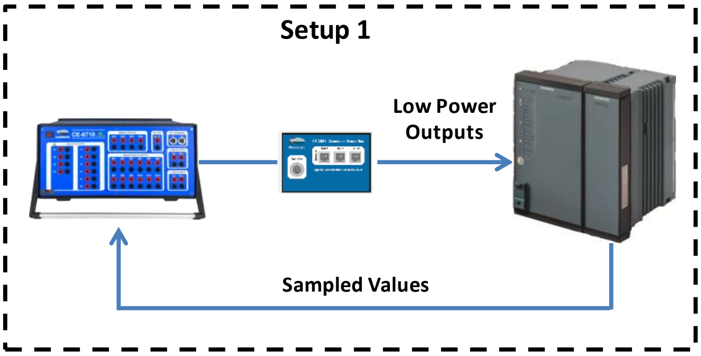

Figure 4 – First Test Setup: Test Set with Low Level Outputs

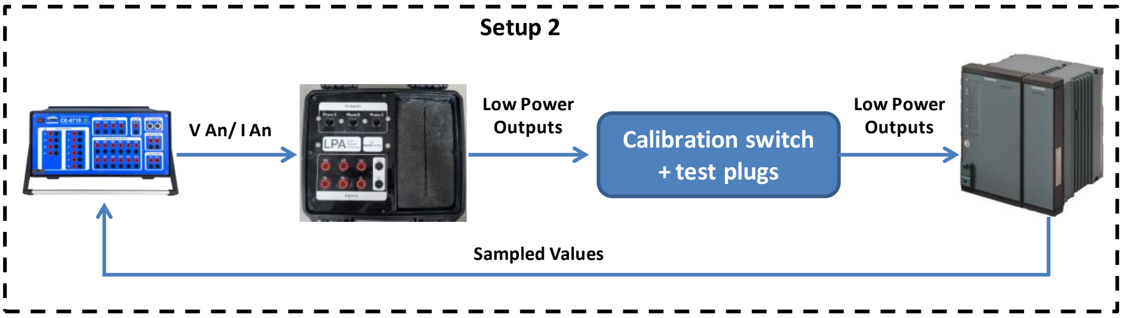

Figure 5 – Second Test Setup: Test Set without Low Level Outputs using LPA

4 Closed-Loop Tests with Merging Unit Considering LPIT Technology

4.1 Explanation of Test Setup

In order to address the use of LPITs as a non-conventional technology for voltage and current measurement in protection systems based on IEC 61850, and to demonstrate their effectiveness, several closed-loop tests were carried out using a test system composed of a test set, low power adapter, calibration switches and test plugs, and merging unit. Low-level signals were injected into the MU, and the published SVs were subscribed by the test set via optical fiber connection. System synchronization was achieved using PTP, with the test set acting as the Grandmaster. Two configurations were used to send low-power signals to the MU: one with the test set connected to the adapter tool set, and the other with the test set connected directly. Cases such as linearity, inter-frame time, MU digitization time, sample loss, duplicated samples, corrupted samples, time synchronization, and accuracy of amplitude and phase angle in the current and voltage data were analyzed.

For the tests carried out, LPITs that are not based on optical principles were considered.

A particular feature of the MU used is that it allows the direct connection of signals from Rogowski coils for current measurement, without the need for external signal conditioners. All signal conditioning and gain correction are performed by the MU through software parameterization. Similarly, the voltage measurement input is connected directly to the capacitive voltage measurement group.

To match the gain of each LPIT phase to the MU input, a JSON (JavaScript Object Notation) file containing all necessary parameters was used. This file is easily editable to allow fine adjustments, compensation, calibration, and more. Figure 6 shows an example of a JSON file used in the tests.

```
{
  "Id": "FB1_NCIT_Sensor",
  "Settings": {
    "RogoInduc": 1378.34,
    "RogoInducFac": 2000,
    "RogoResis": 199.0,
    "RgoInv": "no",
    "EFPCap": 9.92894,
    "ICorrection": {
      "fr50Phase": 0.0,
      "fr60Phase": 0.0
    },
    "VCorrection": {
      "fr50Phase": 0.0,
      "fr60Phase": 0.0
    },
    "SBProID": "none",
    "RogoTempCoe": [0,0,0,0,0,1],
    "EFPTempCoe": [0,0,0,0,0,1]
  }
},
```

Figure 6 - Example of JSON File Used in Tests

The test system consisted of two setups. The first setup used the test set connected directly to the MU, where low-power signals were injected. In this case, the test set is capable of importing JSON files and was specially modified to be compatible with the MU. Figure 7 illustrates the test set configuration screen.

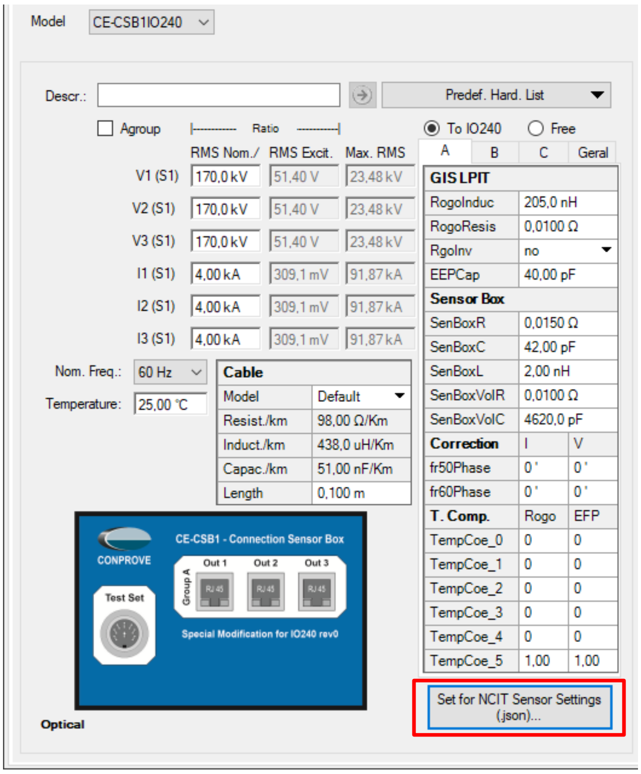

Figure 7 – Test Set Configuration Screen

The second setup used the test set connected to the low power adapter, the test plug, and the calibration switch. The JSON file was adjusted to match the low power adapter gains to the configuration already implemented in the MU.

4.2 Tests Performed and Results

Through these adjustments, injecting 100 V and 5 A into the low power adapter caused the MU to indicate nominal voltage and current values (100 kV phase-to-neutral and 500 A). Similarly, gains were defined for low-level signal injection directly into the MU's input using the test set. This allowed the tests to be carried out in a standardized way, enabling comparison of injected and measured values in both methods.

With these nominal values in mind, several tests were carried out to explore the technology's limits, varying amplitude, frequency, harmonics, interference, and crosstalk for analog tests, in addition to tests focused on SV message exchange.

Figures 8 and 9 show the two test system setups.

Figure 8 – First Test Setup (referenced in Figure 4)

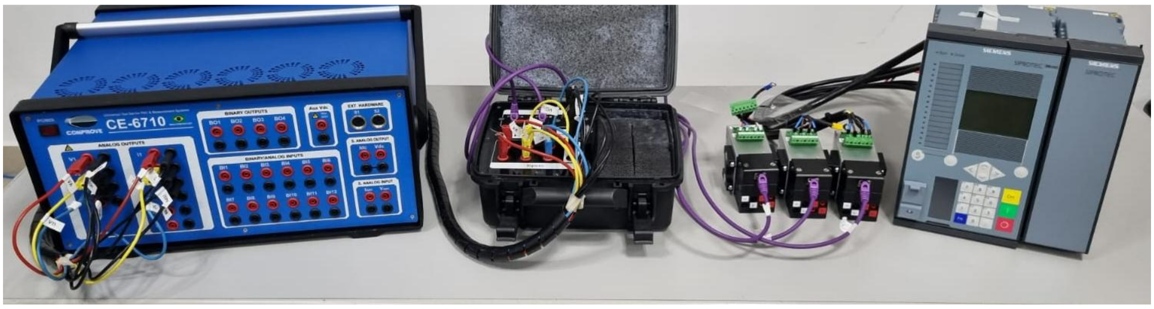

Figure 9 – Second Test Setup (referenced in Figure 5)

In both setups, injections were performed with varying amplitude, frequency, harmonic content, and angle, and the MU's behavior was observed for each test case. In all situations, the responses were similar between the two methods/setups used.

As the main test, a linearity test was conducted, focusing on the voltage and current inputs of phase A. The injected voltage varied from 10 Vrms to 200 Vrms, and the injected current varied from 250 mArms to 20 Arms. The voltage and current injection ranges were based on the nominal values of 100 V and 5 A. Therefore, a variation from 0.1 to 2 times the nominal voltage, and from 0.05 to 4 times the nominal current was established.

The objective of these tests was to evaluate the linearity of the amplitude and angle responses, as well as crosstalk between channels. The test was performed in both three-phase and single-phase configurations.

Figure 10 shows the results of linearity and the percentage error for voltage and current measurements, respectively.

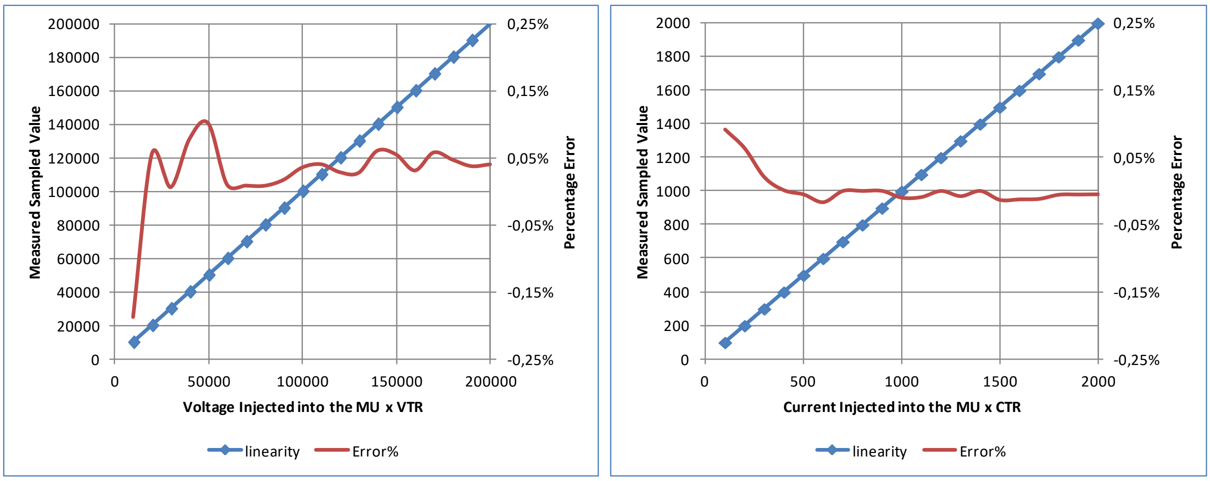

Figure 10 - Linearity and Percentage Error for Voltage and Current

The test set monitored the SV frames published by the MU, subscribing to and processing them to detect any failures, such as lost, duplicated, or corrupted messages. These parameters are important to verify in order to ensure that the Merging Unit is correctly publishing SV messages and that the network health is adequate. As a result, none of the aforementioned failures occurred during the 1,723,340 analyzed samples.

Additionally, the test set also monitored synchronization aspects of the MU, the interval between SV samples, and the digitization time. The test set acted as the Grandmaster of the network providing the global clock, and it was verified that the published SV samples were globally synchronized, indicated by "SmpSynch: 2".

The MU was configured with a 4000 Hz sampling rate. For a frequency rated at 50 Hz, and considering 80 points per cycle, this was correctly monitored by verifying an average frame interval of 250 µs, based on 1,723,340 samples.

Digitization time, or MU processing time, refers to the time the Merging Unit takes to sample the current and voltage signals and publish the SVs on the network. As the system was synchronized via PTP by the test set, and due to its highly accurate SV message processing algorithm, the test set monitored a stable digitization time averaging 1.287 ms, considering 431 samples. This result demonstrates that the sampling and publication times of the MU, along with network latency, are below the 5 ms threshold defined in IEC 61850-5 Ed.2, clause 11.2.4 Type 4 – Raw data messages ("Samples") and IEC 61869-9 Ed.1, clause 6.902.2 – Maximum processing delay time requirement.

Figure 11 presents the results of the monitoring of the Sampled Values frames published by the Merging Unit.

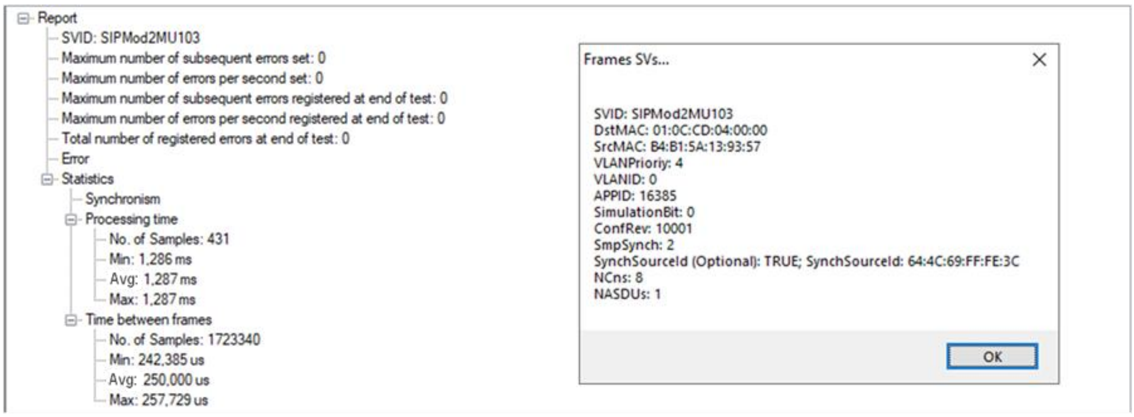

Figure 11 - MU SV Monitoring Results

The test set also subscribed to and processed the SV messages to verify whether the amplitude and angle values were within expected limits, performing oscillography and phasor analyses. Throughout all the tests with amplitude variation, the angle response remained practically constant across the entire range, indicating that amplitude had no influence on the angle response.

5 Conclusions

The major advantages of LPITs over traditional systems are their intrinsic safety, high linearity, immunity to saturation, smaller size, and lighter weight. Moreover, this is a well-established, proven, and reliable technology that has been employed for decades in low and medium voltage systems. Today, manufacturers successfully offer LPITs compatible with high-voltage substations, marking a significant technological shift.

Through closed-loop testing, injecting secondary current and voltage signals into a Low Power Adapter or injecting low power signals directly into the MU input to simulate an LPIT, and monitoring the SV output via optical fiber connection with the test set, it was possible to perform various analyses of current and voltage data in terms of amplitude and phase angle. Additionally, aspects such as synchronization, message integrity, packet loss or duplicate samples, and digitization time were verified. It was also possible to assess the ease of connection for these tests, conducted similarly to traditional secondary injection tests, thanks to the use of connection interfaces that preserved the low-voltage signals without influencing sample accuracy.

The results were satisfactory and demonstrate the reliability of the applied technologies. Moreover, they help expand the range of options available for protection projects based on IEC 61850. The use of connection interfaces between LPITs and Merging Units, along with test sets adapted to the IEC 61850 context, facilitates understanding, demystification, and easier adoption of the technology. It allows for secondary injection tests analogous to those already performed daily in traditional systems, including the reuse of existing procedures and routines, serving as a transitional bridge. Additionally, it was shown that modern test sets are ready to simulate LPIT low-voltage outputs, proving that current technologies are already prepared for safer and more robust systems to replace conventional current and voltage transformers.

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