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A3 – Transmission & Distribution Equipment
PS3 – Digitalisation of T&D Equipment

Optimized LPIT (Low Power Instrument Transformer) applications in GIS using SF_6 and climate-friendly insulating gas g^3

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SUMMARY

These last few years have shown increasing demands of new features in the electrical grid, such as the integration of renewables. These new features request adaptive solutions providing vital data to the system operator. Digital substations are a part of the answer. Some key elements of the digital substation are the Low Power Instrument Transformers (LPIT), allowing to provide accurate measurements of actuals status of current and voltage in a standardized format. The Technical Brochure B3-814 “LPIT applications in HV Gas Insulated Switchgear” [1] was published in 2020 and is providing guidelines and a collection of recommendations on various subjects related to this topic .

After the installation of several pilots more than fifteen years ago, some recent substations are now equipped with LPITs. An example for such a digital substation, based on climate friendly insulating gas g^3, has been presented in the Cigre Paper, B3-312 [2] in the 2020 session.
The digital protocols were not mature in the early days and start to become established and finally standardized by the IEC 61869. The requested accuracies are mainly 3P/5P for protection and 0.2/0.2S for metering. This can be reached by the same primary sensors for currents from a few A to several kA with complete linearity and no saturation. In compliance with the IEC 61869 standards [5, 6, 7, 8, 9], all the type test measurements are carried out in a controlled environment in the laboratories.

In this paper, we report on investigations of the measurement accuracy of LPIT for GIS insulated by pure SF_6 and using the new generation of climate-friendly insulation media g^3 ($C4\text{-}FN/O_2/CO_2$ mixtures) under different environmental conditions and exposition to severe electromagnetic conditions. The learnings to improve the accuracy of the measured values over a wide temperature application range of -40°C up to +80°C by applying correction to the measurements have been implemented and proofed.
The GIS environmental conditions, typically temperature variations may affect the primary sensors directly or cause variations in the gas pressure. The primary sensors have been tested in climatic chambers to obtain the, by design minimized, thermal drift of the measurement accuracy. Based on these tests and further investigations on the behaviour of the insulating gases, the parameters could be

retrieved to apply compensation methods, improving the metering capabilities over a range of applications covering essentially all expectable operating conditions.
These compensations have been implemented in a 145kV GIS and tested live in laboratories by recreating the temperature and density conditions. The accuracy of the GIS Low Power Voltage Transformer (LPVT) with the two insulation gasses SF_6 and g^3 has been tested simultaneously in the same climatic chamber applying temperature cycles between -25°C and 55°C.

The electrical environment of the GIS may also influence the measurement accuracy of LPIT, therefore the full measuring chain was exposed to severe electromagnetic conditions. To complete the overview, parts of the results to prove the immunity of potential interaction of voltage vs. current and phase-to-phase crosstalk injecting high currents (up to 3000A), high voltage (up to 275kV) at rated frequency and lightning impulses (up to $650kV_{peak}$) are displayed in the paper.

KEYWORDS
GIS, LPIT, Low Power Instrument Transformer, g^3, C4-FN mixtures, IEC 61869, IEC 61850-9-2, improved measurement accuracies by application of compensation algorithm

1. Introduction

The demand for precise real-time current and voltage signals to control the operational state of the future electrical grids is increasing. Low power instrument transformers (LPIT) as an important part of digital substations can provide more and more accurate measurement data. This paper investigates measurements for LPIT integrated in GIS using pure SF_6 and the new generation of climate-friendly insulation media g^3 (C4-FN/O_2/CO_2 mixtures) in different operating conditions like varying temperature, the influences of external electrical and magnetic fields.
The guidelines and recommendations published in the Technical Brochure B3-814 “LPIT applications in HV Gas Insulated Switchgear” [1] and the IEC 61869 standard series [5, 6, 7, 8, 9] have been applied.

2. The basic principles and investigations on the measuring chain

The verification of the basic principle of the measuring chain has been done in the years 2000 to 2004. The setup was made by a precision current and voltage- measurement on **Rogowski Coils** and **Capacitive Voltage Dividers.** To determine the performance of the basic design a direct output of the sensors was compared to reference measurements.
In a further step the output of the primary sensors has been digitized in a proprietary format by primary A/D converter units and the followed conversion has been done in a merging unit to low power analog signals and digital IEC 60044-8 format [8]. Several test campaigns have been performed in a climatic chamber by testing the sensors itself or the full measuring chain by applying variations of voltage, current and temperature.

2.1. The design and its basic capability

The primary sensor for current measurement is a non-saturating Rogowski coil on a printed circuit board (PCB) located outside of the gas compartment of the GIS, the undistorted, hysteresis-free output signal is a voltage proportional to the first derivate of the primary current.
The voltage measurement is using capacitive dividers arranged concentric around the high voltage primary conductor inside the gas compartment of the GIS. The high-voltage conductor and the electrode form the high-voltage capacitance part "C1" of the divider. The electrode is arranged on a PCB and separated from the enclosure, "C2". The signal amplification and the precision capacitor "C3" is implemented in the main electronic measuring path.

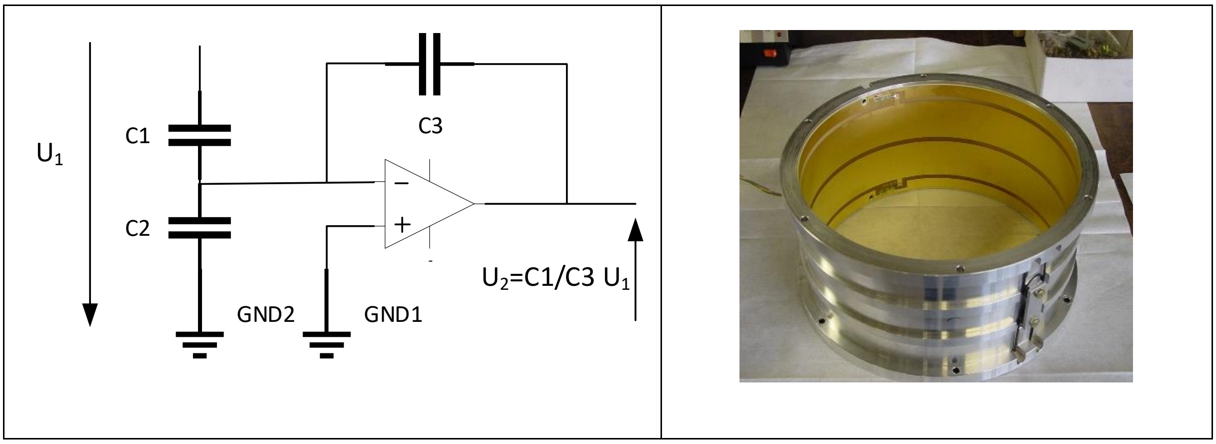


Figure 1 – Capacitive dividers for GIS;
Left: Measurement principle
Right: Measurement electrode for a single-phase bus

In the Figure 2 the complete assembly of a combined LPIT is shown, consisting of redundant Rogowski coils and redundant capacitive dividers. The assembly is part of a single-phase encapsulated GIS, rated for 245 kV, 50 kA. This measuring instrument can be implemented inside a GIS at any position in the layout since it is used as a part of the current flow through the overall switchgear.

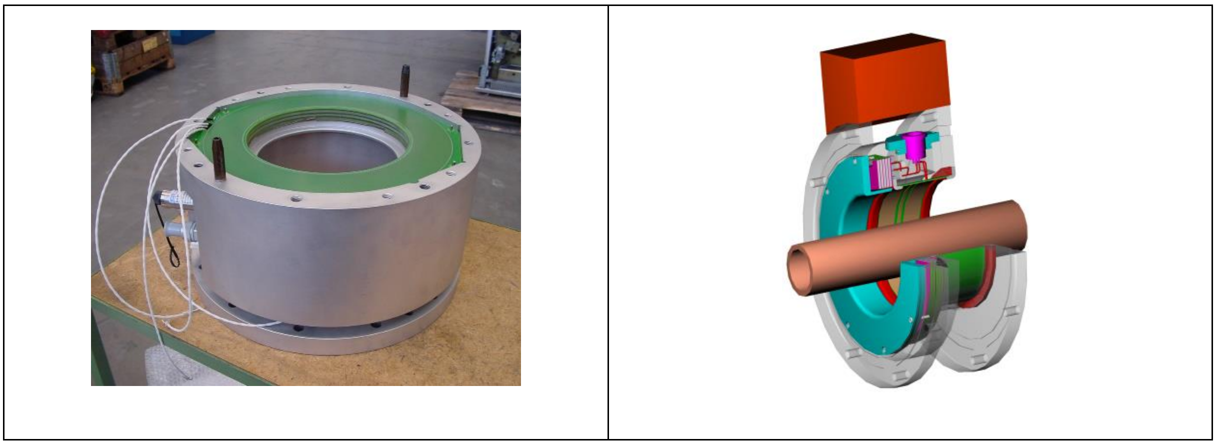
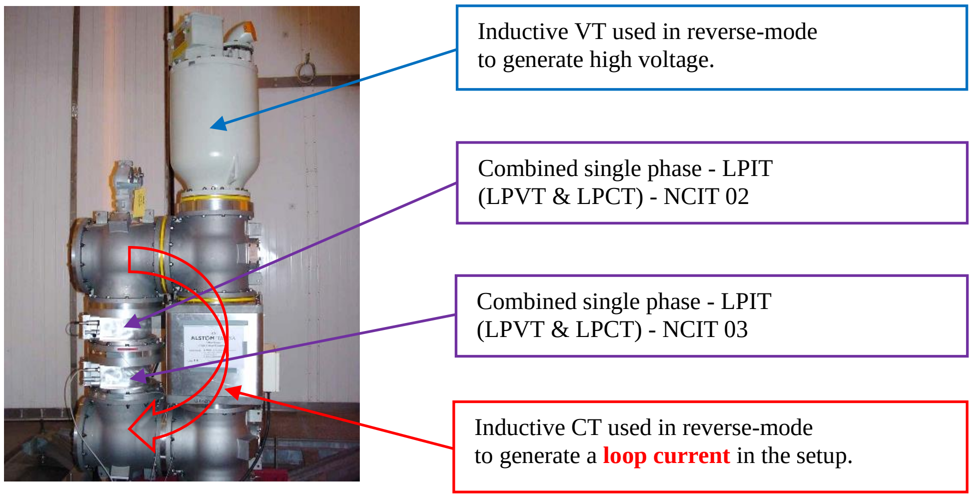


Figure 2 – Left: Redundant Rogowski coils
Right: Complete assembly of an LPIT

Several technical optimisations have been chosen and applied to achieve a low thermal drift for the primary passive sensors, (Rogowski coils and capacitive voltage divider). The sensors itself were capable to achieve accuracy classes with <0.2% error over a wide temperature range. The Figure 3 shows a full setup of a single-phase GIS arrangement, consisting of a loop with a conventional CT, used to create primary currents of up to 4’000 A and a conventional voltage transformer, that could create high voltages up to 245kV/√3 in the main circuit by reverse injection through the secondary terminals.



Inductive VT used in reverse-mode to generate high voltage.

Combined single phase - LPIT (LPVT & LPCT) - NCIT 02

Combined single phase - LPIT (LPVT & LPCT) - NCIT 03

Inductive CT used in reverse-mode to generate a **loop current** in the setup.

Figure 3 – Single phase encapsulated GIS, type GIS B105-3 (245kV/50kA) combined LPIT in the climatic chamber, CERDA (F) Laboratories - November 2002

The thermal drift characteristics in the capacitive divider for example were minimized by choosing the appropriate materials and their combinations of primary conductor, flange material and sensor design. The results of the measurements showed the achievement of magnitude errors below 0.2% and phase error far below 10 minutes.

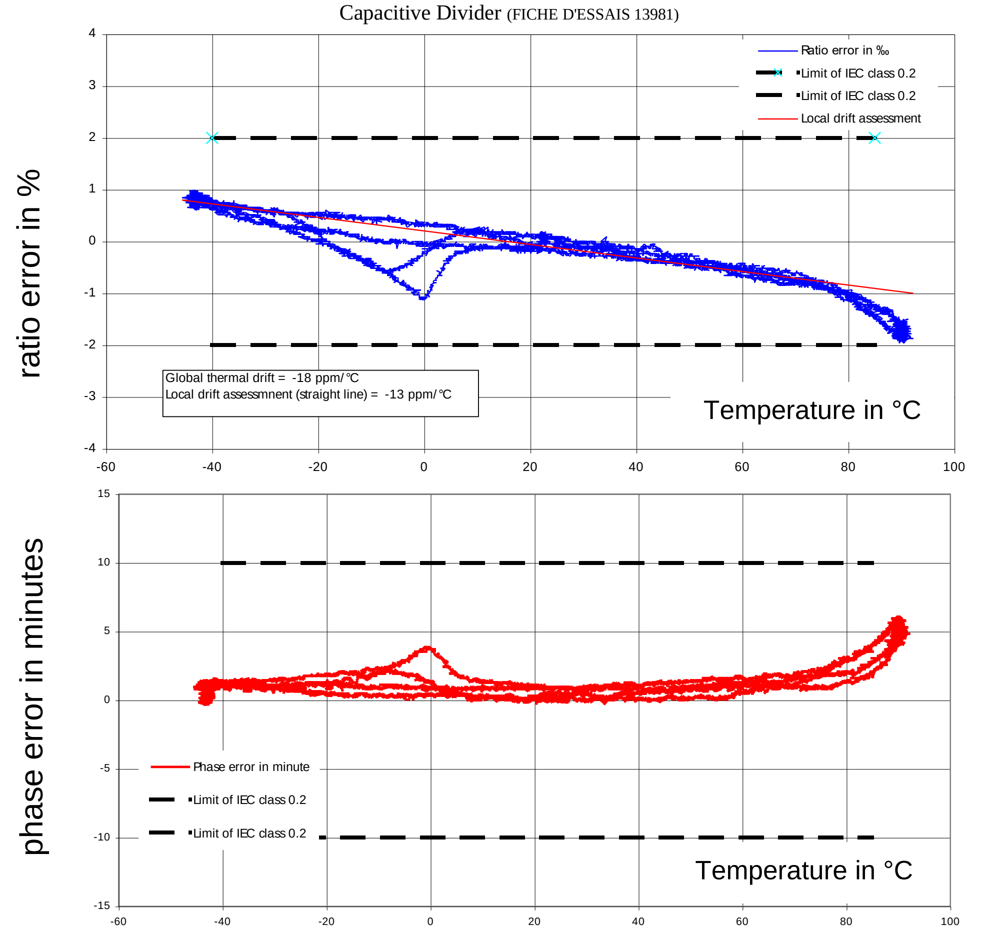


Figure 4 – Temperature vs. magnitude and phase error for capacitive divider Results of the primary sensors, CERDA (F) Laboratories - (2000 – 2004)

The graphs in Figure 4 and 5 represent an extract of the obtained results at that time in 2000-2004. The magnitude and phase error for both the Rogowski coil and the capacitive divider over a temperature range from -40°C up to +80°C compared to conventional reference current and voltage transformers showed slight temperature dependency due to the practical limitations in the design.

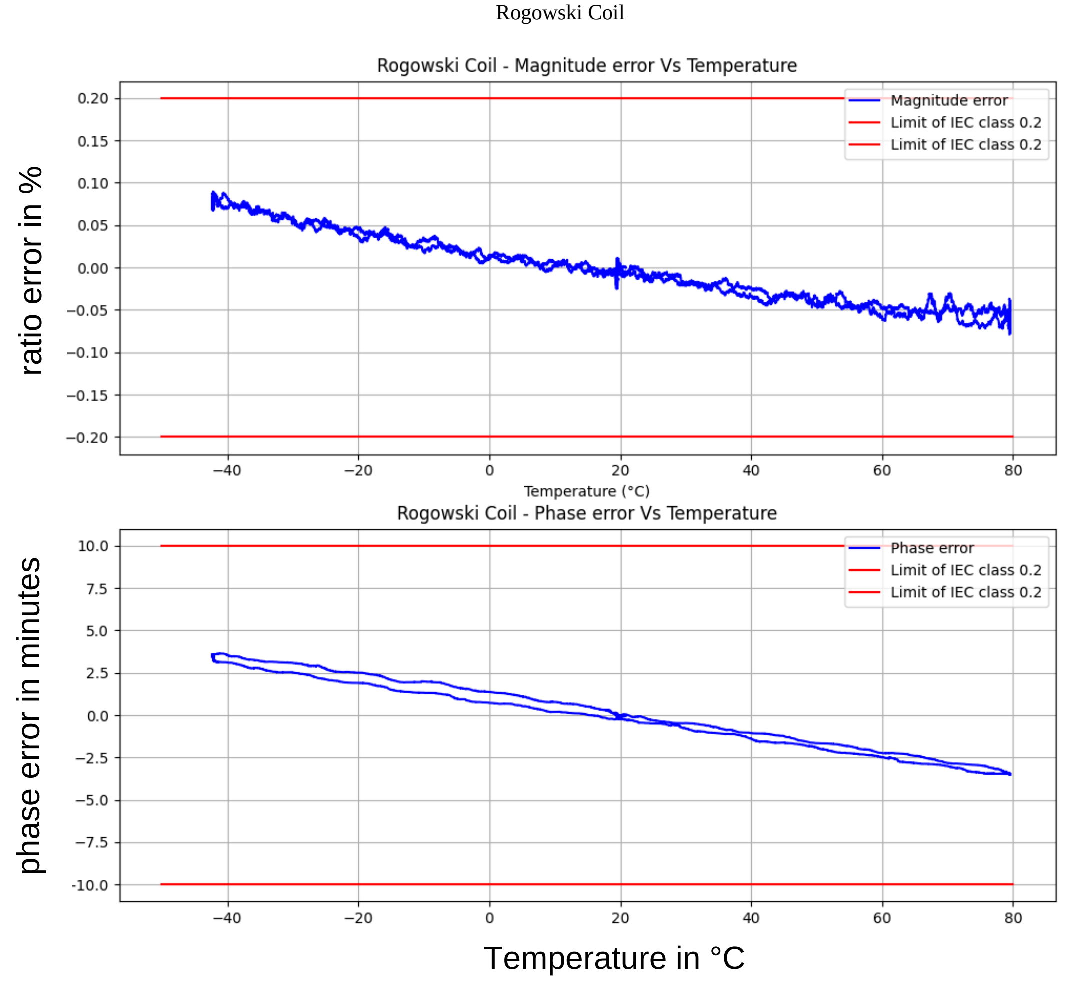


Figure 5 – Temperature vs. magnitude and phase error for Rogowski coil
Results of the primary sensors, CERDA (F) Laboratories - (2000 – 2004)

2.2. Investigation tests in the power labs

The full measuring chain at that time was consisting of:

- Redundant primary sensors:
  - Rogowski coils for current measurement
  - Capacitive dividers for voltage measurement
- Primary converters, merging units (CVCOM) with low power outputs for protection and metering and optical conversion to not yet fully standardized IEC 60044-8 [8].
- Analog and digital distance protection relays with analog and fibre optic inputs, type MICOM P442.

During a circuit breaker test campaign in KEMA laboratories in the year 2003, two piece of combined voltage/current measurements “NCIT-02” and “NCIT-03” have been used as shown in the Figure 6 below.

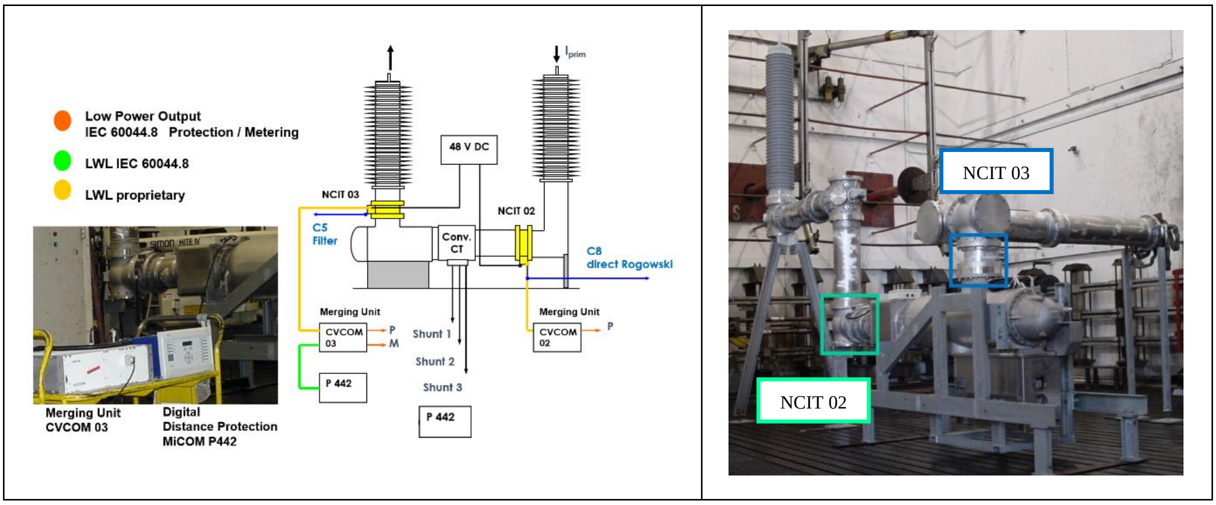
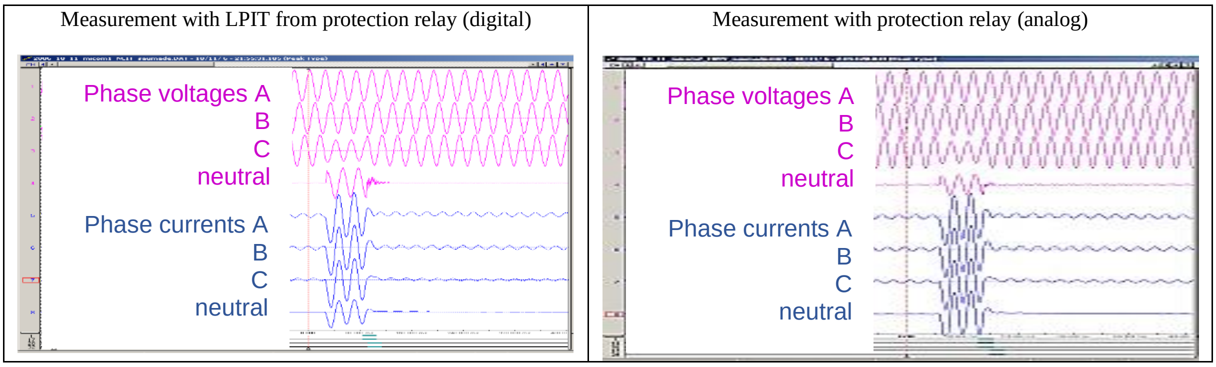


Figure 6 – Single phase encapsulated GIS, type B105-3 (245 kV, 50 kA) with combined LPIT during CB T100a breaking test in the KEMA Laboratories (NL) - 2003

The quality of the data by reading out the fault records in the two relays was satisfactory and this sequence has been properly detected and analysed by the two protection relays (MICOM P442), one using a digital input and the second using an analog one. The comparison is shown in Figure 7.


Measurement with LPIT from protection relay (digital)

Measurement with protection relay (analog)

Figure 7 – The results of the read-out of two independent protection relays of the same Close-Open sequence with the breaker (peak current values up to 135 kA)

3. Optimization

3.1. Determination of influencing parameters

A recent campaign has been performed to determine the temperature influence on the full measuring chain. The arrangement in Figure 8 was used to evaluate the temperature influence on the three-phase voltage measurement, using a climatic chamber. The equipment was filled with the rated density of the equipment. This GIS equipment is designed to work with SF_6 gas and with a climate-friendly gas mixture, g^3, consisting of a mix of C4-FN (also called Fluoronitrile, or Novec 4710), O_2 and CO_2. All parameters have been determined for both insulating gases. Furthermore, all the GIS components are designed to work with a rated, down to a minimum gas density level (or alternatively the corresponding pressures at 20°C). The gas-filled equipment may have a certain leakage over time, therefore the density or pressure levels may drop and are monitored over the lifetime of the equipment.

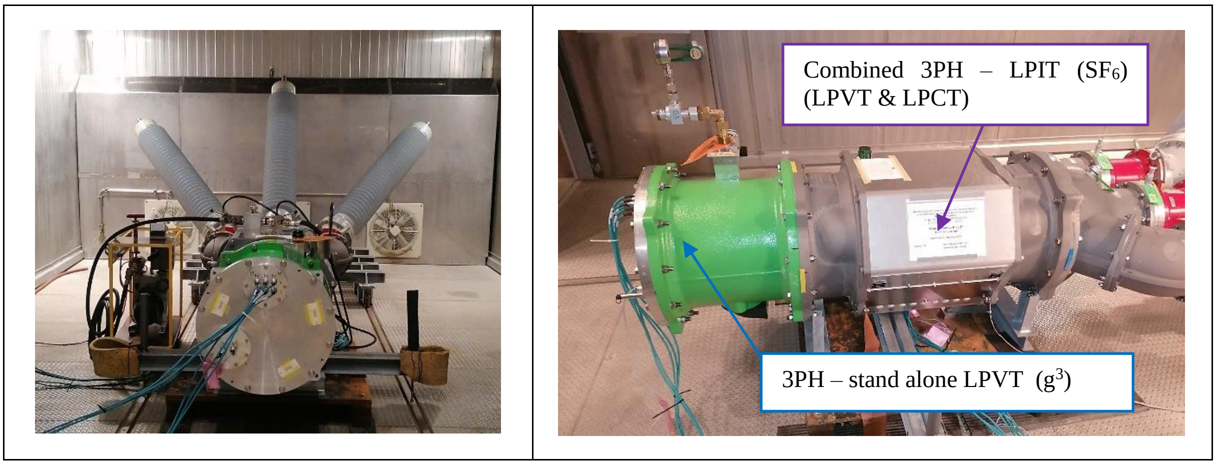


Figure 8 – Three phase encapsulated GIS, type F35 (145kV/40kA) combined LPIT in the climatic chamber, Cottbus Laboratories - November 2020

The full measuring chain contains basically the same items as in the original design used decades before in the first prototypes, but now in a three-phase encapsulated GIS arrangement with redundant primary sensors (Rogowski coils and capacitive dividers), primary converter units, and a merging unit with standardized IEC 61850-9-2 [4] fibre optical communication to the IED as shown in Figure 9 during the tests in the climatic chamber, Cottbus Laboratories (DE) in November 2020.

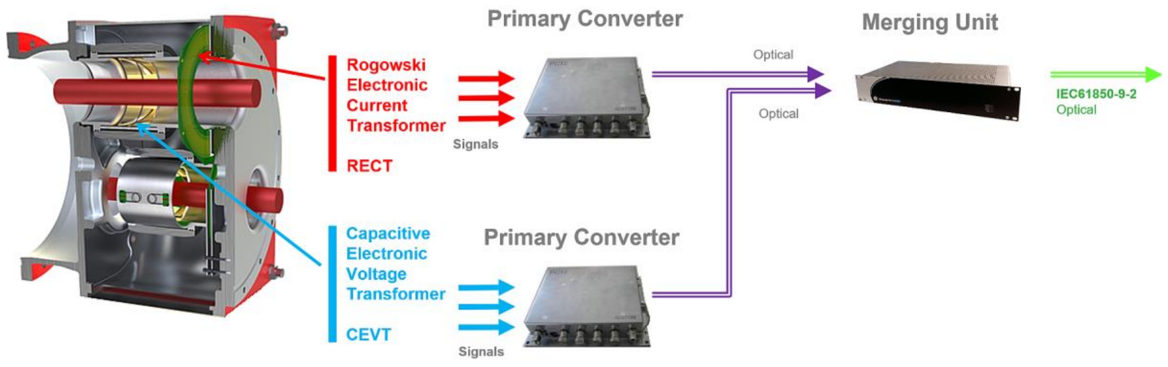


Figure 9 – Full measuring chain for current RECT and voltage CEVT according IEC 61850-9-2 of a three-phase encapsulated LPIT for GIS

3.2. Summary of influences

Figure 10 represents the measuring setup in the climatic chamber. The three-phase encapsulated GIS was equipped with air to SF bushings. High voltage was applied to two phases in parallel via the bushings (U_A and U_B), the third phase was grounded.

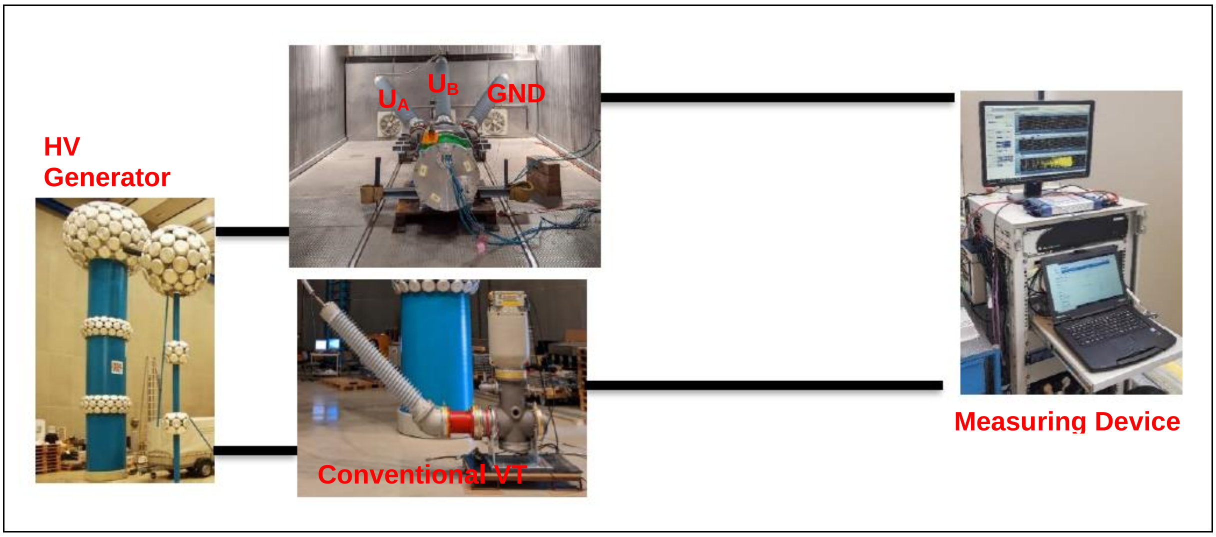


Figure 10 – Direct error measurement of LPIT in the climatic chamber relative to a conventional (VT) at 20°C, Cottbus Laboratories - November 2020

While applying the high voltage, the climatic chamber was going through some temperature cycles between -25°C and 55°C. The outputs of the digital LPIT voltage measurement (CEVT) of the two devices were compared to a conventional inductive metering 0.2 class voltage transformer (VT) at 20°C.

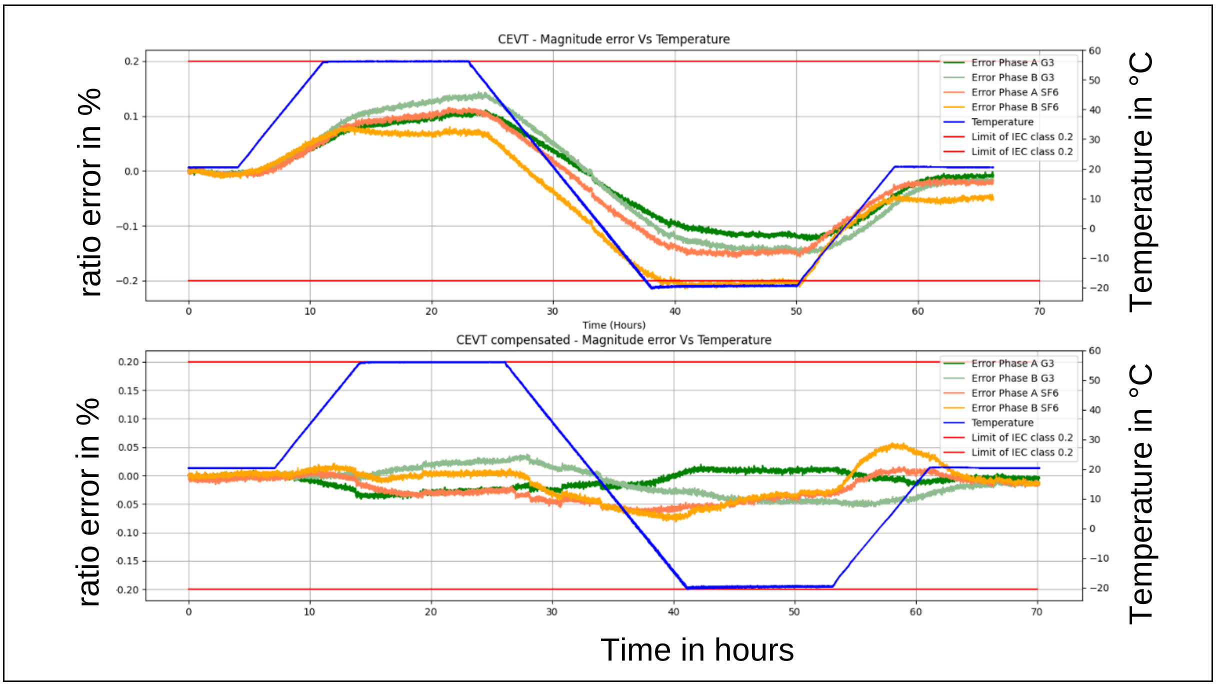


Figure 11 – CEVT in SF_6 & g^3 magnitude errors during temperature cycles
top: non compensated CEVT magnitude errors up to +/-0.2%
bottom: compensated CEVT magnitude errors within+/-0.08%

One LPIT device was filled with SF_6, whereas the other device was filled with a g^3 mixture (6% C4-FN, 5% O_2, 89% CO_2). The results displayed in Figure 10 on top showed the voltage sensor error in % vs. temperature. The full tolerance of metering class 0.2 was used. The graph in Figure 11 shows the voltage sensor error in % vs. temperature with an “active compensation”. The error remains within a remarkable low tolerance of +/-0.08% over the full temperature range.

4. EMC requirements

To assure a proper operation of the protection and measurement chains a strong immunity to external electromagnetic fields of LPIT is necessary. The potential effects with this type of coupling are a possible undesired trigger of a protection system e.g., in the case of differential protection, a leakage current may be detected despite it is not existing and, having set a low detection threshold in the protection relay, an unwanted tripping of the circuit breaker may occur. Under normal operating conditions a possible influence of the electromagnetic field to the LPIT may impact high accuracy measurements used for billing purpose.

In addition, high voltage tests are necessary to verify the behaviour in case of lightning and/or switching impulses. Regarding lightning strikes, the response of the system must be representative of the duration of the physical phenomenon so that it does not produce a lasting overvoltage which would cause a protection system to trigger inadvertently, thus leading to a loss of operation. Finally, a high voltage switching transient behaviour test is essential to complete EMC electromagnetic compatibility tests.

Various tests have been performed to distinguish the influence of the magnetic and the electric field to the measuring chain, cable lengths, orientation, and proximity of the primary converter units to the injected currents and applied voltages.

4.1. Immunity against the magnetic field

Using Electronic Current Transformers (ECT) based on the principal of a Rogowski-sensor integrated in a GIS, the performance concerning the immunity to the external magnetic field is a fundamental element. Having single-phase compartments there are return currents flowing in the housings of the high-voltage equipment. These return currents flow non-uniformly around the circumference of the GIS housing due to impedance imperfections and therefore parasitic coupling is possible. In the case of a three-phase encapsulated GIS, where the three phases are in the same gas compartment, the conductors of the three phases are relatively close to each other, compared to a GIS made up of single-phase enclosures. Consequently, the exposure of the ECT to the magnetic field caused by the currents flowing in the neighbouring phases is of a significant importance. Considering the elements of the entire measurement chain and not only the direct influence on the Rogowski sensor is important. Multiple tests have shown, that a bad choice of connection pad, cables, connection, or an improper design of the electronic input stage of the acquisition system can each cause additional errors.

In Figure 12, a stand-alone test setup in the lab was created to compare Reference Rogowski Coils, Precision Inductive Current Transformers to different Rogowski Coils under tests. The influence of any neighbouring current flows was investigated and potential influence on the Rogowski Coils under test. The design of the Rogowski Coils was optimized to mitigate any parasitic effects.

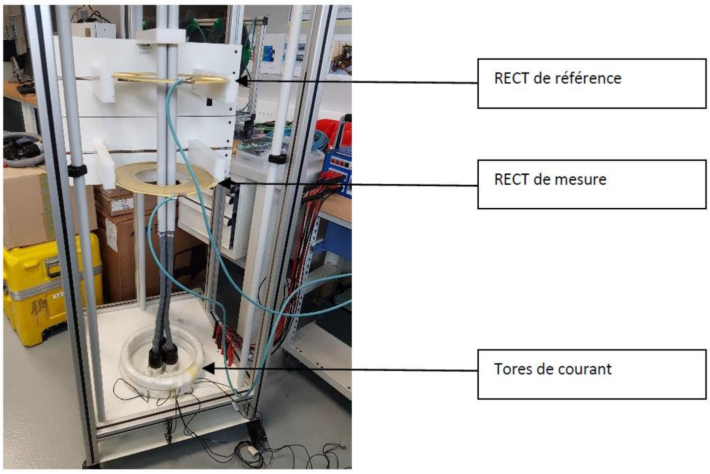


Figure 12 – High current injection and EMC influence of magnetic field to Rogowski Coils

The “crosstalk” or the impact for the electromagnetic field at rated frequency from other phases on the accuracy of ECT has been tested by high current injection on a combined three-phase LPIT representing the configuration of the real installation in the current transformer routine test laboratory as per Figure 13. Applying the proposed test procedure (Cigré B3.39 – TB 814 [8] / IEC CD 61869-8 38/655/CD [9]) the test has been carried out in two steps. In the first step the current is flowing through the primary conductor phase by phase, the influence of the neighbouring phases and the external return path can therefore be neglected. The ratio and phase error of the ECT under test are measured against a conventional standard current transformer. In the second step the current is flowing through two neighbouring phases at the same time (Phase A+B, B+C, C+A), the ratio and phase error on the metering channel of both ECT under test are recorded. Over the full primary current range the potential effect of the crosstalk was less than 0.06% for the ratio error (1/3rd of the permitted amplitude error) and lower than 0.5 min phase error was achieved (1/3rd of the permitted phase error). The measurement of the voltage channels has not shown any measurable disturbances during those procedures.

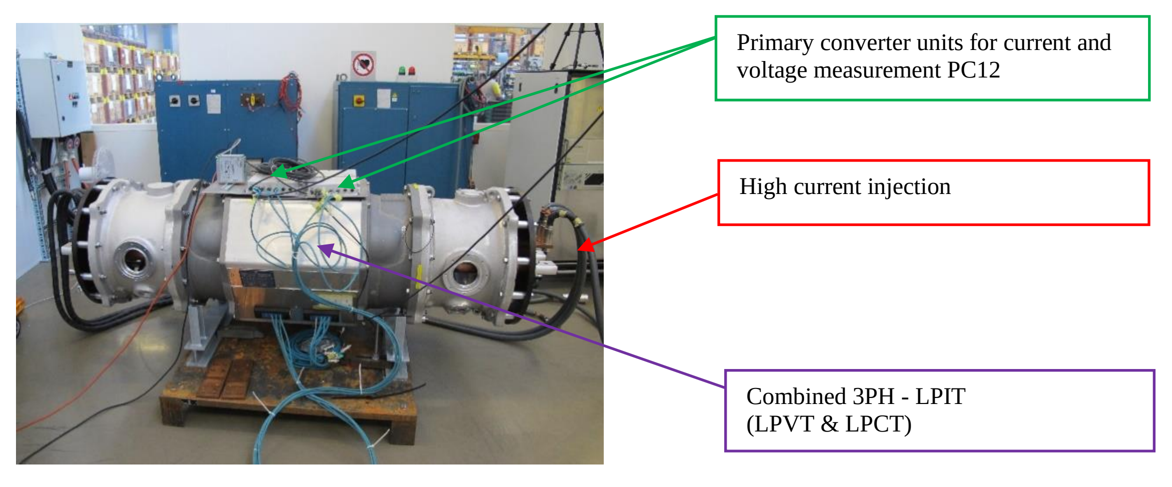


Figure 13 – High current injection and EMC influence of magnetic field to primary electronics in GE routine test area (ISO 17025), Oberentfelden (CH)

4.2. Immunity against the electric field

AC test

During the dielectric type-tests of a combined three-phase LPIT and a three-phase stand-alone LPVT, the influence of the electric field on the ECTs of the phase under test and on the electronic voltage transformers (EVT) on the other two phases has been examined. Up to a test voltage of 275kV, no signal except the noise was detected on the ECTs. By looking at the EVTs with the phases not under test on a defined potential (earthed), no signal except the background noise was detected. In the extreme configuration, having the two phases not under test on floating potential, the voltage detected there is up to around 15% of the applied test voltage on the phase under test.

Lightning impulse test

Applying positive and negative lightning impulses up to 650 kV_{peak} to the test object phase by phase with the complete measurement chain running and connected to the measuring device it can be concluded, that the ECTs and EVTs of the phase under test register a short disturbance of the lightning impulse. The other phases on defined potential (earthed) are immune and do not show any disturbance. The sampling rate during these tests has been set to 12.8 kHz (quality meter application for 50Hz) to register anything visible, since the fall and rise time of the lightning impulses are normally too short to be fully detected with the standard sampling rates for protection and metering.

The primary electronics (PC12) have been placed near to the test object and withstand the harsh conditions during lightning impulse testing fully running and without restrictions. Those primary electronic boxes were fully exposed and not put in a shielded local control cubicle box, that would help to shield it. Figure 14 shows the complete measuring setup in the HV Laboratory in Oberentfelden, Switzerland.

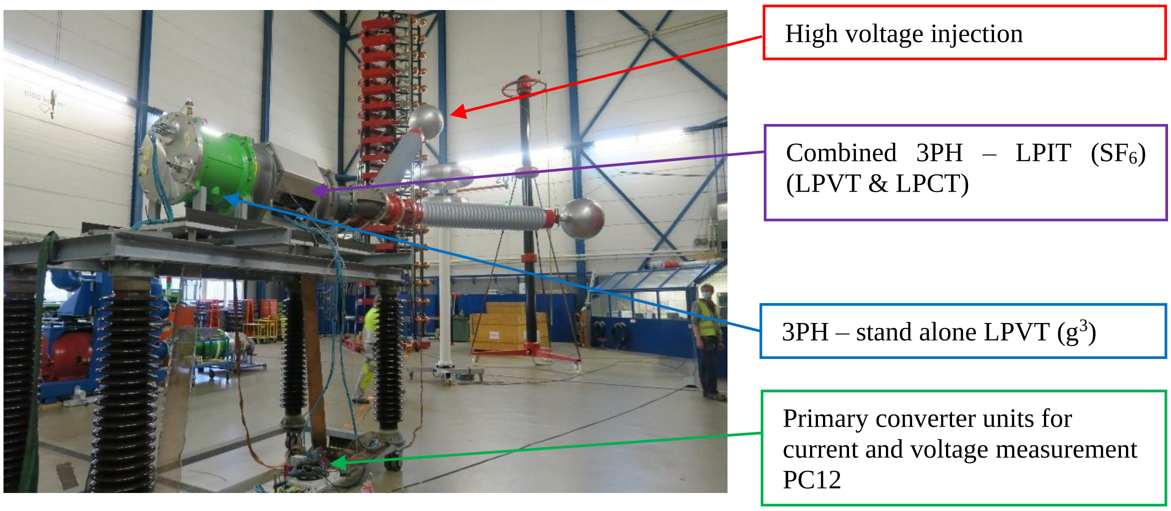


Figure 14 – High voltage injection and check of EMC influence,
test in GE high voltage laboratory (ISO 17025), Oberentfelden (CH)

Figure 15 represents the immunity against lightning impulses for the IEC 61850-9-2 [4] voltage stream recorded with the GE D-Bridge software, the LPIT system and the NI-USB-6361 (BNC) acquisition unit for the “reference signale” are able to detect the transient signal, but only partially due to the restricted bandwidth. Importantly, after the lightning strokes the system has no malfunction and returns to default measurement conditions.

Figure 16 represents the immunity against lightning impulses for the IEC 61850-9-2 [4] current stream recorded with the GE D-Bridge software, the LPIT system is not designed and specified in the standards to be able to detect such fast transients. Importantly, after the lightning strokes the system has no malfunction and returns to default measurement conditions. The background noise level was here in the range of 1…2A. The measured shift of the noise was in the range of additionally 1.5A with a decay to a “standard” background noise within 1s. This very low transient offset has obviously not impact to any protection system and is completely neglectable.

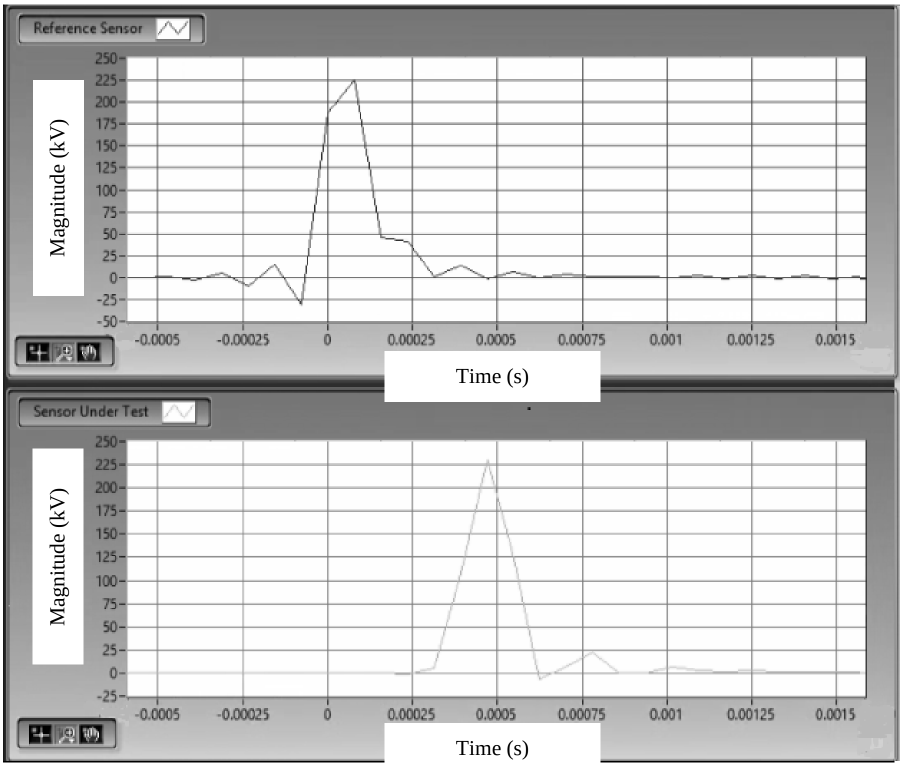


Figure 14 – lightning impulse tests in GE high voltage laboratory
(ISO 17025), Oberentfelden (CH)
Top: Analog output of the reference divider acquired with NI-USB-6361 (BNC) (“Zaengl-Divider”)
Bottom: Sensor output under lightning impulse test, after IEC 61850-9-2 voltage stream

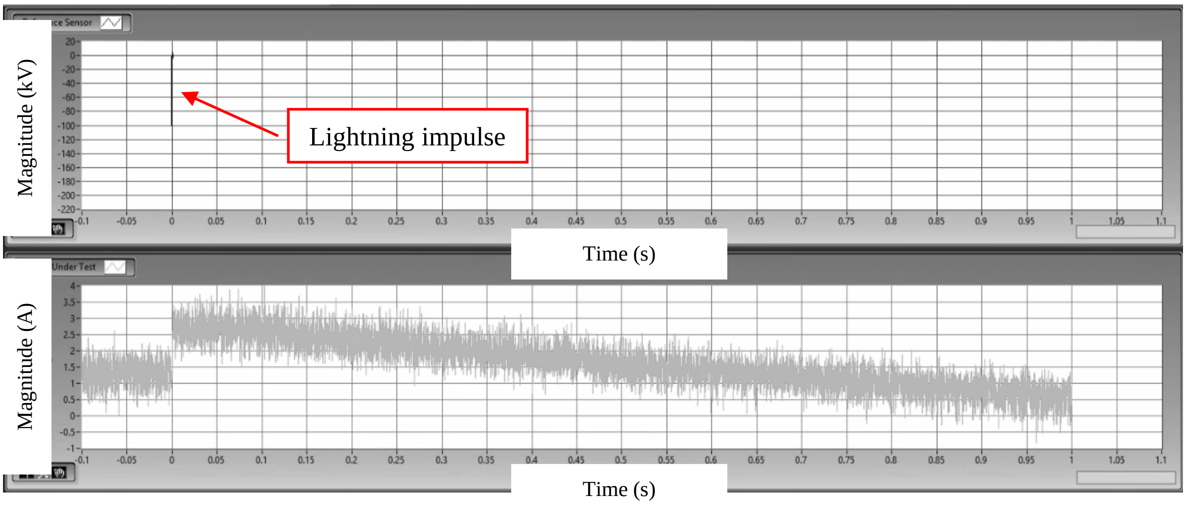


Figure 16 – Lightning impulse tests in GE high voltage laboratory
(ISO 17025), Oberentfelden (CH)
Top: Analog output of the reference voltage divider acquired with NI-USB-6361 (BNC) (“Zaengl-Divider”)
Bottom: Rogowski sensor output under lightning impulse test, after IEC 61850-9-2 current stream

5. Sensor and Electronic calibration

For an excellent result in terms of precision, the whole of the analog chain must be calibrated. A very satisfactory result is obtained with the combination of two memories for the calibration data. One calibration parameter is located on the sensor side and the other is in the acquisition unit. Thus, the sensor and the electronic acquisition unit, and in particular its analog measurement stage, can be calibrated independently. This allows an overview of such a system as shown in Figure 17.

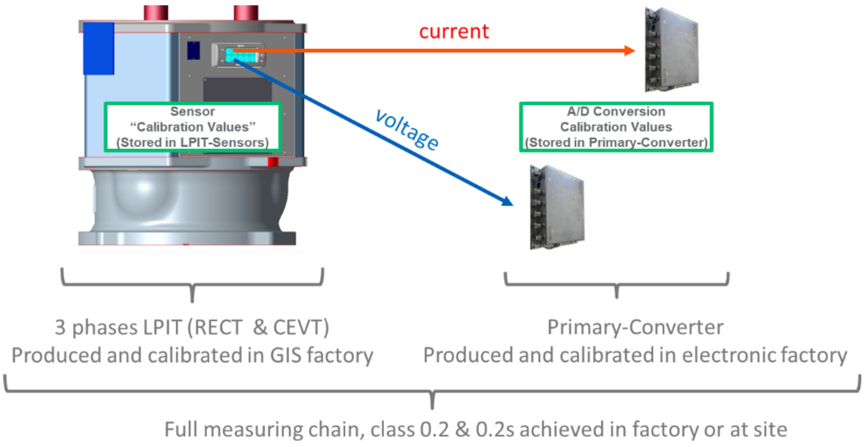


Figure 17 – Independent calibration of the sensors and the electronics, allowing to combine a full measurement chain without any recalibration on site during the whole GIS lifetime

By taking into account the variability of the electronic components and the physical phenomena which can influence the metrology, such as for example the temperature, it is possible to achieve a quite exceptional precision of the acquisition unit over the entire operating temperature range, thanks to compensation algorithms. Once this performance has been achieved, experiments show that the accuracy classes can be achieved globally by including the sensors. Thus, on the one hand, the performances are achieved, and they are exceptional because they are guaranteed over the entire temperature operating range, but in addition it is made possible to install the acquisition electronics in the factory or possibly on site as the compensation coefficients are read automatically when establishing the connection between sensors and acquisition unit. It is possible to replace one acquisition unit with another and still guarantee the accuracy class. This modularity is particularly interesting because it makes it possible to adapt to different production flows of high-voltage equipment depending on supply times, commissioning dates, or supply limits. The acquisition units are therefore all identical after calibration and can be managed under a single reference in a set of spare parts. The establishment of this entire compensation chain requires a particular effort in research and development, but once this work is done, the implementation of the product is greatly facilitated, which is an advantage for the manufacturer and the operator.

6. Conclusions

Low Power Instrument Transformers (LPIT) integrated in GIS are exposed to various influences which may impact the accuracy of the complete measurement system or may lead to malfunction of the protection system. Considering the possible influences like temperature, gas density, gas pressure, magnetic and electrical fields during the design-phase of the sensors and its technologies, by respecting the behaviour of materials combination, evaluating and understanding the theoretical physical phenomena and finally excessive testing of both sensors and electronics lead to highly accurate and reliable LPIT measurement chains. Such equipment is needed to address the increasing demand of new features in the electrical grid and are available for GIS using SF_6 or the climate-friendly alternative gas, like g^3.

In this paper we present the results based on several laboratory measurement for LPIT from the base of the bare sensors to the three-phase encapsulated GIS device under different conditions of temperature, gas density, gas pressure, varying magnetic and electrical fields applying “active” or “passive” compensation methods. It has been found that the measurement errors are within the limits for metering accuracy class 0.2/0.2S, the influence of crosstalk is below 1/3 of the rated accuracy class for magnitude and phase error according to IEC 61869 standards [9] in the wide range of conditions investigated.

Overall a modular product design makes it possible to meet the requirements over the lifetime of a GIS and its LPIT starting with an industrial production flow, erection and commissioning, maintenance, extension, and a possible replacement of components, by a simple and optimized management of the materials. The application of optimized LPIT in GIS based on SF_6 and g^3 is advantageous for the operators, for the manufacturers and is an important building block of the future electrical grid.

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