

Quiet Revolution: How Low-Power Instrument Transformers and Digital Secondary Systems Are Changing What Is Possible

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Paper ID – 10421**B5 PROTECTION AND AUTOMATION****PS1: Practical experiences in the development of process bus****Quiet Revolution: How Low-Power Instrument Transformers and Digital Secondary Systems Are Changing What Is Possible**

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SUMMARY

This paper discusses the evolution of instrument transformers (ITs) and the recent rise of low-power ITs (LPITs) as an alternative to traditional magnetic induction-based ITs. Initially designed for energy transfer to electromechanical systems, ITs have shifted focus towards providing high-quality information about primary-side quantities rather than the sheer power supply on the secondary side.

Standardization efforts, like IEC 60044-7 and IEC 60044-8, paved the way for LPIT acceptance in modern power systems, aided by the recent introduction of the IEC 61850-based digital secondary systems (DSSs).

The IEC 61869 series standards further consolidated analog and digital interface requirements, enabling industry-wide acceptance and LPIT integration with protective relays, merging units, and revenue meters. The most popular LPIT designs employ Rogowski coils for current measurement and capacitive dividers for voltage measurement, offering wide frequency coverage and a dynamic range.

LPITs are used in medium-voltage (MV) applications due to their smaller size, potential for switchgear weight reduction, and simplified wiring using standardized connectors.

In gas-insulated switchgear (GIS) applications, purpose-built LPITs have demonstrated measurable advantages in size reduction and weight savings. The integration of multiple LPITs into a single GIS partition ensures stability, consistent performance, and accurate measurements across a wide range of currents and frequencies.

KEYWORDS

Low-Power Instrument Transformers, Digital Secondary Systems, Rogowski Coils, Capacitive Dividers, IEC 61869 Series, Gas-Insulated Switchgear, Merging Unit.

1 Introduction

Instrument transformers (ITs) are a key component of the power system protection, control, and revenue systems. IT standardization allowed equipment manufacturers to focus their efforts and expertise in two vastly different fields, namely high-voltage (HV) apparatus design and secondary system development. While the apparatus development requires strong materials background and exceptional understanding of underlying high-energy physics, secondary system design emphasizes the design of robust electronics circuitry, digital signal processing, real-time computation, metrology, digital communications, cybersecurity, and artificial intelligence.

While originally required to provide the energy necessary to move electromechanical actuators and levers, the IT role has changed over time, reducing emphasis on the amount of power that a device is able to supply on its secondary, and now emphasizing the quality of the information it provides about the primary-side quantities being measured. It is, therefore, no surprise that the well-established and highly reliable Ts based on magnetic induction are now being challenged by an avalanche of low-power instrument transformer (LPIT) alternatives.

As much as the LPITs may be trying to displace their classical counterparts, old technology is not ready to give up without a fight. It works exceptionally well and is well understood. Most of the inherent limitations, such as the current transformer (CT) core saturation effect, limited frequency response due to voltage transformer (VT) winding resonance, ferroresonance, safety considerations with an open CT secondary, and VT fusing needs are well understood, are accounted for during the design phase, or are addressed through training and safe working practices. Simply promising to improve some of these limitations has proven insufficient for the LPITs to overturn the excellent track record and to service classical ITs provided every day. To succeed, LPITs must, therefore, deliver tangible value that can be easily recognized and applied in practice. This paper reports on the LPIT history, state of the LPIT technology standardization, and some of the applications in which LPITs have gained a solid industry foothold.

2 LPIT Standardization

Fostered by the early standardization in the IEC 60044-7:1999 and IEC 60044-8:2002, LPITs have steadily gained acceptance in various power system applications [1] [2]. LPIT standardization activity was initially fuelled by the exciting development of optical sensing technology, which promised to deliver high accuracy and inherently safe primary equipment with significantly reduced insulation stress. Disregarding the initial growing pains, optical sensors eventually delivered on those promises but failed to establish a solid foothold in the market. One of the largest challenges was the fact that while the utility engineers in charge of the primary equipment loved the new designs, the secondary system engineers faced a challenge of interfacing the new sensors to the protection and control equipment. High-power amplifiers were added to amplify the optical IT output signals, followed by the development of the 12 V low-energy analog (LEA) interface [3] [4]. The LEA interface never gained sufficient traction due to a lack of support of the corresponding secondary devices.

The final problem was the optical sensor cost that limited the optical sensor applications to 115 kV and higher voltage systems, thus lowering the potential market volume and reducing the secondary device manufacturer motivation to support the new interface. The situation was resolved only recently with the introduction of the IEC 61850-based digital secondary systems (DSSs) [5]. Complex electronics associated with optical ITs can easily support the advanced signal processing, computing, and communications resources necessary to implement the IEC 61850 logical device merging unit. This allows the optical ITs to publish measured data using interoperable data streams compliant with the IEC 61850-9-2 Sampled Values service, thus ensuring a much broader market of compatible secondary devices. An optical CT (OCT) installation example with two OCTs mounted parallel to a conventional CT is shown in Figure 1.

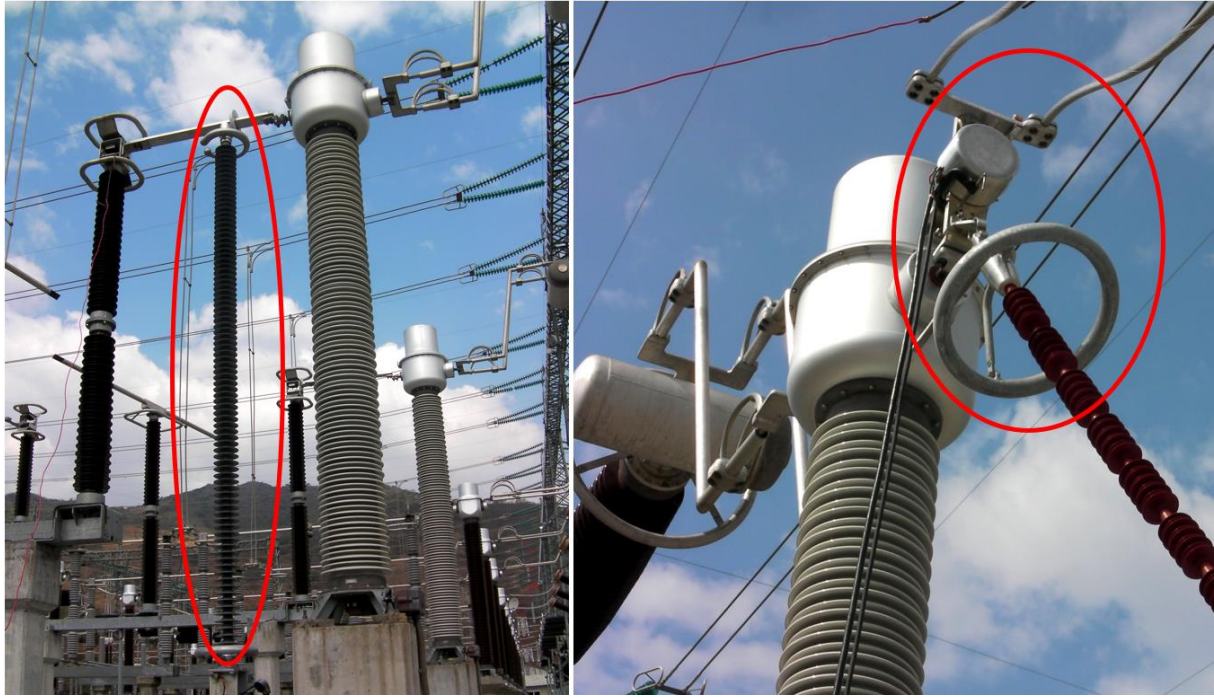


Figure 1. OCT installation example at Chicoasén, Mexico

Against all odds, the LEA interface originally designed to support the optical IT was not forgotten and is being reinvented as a low-cost LPIT interface alternative. Interest is especially high in medium-voltage (MV) metal-clad, metal-enclosed, and HV gas-insulated switchgear (GIS) applications. In these applications, LPITs provide tangible benefits, such as significant reduction in size and weight, improved accuracy, high reliability, a long-life expectancy, and improved operator safety.

Recent updates of the IEC TC38 standards, including IEC 61869-1/-6/-9/-10/-11/-13, solidified the original work pioneered by the IEC 60044 series, creating interoperable analog and digital interfaces that allow LPITs to be interfaced with protective relays, merging units, and revenue meters. The new standards ensured the retention of familiar terminology and specifications, such as accuracy classes and rated voltages and current, while at the same time extending the LPIT frequency-range requirements, adding methods to describe the LPIT dynamic range, and requiring that all low-power current transformers (LPCTs) intended for protection applications be specified with dual rating, thus disclosing their performance in both protection and measuring applications. New IEC 61869 series standards, which, at the time of writing, are being updated to the second edition, can also be seen as a specification language, intended to accurately describe LPIT capabilities, regardless of the technology used in any given product. They will also include advanced corrections mechanisms for crosstalk and temperature drift and an electronic data sheet further improving the capabilities and the interoperability of the analog interface.

Secondary injection test sets and test adapters with LEA outputs as well as test blocks are commercially available from different suppliers, making the test of merging units, relays, and other IEDs with LEA input convenient (e.g., [6] [7]).

Most popular LPIT solutions use Rogowski coils for current measurement and capacitive/compensated resistive capacitive dividers for voltage measurement [1] [2] [3]. Typical implementation is shown in Figure 2. Two types of sensors are often combined with the low-power voltage transformers (LPVTs) electrodes used to shield the Rogowski coil from the HV primary conductor. Both types of sensors are inherently free of saturation and ferroresonance, allowing them to operate over an exceptionally wide dynamic range.

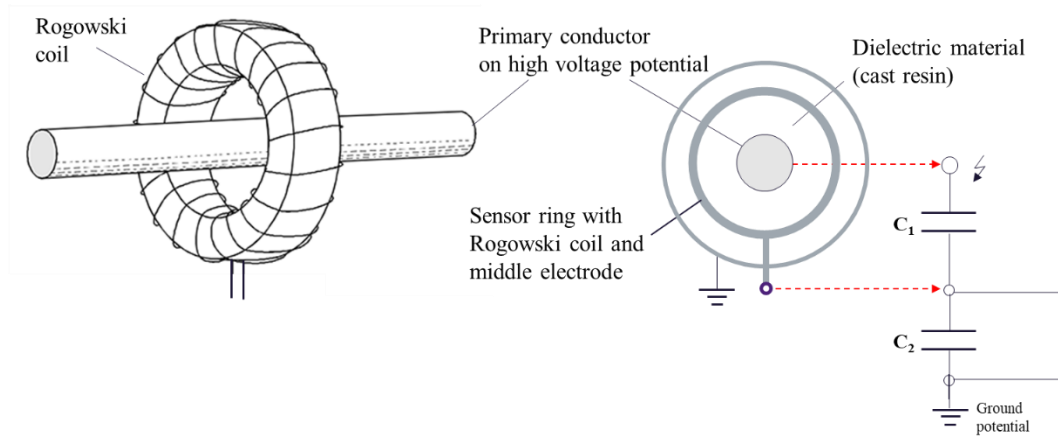


Figure 2. Schematic description of an LPIT with a Rogowski coil and a capacitive divider

In the attempt to address the power quality applications, IEC 61869 introduces a new frequency response mask concept and defines a new set of accuracy class extensions for harmonics named WB0 through WB4. Basic class WB0 defines the minimum requirements up to the 13th harmonic and is mandatory for all LPITs. Although not mandatory for conventional ITs, wide-bandwidth extension classes can be used to describe the capabilities of any IT. The decision to make the class WB0 mandatory for LPITs is driven by the fact that associated sensing technologies can achieve the required bandwidth without significant increase in the device cost or complexity. The highest accuracy class, WB4, is intended for traveling-wave applications with frequencies up to 500 kHz. As the applications space develops, higher bandwidth classes may be added to the standard in the future. A frequency response mask example is shown in Figure 3.

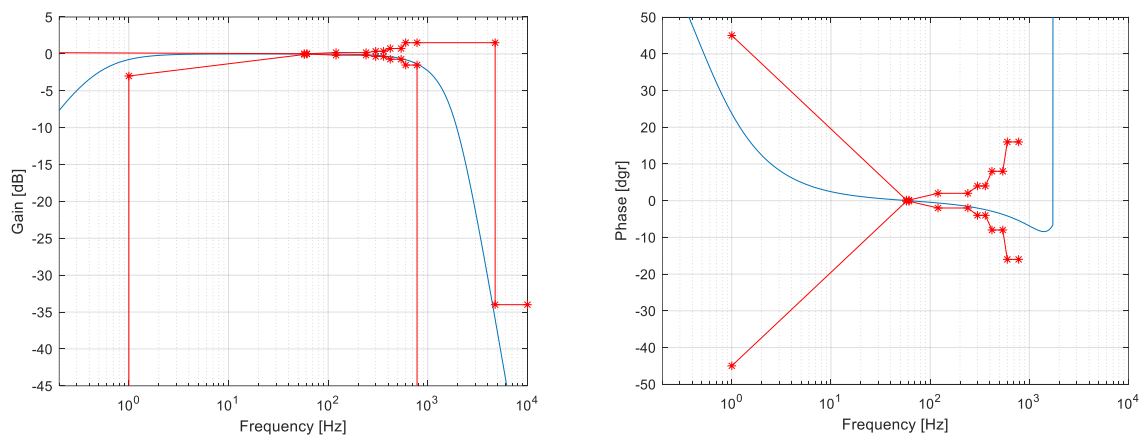


Figure 3. WB0 frequency response mask and filter example for a metering LPIT with the accuracy class 0,2

It is important to note that the frequency response mask changes (gets more stringent) for higher accuracy classes. Another important feature of the mask is the fact that it allows direct current (dc)-capable LPITs but does not require them. Instead of taking the more prescriptive approach, IEC 61869-1 establishes a $-3 \text{ dB} / 1 \text{ Hz}$ as the worst-case cutoff frequency allowed for an alternating current (ac)-coupled device. Clearly defined cutoff frequency establishes an interface point between ITs and intelligent electronic devices (IEDs) using the IT output. It also establishes a clear interface point between the IEC technical committees, such as the TC38, which is responsible for ITs, and the TC95, which is responsible for protective relays. Asking the LPITs to faithfully reproduce primary signals down to at least 1 Hz and asking relays to ensure applicable protection functions are not affected by the presence of low frequencies. This is a major change from the IEC 60044 series in which the LPVTs were required to remove long, trapped charge-related decays. Although not immediately obvious, this change is instrumental in matching the relative phase of the voltage and

current measurements across a wide frequency range and enabling highly accurate synchrophasor applications.

The dynamic range offered by the new LPITs can be exceptionally wide. This is best illustrated with Rogowski coil-based LPCTs, which are normally designed to match the switchgear short-circuit current capability (i.e., 100 kA-rated short-time thermal current) while simultaneously maintaining an accuracy class 0,2S performance at a rated primary current (I_{pr}) of 200 A. The same sensor may also be rated for 5 kA continuous thermal current. Specifications for such an LPCT would include a rated extend primary current factor K_{pcr} of 50 (5 kA / 200 A = 25) and an accuracy limit factor (K_{ALF}) of 1000 (100 kA / 200 A = 500). The rated symmetrical short-circuit current factor may also extend all the way to 100 kA, resulting with K_{ssc} of 500. Such an LPCT would be specified as follows:

$$0,2S / 5P500, I_{pr} = 200 \text{ A}, K_{pcr} = 25, K_{ssc} = 100 \text{ kA}$$

Corresponding accuracy limits for this example are illustrated in Figure 4.

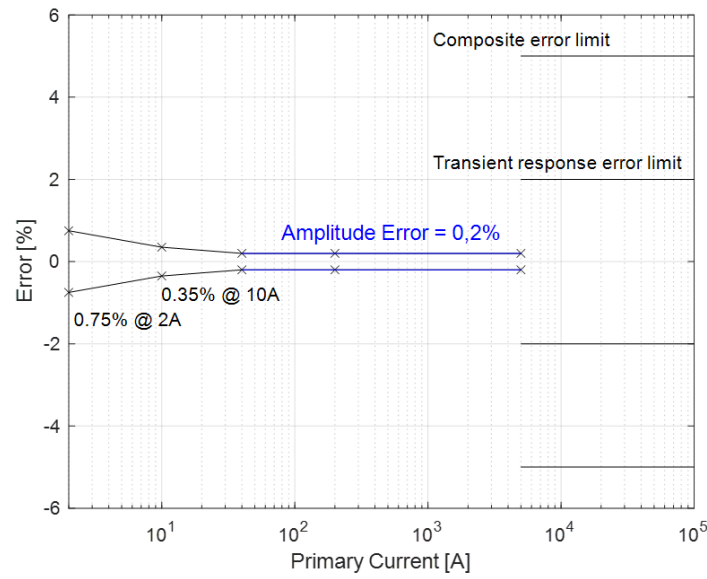


Figure 4. Accuracy limits, as defined by IEC 61869, for an LPCT with an accuracy class of 0,2S/2TPM and a rated current covering 200 A to 5 kA range

Once the Rogowski coil is combined with the merging unit or IED electronics, the digital secondary signal intended for protection applications gains yet another accuracy class describing transient performance with fully offset faults, namely the TPM accuracy class. The final accuracy class designation for the digital stream produced by a merging publishing the data from our hypothetical LPCT may have the accuracy specified as follows:

$$0,2S / 5P500 / 2TPM, I_{pr} = 200 \text{ A}, K_{pcr} = 25, K_{ssc} = 100 \text{ kA}, T_{sec} = 0,5 \text{ s}, T_i = 250 \text{ ms}$$

The merging unit/IED electronics may additionally introduce input-signal clipping and may, therefore, lower the rated symmetrical short-circuit current factor, K_{ssc} , of the combined system to a lower value.

Although confusing at first, the previous specification example accurately describes an LPIT with a rated current between 100 A and 5 kA, clearly indicating the fact that a rated current specification becomes much more flexible when compared with conventional ITs. The increased range allows the users to precisely match the current used in their application. It also shifts the rated current decision from the circuit design (CT selection) phase to the measuring device configuration (setting) phase. LPITs, therefore, allow a reduction in the number of different ITs that must be warehoused and allow

the circuit to be upgraded throughout the life of the installation, accommodating load growth without the need to upgrade the CTs, which is often the case with conventional technology.

It is important to note that by itself, a Rogowski coil LPIT does not have limitations related to the fully offset fault current time constant, T_i . Fault current is accurately differentiated and presented to the coil output as voltage. Problems occur once the secondary signal is integrated by the merging unit front-end electronics, which normally eliminates dc signals and introduces a high-pass filter behaviour with corner frequency typically in the 0,1 to 1 Hz range. High-pass filter behaviour matches conventional current transformers that are equally unable to measure dc and have cutoff frequencies in the same range. Conventional CT behaviour is described with the well-known transient performance classes, TPX, TPY, and TPZ. The main difference, however, is that the Rogowski coils do not saturate and that the transient behaviour is determined by the LPIT electronics. IEC 61869-13 deals with this problem by introducing a new TPM class that is somewhat similar to the TPZ class but can accommodate longer primary time constants and targets merging unit implementations with conventional input magnetics. To provide parity with the TPx/TPY classes, IEC 61869-8 (which is presently in development) plans to introduce the TPE (electronic) transient response class.

The digital output naturally requires a proper anti-aliasing filter. This introduces damping at the higher harmonics, which has a negative impact on the accuracy of the harmonic measurement of connected PQ devices. Fortunately, this damping is well known. IEC 61850-7-4 already defines a mechanism that allows the IT frequency response compensation factors to be exposed to the IED by using the frequency correction setting « CorCrv » contained within the logical nodes for current and voltage transformers (TCTR and TVTR). Correction factors are provided in the form of « curve shape setting » (CSG).

A wide dynamic range inherent with new LPITs also means that the LPIT ceases to be the main performance-limiting factor, thus shifting the burden to the electronic device used to measure the LPIT output. IEDs, such as relays or merging units, must have a well-protected front-end interface capable of accurately measuring signals with a dynamic range that may exceed 120 dB ($>10^6$). Novel solutions used to meet this challenge include the use of variable gain amplifiers, high-resolution analog-to-digital converters, and dual sets of high-resolution converters.

3 Medium-Voltage (MV) Applications

LPITs with LEA output have found their sweet spot in MV applications. They are especially popular in metal-clad, metal-enclosed, and pad-mounted applications in which the small size and locally mounted IEDs make it possible to also reduce the MV switchgear size. This is especially visible in purpose-built LPVTs used as busbar support insulators [8] and MV bushings. An LPVT-based insulator example is shown in Figure 5.



Figure 5. MV support insulator and MV bushing insert with built-in LPVTs

A support insulator approach eliminates the need for a separate VT-truck compartment and the associated VT fuses. Switchgear optimized for LPIT technology, therefore, offers a smaller size and higher density, providing immediate savings to the end user. LPIT wiring is also simplified by using standard shielded twisted-pair cables preterminated in the factory with standardized low-cost RJ-45 connectors. Standardization allows IEDs to adopt the same connector pinout, resulting with a simple, plug-and-play system. Low voltages provided by the LEA interface make the equipment safer and easier to use. A protective relay equipped with a standardized LEA interface is shown in Figure 6.



Figure 6. Typical protective relay with LEA interface shown with Rogowski coil optimized for MV underground cable applications

Due to limited dielectric withstand and the possibility of exported potential problems, the IEC 61869 series standard limits the use of RJ-45 connectors to installations in which the maximum distance between the LPIT and the IED is below 10 meters. Larger distances are possible but require additional engineering effort. IEC 61869 series standards also require that such interfaces support the full 3 kV dielectric withstand test, matching the conventional IT secondary wiring requirements.

LPITs used in MV applications offer excellent performance during power system faults and are reasonably competitive in power quality type applications. Revenue metering accuracy below 0,3 percent is still easier to achieve using conventional ITs. Main factors limiting the LPVT accuracy are external magnetic field susceptibility and primary conductor position sensitivity associated with Rogowski coils, neighbouring phase electric field sensitivity affecting voltage dividers as well as ageing and environment temperature. Active LPVTs may also be susceptible to radio frequency fields and conducted disturbances, which may be present while supplying sensor power.

4 GIS Applications

GIS systems are experiencing accelerated technology development with the introduction of alternatives to the traditional sulphur hexafluoride (SF₆)-based systems. New designs are offered with purpose-built LPITs that clearly demonstrate the advantage of the new technology, which has now been introduced by all major HV GIS manufacturers. Figure 7 illustrates the LPIT sensor technology potential, with the LPIT application resulting in a 30 percent reduction of the 145 kV bay length and a 25 percent reduction of its weight. Both reductions directly translate to tangible end-user benefits.

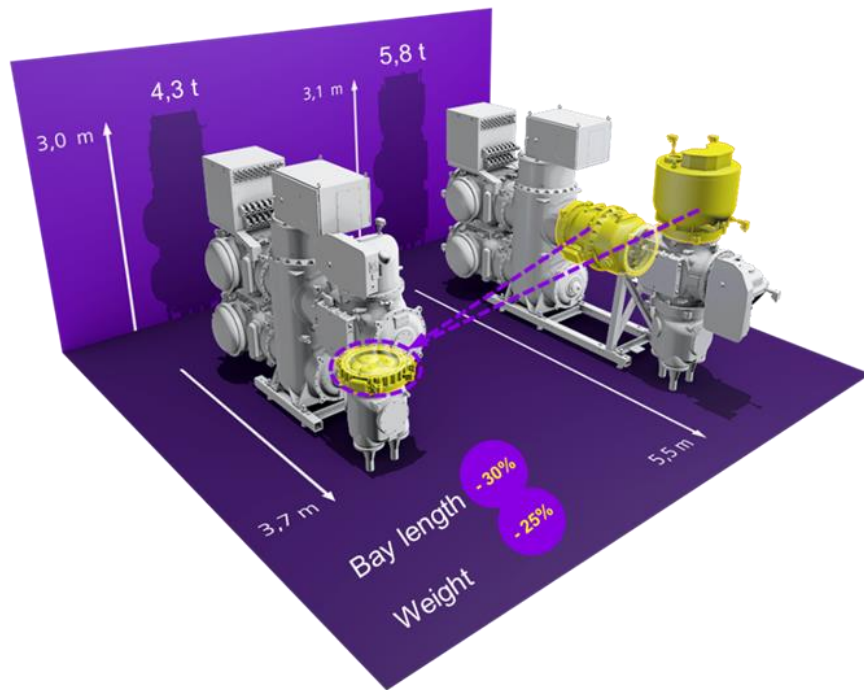


Figure 7. Schematic overview of the 145 kV clean air GIS space and weight savings introduced by the LPIT technology application

The LPIT unit is highly integrated, housing three LPCTs and three LPVTs that are encapsulated and built into a standard GIS partition. The unit is sealed for life using cast resin and protected from impact, mechanical shock, vibrations, and heat excursions. LPCT measurements are based on the Rogowski coil technology with direct LEA output provided using a double shielded twisted-pair cable. LPVT is implemented as a capacitive divider with the partition resin acting as the HV capacitor dielectric [9] [10]. GIS partition is shown in Figure 8 with internal details shown in Figure 9.

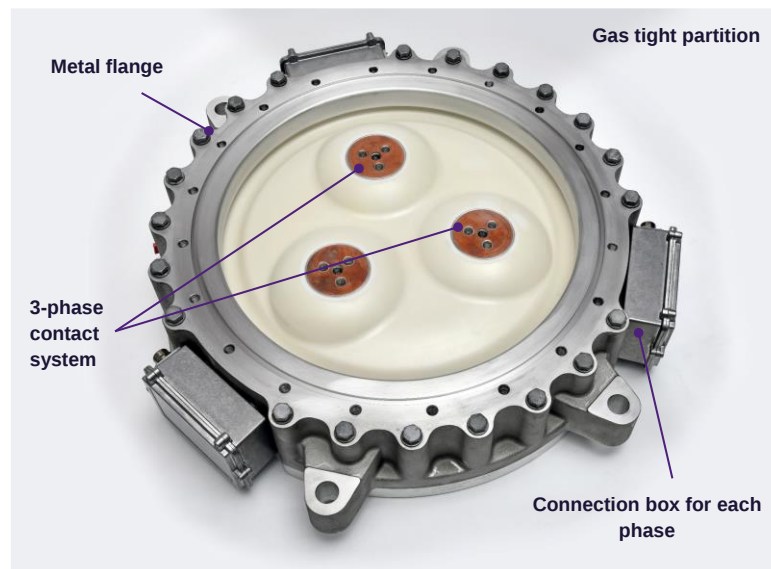


Figure 8. 145 kV three-phase GIS partition with integrated LPCT and LPVT sensors

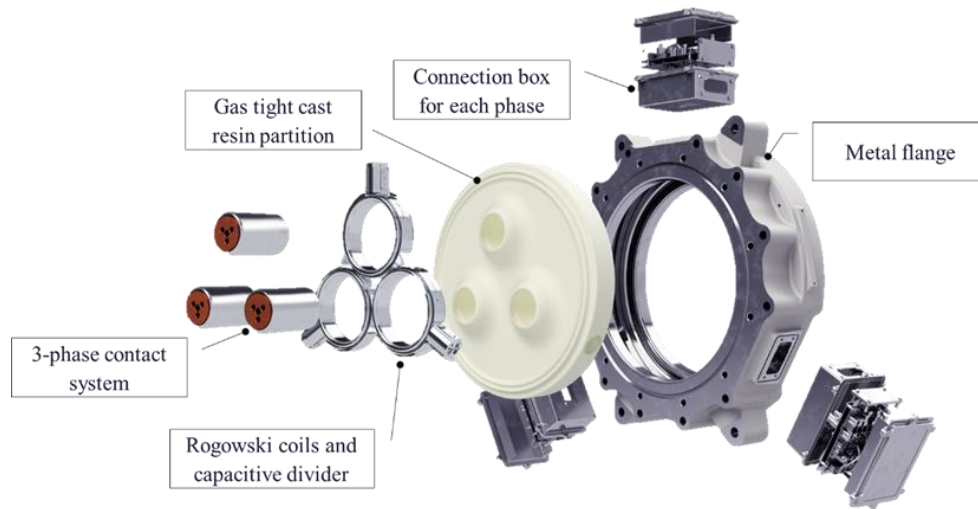


Figure 9. Key components of the 145 kV three-phase GIS partition with integrated LPCT and LPVT sensors

The integration of multiple LPITs into a single mechanically stable partition offers unique advantages not commonly found in other sensor applications. On the LPCT side, it ensures the Rogowski coil position is fixed during manufacturing and guarantees that the coils remain centred around the primary conductor throughout the LPIT lifetime. The fixed position means that the measurement crosstalk caused by small, winding uniformity errors introduced during the Rogowski coil manufacturing process will be constant once the partition resin is fully cured. Due to the physics involved, crosstalk is fully linear, meaning it can be compensated by using the sensor-specific calibration constant recorded during final test at the factory. Careful construction, material choice, and coil loading further ensures LPCT output remains constant over time and temperature. The previously described factors make it possible to mathematically derive high-quality zero-sequence current measurement in which accuracy exceeds levels achievable by adding independent coil output, as is often done in metal-clad switchgear applications. Furthermore, GIS partition provides sufficient space for two sets of Rogowski coils per phase (total of 6 LPCTs per partition), making it possible to provide two sets of fully independent current measurements (Systems A and B). The Rogowski coil dynamic range and wide frequency response make it possible to cover the full range of currents, from 100 kA fault current with protection accuracy (2TPE, 2TPM) on the high end, down to 200 A nominal with metering accuracy (0,2S) on the low end. The frequency response easily exceeds the 50th harmonic, making this LPIT suitable for most demanding power quality applications. The typical coil output during high-current faults is in the order of 20 V.

The LPVT sensor is implemented as a capacitive divider and can be operated as a displacement (capacitive) current sensor with low-resistance burden or in a capacitive divider mode with voltage output compatible with the IEC 61869-1 two megaohm burden. When operated in the voltage output mode, LPVT output can be connected to two redundant merging units, thus matching the LPCT subsystem. LPVT sensors are further enhanced with resistance temperature detector-based temperature measurements performed individually for LPVT. The temperature compensation is performed downstream inside the merging unit and is based on the factory-supplied temperature compensation constants, which enable the LPIT to achieve the 0,2P accuracy level. The resulting LPIT offers an exceptional dynamic range and dual redundant output, and it is fully integrated, saturation-free, and inherently ferroresonance-free. Furthermore, by eliminating VT magnetics capacitive sensors eliminate the need for VT disconnection during GIS and HV cable tests.

The native low-voltage analog output provided by the GIS partition-based LPVT does have its own limitation. To achieve the full dynamic range offered by the sensors, the secondary output must be well shielded and carefully routed through the switchgear. The dual shielded twisted-pair cable used for this purpose allows relatively long runs, significantly exceeding the IEC 61869-1 ten-meter limit

associated with the RJ-45 based connector system. For best results, it is, however, advantageous to use an IEC 61869-13-compliant merging unit to convert the LEA signals into an interoperable digital signal compliant with IEC 61850-9-2 and IEC 61869-9 standards. The CIGRE technical brochure [11] prepared by Study Committee B3 (WG B3.39) and published in 2020, gives a comprehensive overview of the technologies involved.

Two redundant merging units are typically mounted inside the GIS bay control cabinet, thus limiting the LEA signal run to several meters, and replacing it with a digital signal transmitted using optical fibres. The merging unit performs all the necessary signal corrections, including gain calibration, LPCT crosstalk correction, and the LPVT temperature compensation. Bay control and tripping commands are performed using IEC 61850 GOOSE and MMS services. A detailed description of a control and protection system using LPIT can be found in [11].

The use of LPITs provides many benefits versus conventional ITs, including the following:

- Smaller size and weight of the entire GIS due to smaller dimensions of the sensors and their integration into a GIS partition
- Easy low-voltage connection lowering the cabling and wiring effort
- High reliability and long lifetime expectancy due to the robust design embedded in cast resin
- Less insulation gas in the switchgear
- Excellent overvoltage performance—no need for disconnection during GIS or HV cable tests
- No hazardous overvoltage at open IT terminals
- A single LPIT covering all protection and metering requirements, and thanks to its linearity, also a wide range of primary currents and voltages, simplifying stock management, engineering, and logistics
- Flexible definition and modification of the settings for rated primary current and voltage in the protective devices at any phase of the project and afterwards (in this way, the GIS remains flexible for future increases of its nominal current)

The exceptional dynamic range offered by the LPIT sensors makes it possible to perform field verification and, if necessary, field calibration at significantly reduced signal levels (<500 V and <100 A). This means that not only the common primary injection test sets can be used for commissioning tests, but also test sets designed for secondary injection [7] [12]. For a system test of an LPIT connected to an electricity meter, industry standard mobile meter test equipment [12] [13] can be used. Such primary injection allows the user to verify the end-to-end performance of the LPIT in combination with the merging unit and even the meter. Based on IEC 62052-11 (electricity meters) and IEC/IEEE 61869-21 (instrument transformer accuracy tests), a certification of an LPIT-based metering system for revenue metering according to legal requirements as a directly connected meter is feasible [12].

5 Conclusion

Fostered by recent standardization, LPIT technology is making significant inroads into the traditional IT market. Advances are especially visible in the MV and GIS applications in which the combination of LEA outputs and IEC 61850-based DSSs is providing tangible benefits to the end user. Although superior in many ways to the conventional ITs, the shared number of such devices already in the field means the two technologies are likely to coexist and complement each other for a very long time. Based on the recent advances and the wealth of the LPIT products in the market, the authors of this paper are very optimistic about the future of LPIT technology.

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