Smart Medium Voltage Switchgear with LPITs and IEC 61850 - Experiences after 10 years and the next evolution

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Abstract

Over the past decade, significant advancements have been made in medium voltage (MV) switchgear technology, driven by the need for enhanced reliability, efficiency, and safety in electrical distribution systems. This paper explores the experiences with Smart (Digital) MV Switchgear in primary distribution applications, focusing on key components such as Low-Power Instrument transformers (Rogowski coil current sensors and voltage sensors based on voltage dividers), and IEC 61850 communication, including GOOSE and Process bus (Sampled Measured Values). The paper provides insight into how the main technology gaps have been resolved in the last decade. Additionally, it discusses the future outlook and contributions of Smart MV Switchgear to sustainable and resilient MV networks. The advancements in Low-power passive Instrument transformers LPITs), offering higher accuracy and better linearity, have enabled more precise monitoring and protection of electrical networks. The adoption of IEC 61850 communication standards has revolutionized MV switchgear systems by facilitating seamless interoperability and real-time data exchange, reducing wiring needs, lowering installation costs, and improving system flexibility and scalability. This paper aims to provide utility and industry professionals with a detailed understanding of these developments and their practical implications, supporting informed decision-making and strategic planning in electrical distribution.

1. Application of IEC 61850-9-2 in MV Switchgear with the use of Sensors

MV Sensors (Medium Voltage Low-power Instrument transformers) were introduced on the market in early 90's, however their successful implementation at MV primary distribution level was closely connected with introduction of IEC 61850-9-2 communication. The MV Smart Switchgear solution with optimized implementation of LPITs in Air-insulated switchgear and utilization of IEC 61850-9-2 (process bus) communication for voltage signal sharing between protection relays were introduced at CIRED conference in 2013 [1].

1.1 Brief overview of the advancements in MV switchgear technology over the past decade

MV sensors represent an alternative way of performing the current and voltage measurements needed for the protection and monitoring of medium voltage power systems. These sensors, based on alternative principles such as Rogowski coil for current measurement and Resistive or Capacitive voltage dividers for voltage measurement, have been introduced as successors to conventional instrument transformers and in connection with microprocessors based Intelligent Electronic Devices (IEDs) enable many benefits for both users and applications. However, to be able to fully utilize all advantages of MV Sensors in MV Switchgear at primary distribution level, the way in which the voltage signal can be distributed in the switchgear shall be found. The IEC 61850-9-2 offers the solution.

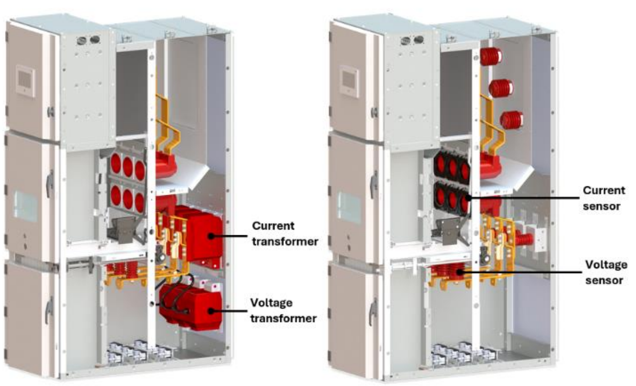

Fig. 1 Cross sections of Switchgear panel with Instrument transformers (left) and with MV Sensors (right)

Protection relays can today act as Merging Units (MU) as per IEC 61850, processing the measured analogue values and further transmitting them into an open communication bus. This practically optimizes the need to use hardwiring in between switchgear panels, while offering self-supervision functionality of the communication bus. The receiver of this process bus communication can be another protection relay, or a dedicated centralized protection device. The combination of digitalization by the use of IEC 61850-9-2 and MV Sensors brings a significant change to the way in which MV Switchgear and networks can be built [1].

1.2 Importance of reliability, efficiency, and safety in electrical distribution systems

The reliability, efficiency, and safety of electrical distribution systems are paramount for ensuring uninterrupted power supply, minimizing energy losses, and protecting both infrastructure and human lives. **Reliability** ensures that power is consistently available, reducing downtime and economic losses associated with power outages. **Efficiency** in these systems minimizes energy wastage, leading to cost savings and reduced environmental impact. This is particularly crucial as the demand for electricity continues to rise globally. **Safety** is critical to prevent accidents, equipment damage, and potential hazards to personnel. Implementing robust safety protocols and advanced monitoring technologies can mitigate risks and enhance the overall performance of the electrical grid. Together, these factors contribute to a resilient and sustainable energy infrastructure, essential for modern society's functioning and growth.

The introduction of IEC 61850-9-2 in MV Switchgear offers significant advantages for MV applications. MV Current and Voltage Sensors can be connected through IEDs, allowing flexible signal distribution across substations. Key benefits include:

- **Higher dynamic range**: Sensors have a broader range than Instrument transformers, reducing the number of sensor variants needed.
- **Linear behaviour**: No saturation and measurement of higher frequency components, together enhancing protection functions.
- **No ferromagnetic core**: This prevents ferroresonance and consequent damages.
- **Low energy consumption**: MV Sensors use much less energy than Instrument transformers, positively impacting the environment and enabling higher switchgear ratings without artificial cooling.
- **Space efficiency**: MV Sensors are smaller and more flexible in positioning within switchgear designs.

1.3 Lessons learnt – feedback from applications and technology gaps

Various manufacturers are now offering Switchgear solutions, with LPITs and IEC 61850, and these are well established and accepted solution by various customers on the market. These are mainly recognized by saving space thanks to compactness of MV Sensors, while it does not compromise the switchgear operation functionality. Functionality remains the same as with traditional Switchgear. Furthermore, the usage of MV Sensors with Protection relays and IEC 61850 is very stable, with no faulty operations recognized in the installations, as IEC 61850 was introduced in 2004.

Like with all new innovative solutions there is always a potential for further improvement. Feedback collected during the last +10 years has been highlighting the importance to continue with the evolution of Smart MV Switchgear at primary distribution level due to their advantages and benefits. The main technology gaps identified during the last decade were pointing on missing:

- Solution for revenue metering with LPITs (including MV Sensors with high accuracy classes and Revenue energy meters for LPITs)
- More compatible IEDs supporting LPITs
- Busbar differential protection with LPITs

2. Technological advancement in Low-power Instrument Transformers

Over the past decade, LPITs have been widely accepted due to their advantages and nowadays are used for protection, measurement and control applications in MV networks together with IEDs.

The requirements on LPITs are defined in the standard IEC 61869-6:2016 [2], in addition, Low-power Passive current transformers (LPCTs) are covered by the standard IEC 61869-10:2017 [3] and the requirements on Low-power passive voltage transformers (LPVTs) are defined in the standard IEC 61869-11:2017 [4]. Despite those standards ([2], [3] and [4]) define the same accuracy classes (e.g. 0,2S and 0,2) for LPITs there are several noticeable differences in the requirements and the way how the performance of LPITs shall be extensively verified by relevant type tests compared to conventional Instrument transformers.

The following additional requirements and type tests are defined for LPCTs complying with [2] and [3] and for LPVTs complying with [2] and [4]:

- Temperature cycle accuracy test
- Test for accuracy versus frequency
- Test for impact of magnetic field from other phases (for LPCTs only)
- Test for accuracy with respect to the positioning of the primary conductor (for LPCTs only)
- Test for impact of electric field from other phases (for LPVTs only)

From the list above it is evident that the performance of LPITs is verified in a much more comprehensive way compared to conventional ITs as defined by existing IEC standards. Thus, high requirements are placed on the design of LPITs and the quality of used materials. For LPCTs based on Rogowski coil, the homogeneity of winding, effective shielding of internal parts and high quality of material used for the core play a key role to meet the high accuracy performance. In case of LPVTs based on resistive voltage divider the use of stable resistors and insulation material together with a proper shielding of both the primary and the secondary parts are crucial.

With the evolution of technologies and used materials it is now possible to achieve accuracy classes 0,2S for LPCTs and 0,2 for LPVTs which are needed for revenue metering applications, where the type testing according to [2], [3] and [4] fully proves the performance of LPITs over the full range of various operating conditions [5].

3. Wider range of compatible IEDs

3.1 IEC 61869 standard family as a key enabler but compatibility still needs to be proved by tests

Release of IEC 61869 standardization family has played a significant role in a wider acceptance of LPIT technology as it introduced a high level of standardization of the interface between LPITs and IEDs. Consequently, it enabled developments of more IEDs supporting sensor technology. Three key areas which help with compatibility were defined by IEC 61869 standards:

- Type of secondary connector and its pinout [2], where RJ45 connector is a dominant solution used in primary distribution applications
- Standardized rated burden 2 MΩ / 50 pF for LPITs [2] which shall match with input impedance on IED side to mitigate impedance matching error between LPIT and IED.
- Correction factors as the way how to utilize the signal processing on IED side to achieve the specified accuracy class of LPIT. IEC 61869 standards define the ratio correction factor and phase offset correction factor for both LPCT [3] and LPVT [4].

Despite the defined requirements above, it is still highly recommended and needed to prove the compatibility between LPIT and IED by laboratory tests which shall be focused on:

- Primary injection testing of currents and voltages in the full operating range of LPITs where measurements on IED shall be within specified tolerances, considering the measurement errors of the whole chain.
- High harmonics primary injection testing of currents and voltages in the full harmonics' measurement range of LPITs and IEDs.

3.2 More IED types now compatible with LPITs

IEDs supporting LPIT technologies now cover a wide range of applications for the protection, control, measurement and supervision of power systems. Evolution of microprocess based IEDs and their signal processing now enables to be used as solutions not only as Protection relays, but also as Power quality analysers and Energy meters. The rapidly growing acceptance of LPITs has motivated more vendors to develop compatible IEDs and thus allowed the end user to have wider technical options. Compatible IEDs can now cover following functionality in the MV applications: Protection relays, Fault Passage Indicators, Remote Terminal Units, Control Switching Devices, Power Quality Analysers, and Power Quality and Energy meters.

4. Revenue metering solution

Historically one of the main gaps in using of LPITs in wider range of applications was a missing solution in revenue metering. The main challenges for closing of this gap have not been resolved for a long time:

- LPITs were not able to achieve accuracy performance needed in these applications, but the recent evolution in LPITs technology enables reaching the accuracy classes 0,2/0,2S comparable with conventional Instrument transformers with a much wider operating range.
- Availability of compatible Energy meters for revenue metering applications was also an obstacle for a long time but even this technical gap is closed nowadays.
- The last challenge was represented by legal metrology, where all devices shall be a subject for an approval process done by metrology institute(s) to be certified for revenue metering purposes. For compliance with these requirements the Revenue meter shall be in line with the Measuring Instruments Directive 2014/32/EU (MID).

Even, when the solution with using the LPITs for metering was comparable from the accuracy point of view to the conventional Instrument transformers, with utilization of multiple benefits to the end customer, it was not possible to certify Revenue energy meter with LPITs inputs according to the MID. The reason was the harmonization of the MID with the outdated standards [5]. However, the update of the MID harmonization in 2023 allowed to certify Revenue energy meter with LPIT inputs.

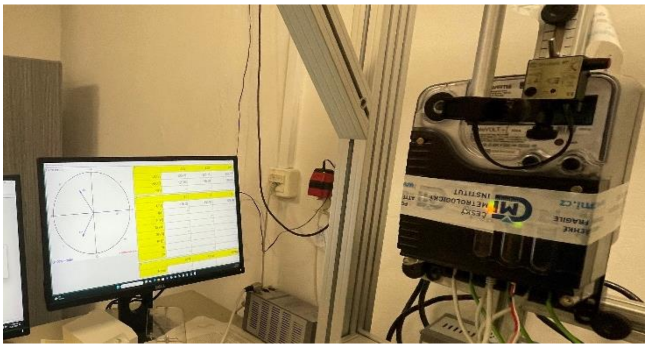

Fig. 2 MID certification of Revenue energy meter by Czech Metrology Institute

To prove the reliability of the Tariff energy meter and to achieve the MID certification tests were performed by the Czech Metrology Institute according to relevant articles of the following standards: EN IEC 62052-11:2021/A11:2022 [6], EN 50470-3:2022 [7], EN IEC 61000-4-19:2014 [8] and WELMEC Guide 7.2:2023 [9] with successful results [10].

5. Busbar differential protection

Protection of power system busbars is one of the most critical relaying applications. A false trip can disconnect numerous feeders, causing outages for many customers. On the other hand, an uncleared bus fault would generate large fault currents, followed by thermal effects and dynamic forces, requiring high-speed operation of busbar protection.

Traditionally, high-impedance differential protection was widely used, but microprocessor-based relays now utilize low-impedance differential protection as a more advanced solution. Both methods require a dedicated set of Current transformers (CTs) in every feeder to avoid saturation and ensure reliable, stable operation. This setup needed Switchgear that could accommodate two sets of CTs, often leading to deeper panels with rear access → an expensive and thus rarely used solution.

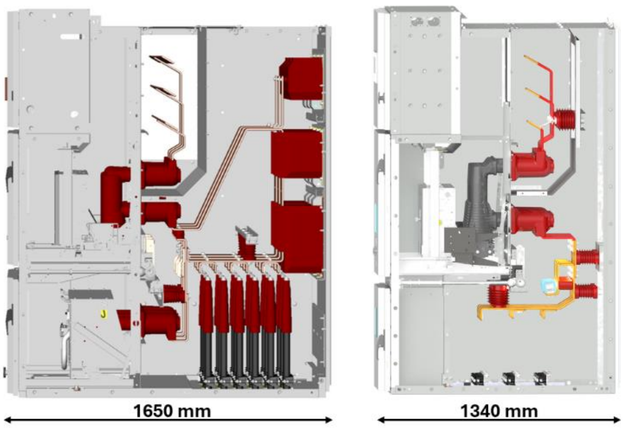

Fig. 3 Cross sections of Switchgear panel for Busbar differential protection with 2 sets of Current transformers (left) and with 1 set of Current Sensors only (right)

Today, we have busbar differential protection systems that overcome these challenges. The most advanced solution leverages the linearity of Current sensors and IEC 61850-9-2 communication. With this approach, only one set of Current sensors per feeder is sufficient to provide both busbar differential protection and standard feeder protection in standard Switchgear, saving up to 20% on Switchgear footprint.

Figure 4 illustrates an example where busbar differential protection is provided by centralized protection. Currents are measured by Current sensors and converted to IEC 61850-9-2 by the Merging Units, which also serve as feeder protection.

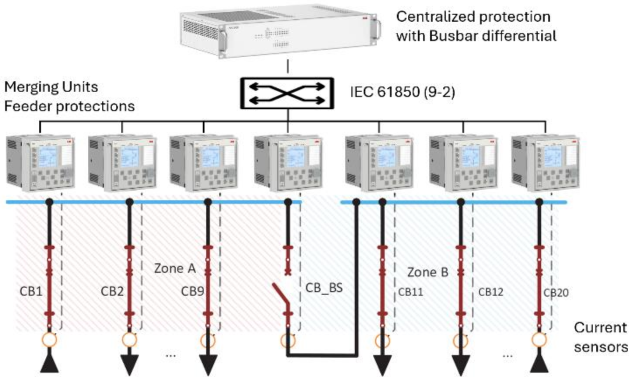

Fig. 4 Busbar differential protection based on Current sensors and IEC 61850-9-2

6. Future Outlook and Contributions to Sustainable and Resilient MV Networks

6.1 Potential future developments in Smart MV Switchgear

The experience on the MV Sensors and IEC 61850 process bus has been very promising since commissioning. The Sensor measurements and SV-signal distribution along the process bus have operated well. The MV Sensors save space, the Switchgear lineup is more compact. LPITs are safer and have more flexibility to different primary values, thus panel's primary circuits are more standardized. The process bus ensuring the voltage distribution removes the wiring between the bays and enables fail safe operations in case any fault occurs. A separate busbar voltage measurement bay is not needed anymore when utilizing LPITs, that saves space and optimizes the cost. And furthermore, all this improves the sustainability aspect of the installation, and Sensors operate with low, negligible, energy losses.

Wider systematic usage of IEC 61850 process bus brings possibilities for other architectures in the future. Centralized and virtualized protection and control (CPC, VPC) has been extensively researched during the past couple of years with real application example at Kalasatama substation in Finland [11], and first commercially available solutions are available. When IEC 61850 process bus is available in bay level devices, either as dedicated MUs or as a functionality integrated in relays, CPC and VPC solutions can be added or retrofitted in later stages. Therefore, introduction of Ethernet based process bus, either based on IEC 61850 or the new MU standard IEC 61869-13 is recommendable for increasing the future-proofness of the protection and automation system, enabling advanced protection application such as Busbar differential protection, now with optimized Switchgear design and footprint thanks to integration of MV Sensors.

The latest IEC 61869 standard family brings significant changes compared to its predecessor, IEC 60044 standards. LPITs benefit from mature standardization. The relevant IEC standards for LPITs, MUs, and communication form the basis for future-proof and interoperable devices. It expands their scope to cover HV applications and emphasizes Sensor technologies. LPIT adoption impacts technical equipment, personnel, and substation operation procedures, and enables higher standardization level between manufacturers (linear characteristic, secondary ratings and rated burden) which guarantees better interoperability for end users. Today accuracy classes for MV applications can commonly reach class 0,5 and class 0,2 (0,2S) has been already introduced in the first designs. Successful MID certification of Revenue energy meter together with high accuracy classes of MV Sensors now enable revenue metering possibilities at Primary distribution MV Smart Substation.

6.2 Significant contribution to the sustainability

MV Sensors have significantly lower energy losses compared with the existing conventional Instrument transformers; they offer higher energy efficiency during Switchgear operation and are a lot more energy efficient. If we take Switchgear panel primary circuit, electrical losses are driven by three main sources: current path and its mechanical joints, Circuit breaker and Instrument transformers. If Instrument transformers are replaced with Rogowski coils and Voltage dividers, it can reduce these losses by one third immediately. For a typical Switchgear line-up with 10 panels, it can represent 260 MWh of electrical energy wasted in losses within a lifetime of 30 years. This equals to 94 tons of CO2 emissions [12].

Table 1 Energy losses for typical Substation with 10 panels

Energy losses	Conventional Switchgear (CTs and VTs)		Smart Switchgear (MV Sensors)	
In 1 year	22.7 MWh	19.6 t CO_2e	14.1 MWh	12.1 t CO_2e
In 30 years	682.0 MWh	246.2 t CO_2e	422.4 MWh	152.5 t CO_2e

Given the lifecycle of Switchgear, investing in new technologies is not a decision to be taken lightly. The timing must be right, and your new installation shall give you more than an immediate boost: it should help you embed long-term resilience, with cutting-edge, energy/space efficient solutions that futureproof your operation for the longest possible time.

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