# LOW POWER INSTRUMENT TRANSFORMER BASED MV AUTOMATION: LESSONS LEARNED AND FUTURE APPLICATIONS

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## ABSTRACT

*In this paper the authors share the experience they gained in the field of Medium Voltage (MV) distribution automation, with particular focus on the use of Low Power Instrument Transformers (a.k.a. sensors) and their implications from the perspective of safety, installation procedures, accuracy, standardisation, interoperability etc.*

*The paper presents the key learnings from several small pilots and one massive scale project, IBERDROLA's STAR project, a smart grids project aiming to provide automation solutions for a MV network of 90,000 secondary substations which is entering its final stage after 6 years.*

## INTRODUCTION

Smart grids are no longer a buzzword but a reality that is gaining traction in the electricity business. The reasons for the adoption of new accurate voltage and current sensors for MV automation, are several and include different factors such as regulatory requirements, the introduction of distributed energy generation such as renewable energies and new loads (such as electric vehicles), energy theft detection and prevention and demand management.

These and other challenges place the need to monitor and control bidirectional MV power flows at the top of the agenda of most DSOs, and, in order to do that, it is necessary to install accurate voltage and current sensors on the MV lines. The first part of this paper presents the learnings from several projects, the second part discusses the results of one massive deployment and, finally, there is a proposal with some ideas for the future evolution of the technology.

## MV DISTRIBUTION AUTOMATION: SOME FIELD-LEARNED LESSONS

For the purpose of this paper, we shall consider the following features on a MV distribution automation project: directional Fault Passage Indication (FPI), MV monitoring (measurement of, at least, V, I, P and Q values) and traditional Remote Terminal Unit (RTU) tasks such as switchgear monitoring (alarms, switchgear status etc.) and automation (open/close commands). With these functionalities and with proper communications networks between the secondary substations and the DSO control centre, it is possible to implement advanced features such as Fault Location Isolation and Service Restoration (FLISR) schemes.

With such a broad scope of works, several challenges arose affecting both definition and technical development phases of these projects. These will be explained in the following sections.

### The importance of standardisation

When it comes to a deployment of thousands of automated Ring Main Units (RMUs) or Load Break Switches (LBS) for underground or overhead lines, the benefits of a standardised approach are obvious and, given the quantities that are involved, it becomes even more important than it is for primary substations. The challenge is combining this with two other factors: the existing installed base of MV switchgear (which will typically consist of several different models from several vendors) and ensuring that the adopted solution will be achievable in the near future for several vendors (i.e., avoiding vendor-specific solutions).

This means that there will be several constraints affecting the new measuring elements that will be in contact with the MV connectors, busbars etc.

### Choice of V & I measurement technology

It is necessary to analyse the installed base of MV apparatus and to assess the available technologies. One of

| | Generic (both for VT & CT) | Generic (both for LPVT & LPCT) |
|---|---|---|
| **Accuracy** | Non linear. Saturates. Higher accuracy classes possible | Linear. No saturation. Extended range For high accuracy classes a correction factor could be necessary. |
| **Logistics & design** | Features must be calculated for each protection, control, or metering scheme. | No need for calculations as there's no saturation and no need to load the transformer. |
| **Burden** | Load in the Ω-kΩ | Load in the MΩ range |
| | **Conventional VT** | **LPVT** |
| **Cost** | Cost of VT >>> cost of LVPT | |
| **Isolation** | Galvanic isolation. | No galvanic isolation. |
| **Size** | More room is required | Smaller and lighter |
| **Secondary status** | Must be loaded or open circuited | Safe by design |
| | **Conventional CT** | **LPCT** |
| **Secondary status** | Safe if protected, if not must be loaded or short-circuited | Safe by design |

**Table 1** VT vs LPVT and CT vs LPCT

the biggest challenges will usually be measuring voltage and current on the MV lines of an RMU. There are some space constraints with important variations depending on insulation technology (GIS/AIS), RMU manufacturer and model, but this is not the only factor. Table 1 summarises the pros and cons of conventional Voltage Transformers (VTs) and Current Transformers (CT) compared to the new Low Power Voltage Transformers (LPVT) and Low Power Current Transformers (LPCT).

When it comes to the introduction of voltage measurement, size is the main technical constraint. The installation of a new VT in an existing (or new) RMU is not feasible in most cases given that it will typically require adding another measurement cubicle thus significantly increasing the total size of the RMU. Cost is another important factor driving this decision in favour of LPVTs.

When it comes to current measuring, both CTs and LPCTs offer similar features regarding size and cost. For those applications requiring **high accuracy and/or not requiring split-core design, conventional CTs are the most reasonable choice**, especially considering the wide field experience that the industry has with them. For those **applications requiring split-core designs**, **other approaches,** such as Rogowski coils, **should be considered**. Rather than discussing well-known CTs, this paper will focus on providing an overview of new and less-known LPCTs.

## Designing LPVTs and LPCTs for simple installation and logistics

Integrating LPVTs, LPCTs or other voltage and/or current measurement devices to an RMU, without affecting safety, requires caution, especially for voltage measurement (there is extensive experience in the electricity industry with current measuring for fault passage indication applications in MV grids). This is critical for field-retrofits which cannot affect the guarantee of the switchgear vendor.

From the commissioning perspective, it is also important to remark that the whole installation procedure should be designed for fast and safe installation and later operation. It is therefore that none of the selected devices should need any site calibration and any site operation should be minimised.

### Designing LPVTs for installation in GIS RMUs

When it comes to Gas Insulated Switchgear (GIS), all the accessible parts are earth referenced, so the only way to reach the active part of the MV cable is the T connector. There are several types of T connectors, so designing and maintaining a sufficient stock of several different types of LPVTs (one per type of T connector) would not be feasible from the point of view of the LPVT vendor, nor considering the complex logistics for the DSO (who in some cases will have no updated database with the type of connector of each RMU) and the workforce. The best standardised option is substituting existing non-symmetrical connectors for symmetrical T connectors (DIN-C on both sides) and always using the same type of LPVT for this type of connector.

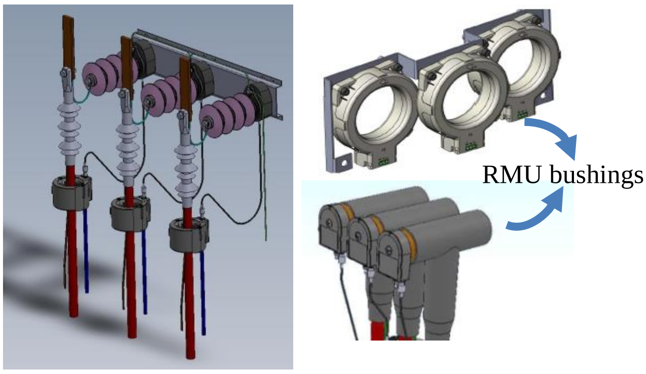


**Figure 1**. Installation in AIS (left) and GIS (right) RMUs

The DIN-C plug-shaped LPVT is plugged in the rear part of the symmetrical T-connector used for cable connection in GIS switchgear (i.e., the LPVT substitutes the plug of the T connector). Isolation is guaranteed by the connector and the design of the plug-in LPVT. The rear part of the LPVT that contains the secondary side of the LPVT, which is outside the connector, is earth referenced.

Given the reduced size of the cable compartment of the GIS RMU, it is necessary to take any detail into consideration. For instance, the low voltage connection on the secondary side should be designed to ensure that the installer can choose in which direction it will be pointing in order to ease wiring.

Thanks to these design principles, the interference of the LPVTs in this kind of RMU would be minimal.

### Designing LPVTs for installation in Air Insulated Switchgear (AIS)

The dimensions needed to install LPVTs in this kind of switchgear are bigger than those for GIS RMUs due to the lack of an insulating material (other than the air) on the MV connection. The LPVTs for AIS have to be designed to comply with the leakage distance requirements for indoor MV cubicles while also keeping the whole design as compact as possible in order to ease their installation.

The engineer on charge of guiding the installation should pay special care to the selection of the position of the LPVT within the MV cable compartment. Prior to the installation, the minimum distance between MV-referenced and ground-referenced conductive parts in the compartment should be identified. Once this is done, the LPVT should be installed in such a way that it will always respect that minimum distance. The same applies for all the cables that are used for the low voltage signals on the secondary side of the LPVT and/or LPCTs. Should it be impossible to respect that minimum distance, some additional calculations and testing might be necessary to ensure that the RMU can be commissioned safely.

**Installing CTs or LPCTs**
The optimal installation location could be the bushing. Measuring current at the MV cable would require either disconnecting the MV cable or using a split-core CT/LPCT; besides this, it would also be necessary to pass the cable-shielding through the CT/LPCT as depicted in figure 1, AIS installation.

## Connecting LPVTs and LPCTs to IEDs and IEDs to the SCADA

Intelligent Electronic Devices (IEDs) that collect and process the measurements of the LPCTs and LPVTs are another important factor to ensure the success of MV distribution automation projects. It is not only necessary to clearly define all the SW requirements to ensure a seamless integration with the SCADA and other backend systems (for which a comprehensive test book should be defined and then all IEDs should be tested against it by a vendor-independent laboratory), but it is also important to ensure HW interoperability with LPVTs and LPCTs.

The standardisation work for LPCTs and LPVTs is quite advanced and most probably the final version of the standard will allow **different secondary voltage levels**. Besides this, it is also important to remember that some types of sensors such as Rogowski coils will set special requirements regarding how the IED will process this type of input. It is therefore necessary to specify the requirements for each **type of analogue input** considering the specific requirements from LPCTs or Rogowski coils (different from conventional CTs).

**Mechanical design of IEDs for optimal installation with sensors**
The IEDs should be designed with their installation in mind. For brand new installations, the best would be that they would come integrated from factory. In case of mounting a MV monitoring solution for an existing non-motorised RMU, for which no remote control is required, given the variety of RMU models, the only standardised way is choosing wall-mounted designs for the IEDs (or IED cabinets). The IED (or IED- cabinet) should be installation-ready to minimise field commissioning time and troubleshooting by providing means to ease wiring (with pre-labelled terminal blocks) and avoid human errors.

**The choice of connectors for V and I signals is not a given as it used to be**. Contrary to CTs and VTs, the output of Low Power sensors can be wired to an IED by means of a thin wire such as the ones that are used for communications. Some vendors are leveraging on this to propose new connector options such as RJ45 connectors that could carry both the V and I signals of a given phase in a single connector. Each DSO should ensure that the choice of wiring and connectors is standardised to avoid re-wiring the installation if a given IED, LPCT or LPVT has to be substituted in the future for a device from a different vendor/model.

**Beyond interoperability: Considerations for interchangeability**
Fully interchangeable solutions (in which the seamless substitution of item A from vendor X for item B from vendor Y is possible) are advisable, but some mechanical aspects should be taken into account in order to ensure interoperability. Some key aspects regarding dimensions and interconnections (digitals and analogues) have to be specified and accepted by IED manufacturers (and by RMU manufacturers if the IED is to be integrated in the RMU).

## Ensuring performance, accuracy and safety for LPVTs and LPCTs

As we mentioned earlier, one of the main challenges is ensuring compatibility between LPVTs or LPCTs and IEDs. The goal should be to guarantee that any LPVT or LPCT will be able to operate with any IED. Some reference tests are necessary for doing this. Even if the IEC-60044 standard specifies the tests that are required for electronic instrument transformers from the point of view of electrical safety, there is no directly applicable standard that specifies accuracy requirements for different temperature, voltage or load conditions applicable to LPCTs and LPVTs. This is why it is important to pay special attention to ensure that the selected solution meets the accuracy requirements according to these variables. This will be solved shortly, when the new IEC-61869 standard is approved. This standard includes specific safety and accuracy tests for LPCTs and LPVTs that will fill the existing gaps soon.

## Considering Operation & Maintenance

With the introduction of any innovative solution it is critical to carefully manage this change throughout the involved organisations. The DSO’s project team and the equipment vendors will usually lead the change, but project leaders should bear in mind that operation and maintenance engineers should also be properly trained in order to exploit the benefits of the new systems.

The introduction of LPCTs and LPVTs in the MV network will affect mainly 2 aspects of the usual operation and maintenance procedures: MV cable insulation testing and RMU wiring testing. It is important to work together with the technology suppliers to train the staff, to provide a timely technical support and to re-define O&M procedures when necessary.

**MV cable testing**
In many cases, these LPVTs only can be installed

downstream from the Load Break Switch, so in this case the usual procedure for testing the insulation of MV cables (opening the switch and then testing the cable) will have to be redefined when LPVTs are used. Typical LPVTs will be resistive dividers, i.e., some resistors will be connected between each MV phase and the local earth.

**Checking the wiring**

Traditional wiring schemes use disconnect terminal blocks for testing both the CTs and VTs and the IEDs and colour codes for identifying each signal.

With the introduction of LPCTs and LPVTs it is still possible to use these terminal blocks but we should bear in mind that, given the very low voltage level of the signal on the secondary side of the LPCT or LPVT, the connection quality becomes critical.

Due to the low power nature of the signal, it is also possible to introduce some innovations on the wiring schemes. The use of coaxial cables with BNC or TNC connectors or STP cables with RJ45 connectors (such as the ones used on Ethernet networks) is a convenient and cost effective option that allows avoiding polarity errors in wiring. In order to use these new wiring schemes, field crews would have to be trained and equipped with appropriate tooling and procedures to ensure that safety requirements are met and that the tests are performed correctly.

## CASE STUDY: STAR PROJECT APPROACH AND RESULTS

The STAR project's MV part had to provide monitoring and automation solutions for a network of approximately 90,000 secondary substations, so it is an excellent example of the challenges that a massive MV distribution automation project involves.

**Deciding which RMUs to automate/monitor**

One of the most important decisions on the project was deciding which secondary substations had to be automated and/or monitored. Given operational needs, MV network topology and investment return considerations, the decision was to automate 12% of the secondary substations and to monitor 10% of them.

Automation was made by installing brand new automated switchgear (RMU and LBS). Field retrofitting operation was seldom used as it proved to be an economically less efficient solution with some additional technical drawbacks, due to the additional field-work.

MV monitoring (MV measurement and FPI) was made by upgrading on site the existing RMUs with standardised retrofit kits.

**Automation vs Monitoring: Decision criteria**

The decision of where to install MV automation or MV monitoring was driven by several factors: configuration of the MV network, number of customers, power that was supplied, analysis of the historical record of events, possibility of backup supply, penalties, etc. Some of the distribution transformer substations (DTS) had to be automated in order to recover service after an outage. Monitoring DTS-s completed the smart grid development of the network by giving additional information for fault location by field crews.

The cost/benefit analysis of such a project takes these factors into account and defines a clear target percentage of automated/monitored secondary substations that optimises the ROI of the project.

### The choice of LPVTs and CTs

The choice of **LPVTs** was quite obvious after analysing the requirements as they had several relevant advantages, including size and price. In some solutions they are already being supplied integrated in the RMUs.

Given that it was necessary to access the MV cables to mount the LPVTs, there was **no need for split-core** current measurement devices and, given that **conventional CTs** were a more extended and standardised solution, with a **higher accuracy** and **integrated in the RMUs,** they were chosen for this purpose.

### STAR project: Standardisation

The IEC-61869 is expected to be ready soon, but when the STAR project started, the lack of a reference standard for MV automation or monitoring solutions based on LPVTs, CTs and IEDs required a system approach where the LPVTs would be bundled with a particular IED. Later on, the evolution of the specification and additional testing allowed "unbundling" LPVTs from IEDs.

This was done including some additional requirements for the interfaces of the IEDs and the LPVTs, with some additional routine and type tests for each equipment that were defined between the DSO and the vendors in order to be sure that the LPVTs met the accuracy requirements even in the worst possible scenarios.

Another concern that arose with the adoption of LPVTs was related to the use of very low voltage signals to measure V values. In order to ensure that these signals were not affected by the operating conditions, screened cables (coaxial) were selected to connect the LPVTs to the IEDs.

The validity of this approach was successfully tested in laboratory with a completely automated RMU (with the IED, LPVTs, CTs and all the wiring from many different manufacturers) in a climatic chamber for immunity under

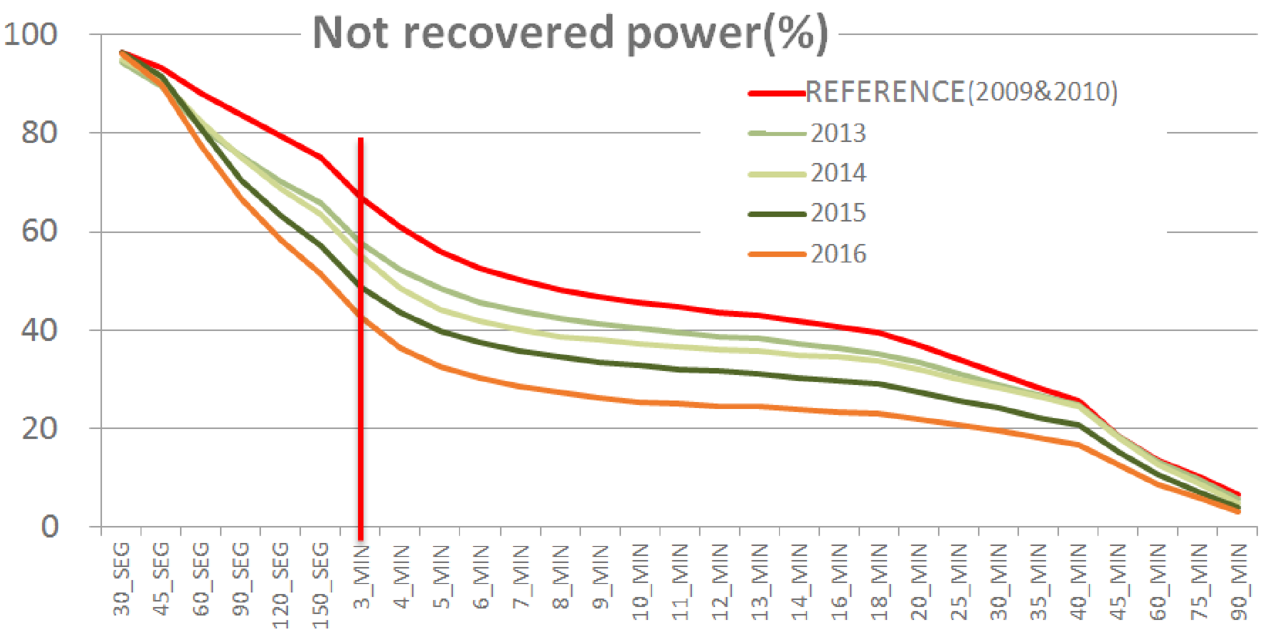


**Figure 2**. Restoration improvement: Over 55% recovered power after 3min. with the current status of the deployment

operating conditions. **After 6 years of field experience with these devices and over 50,000 installed LPVTs without any safety nor any performance problem, we can conclude that the adopted testing approach is field-proven, safe and reliable.**

## Results of the STAR project

When adopted and deployed in an industrialised way, the aforementioned technological solutions will provide some important benefits both for the DSO and the consumer.

Even if still some RMU and LPVT sensor designs require sensors installation on field, the integration of the sensors in the RMUs is a reality for various solutions. In this case RMU manufacturers and DSOs benefit from a 100% "plug and play" solution.

The improvements in quality of supply for consumers and streamlined supply chain with standardised solutions (from the DSO point of view), make the STAR project a remarkable success case in this field.

The cost of MV automation and monitoring is determined based on the prices of the required equipment (automation, communications, sensors and power equipment) plus the installation and commissioning; the benefits can be divided in several categories.

For instance, outage recovery time based in real time FPI and FLISR was reduced over 55% both in time (the outage is recovered earlier) and scope (total power affected by the outage is reduced in a certain point of time) and is still improving as the deployment goes on. Investment savings were another important factor in the success of the project. Savings in investment amounted 30% thanks to several factors such as the use of less devices integrating several functions (RTU, FPI, logics…), higher competition due to standardisation, optimised plug & play installation, extended asset lifetime (automatic accurate fault detection and location, without trial and error, and optimal switching sequences).

Savings from the DSO also included a 35% reduction in penalty costs (due to regulatory incentives) thanks to increased efficiency, Quality of Service etc. based on real time data and related applications in DMS, reduced outages, faster restoration etc.

Finally, the cost of local operations is also reduced by 25% thanks to the aforementioned factors allowing a reduction of field-staff and less auxiliary equipment.

## FUTURE APPLICATIONS

The field experience taught some important lessons and also shows the way for future vectors of improvement in the field of MV distribution automation thanks to these new devices. Gaining visibility of the MV network with Power Quality measurements will ease the integration of DER and, combined with advanced MV automation, including remote control of tap changers of distribution transformers will also allow enhanced MV voltage regulation. This visibility, combined with the available data of the DSO, will also help detect energy theft at the MV network; however, it might be necessary to enhance the accuracy of IEDs and sensors to enable this.