ADVANCED SENSORS FOR THE SMARTGRID: HOW TO DEAL WITH EXISTING SWITCHGEAR IN SECONDARY SUBSTATIONS

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ABSTRACT

The recent interest of the utilities for the automation of the electrical distribution in medium voltage grid, with the aim of improving service, while reducing operation costs, and at the same time managing the grid in real time, requires the installation of electronic equipment inside the secondary substations. These electronic equipment need sensors to measure the most important electrical parameters such as the voltages, currents and phases. At the same time, the necessary communications between equipment, located in the secondary substations that compose the medium voltage network, need, when using PLC (Power Line Carrier) technology, capacitive or inductive couplers, in order to inject the high frequency signals in the conductors.

The sensors and couplers installed in secondary substations must fulfil all the standards and existing regulations which apply to elements subject to high voltages and currents. They must be adapted in each situation to the available space, which differs greatly from one secondary substation to another, depending on its type, such as those of masonry, metallic air cabins or SF6 gas cells. However, there is currently no sensor solution for many of the existing switchgear in the distribution grid. As a result of this, a careful analysis of the requirements and existing scenarios, and available sound technology must lead us to the development of the required sensors.

INTRODUCTION

We are currently in the dawn of a new era for the energy sector, where significant innovative infrastructure rollouts are already on the way and more are coming. Also the electricity distribution business is nowadays a scenario of accelerated innovation, fuelled by CO2 emission reduction goals, distributed energy resources integration, increasing quality of supply requirements, smart metering for big-scale load curve management, the advent of electric vehicles... all these factors are pushing the introduction of the so-called Smartgrid concept.

The introduction of Smartgrids in Secondary Substations, with the goal of automating the distribution grid, requires the addition of several different functions to the existing infrastructure, such as Smart metering Concentrators, LV/MV monitoring functions, automation functions, Communications Equipment, and sometimes ancillary devices, such as power back-up systems. These functions are very innovative and currently implemented by suppliers in separate boxes (products). These products are still young in their lifecycles, as the technology and applications are being developed right now [1].

In this phase of the Smartgrid concept adoption, this leads to expensive solutions, with complex installations, as the Secondary Substations are already filled with equipment. Also the commissioning and troubleshooting is more difficult, since different new devices interact and unforeseen interoperability problems are not uncommon.

The need of measuring voltage and current with the required accuracy, and to the ability to enable PLC communication, across the medium voltage cables in environments with limited space, is one of the biggest technical hurdles faced in these applications [1]. Ease of installation and accuracy, in the case of sensors, and PLC transmission performance, in the case of couplers, are fundamental factors. It must be kept in mind that the available space is reduced, and moreover the different sensors' and couplers' dimensions need to adapt to the tee connector plug taps delivered by every switchgear manufacturer.

This paper will present and analyze the R&D and testing problems faced at each type of switchgear and secondary substation in order to obtain high quality sensors adapted to every environment and application, and thus be able to incorporate the Smartgrid functionality to the already existing MV distribution grid. Additionally, this paper will discuss the problem of integrating Smartgrid functionalities in existing secondary substations, which are already in operation. Most of secondary substations being upgraded now belong to this type. For new secondary substations, electronics and sensors can be custom built and integrated into the switchgear or transformer, so the most difficult challenge affects primarily the upgrading of the existing grid.

THE DIVERSITY OF THE MV DISTRIBUTION GRID

One of the main obstacles faced by the introduction of Smartgrid functionalities in the existing distribution grid is the diversity of the MV distribution network. The grid has evolved over time, and for any given area there are coexisting secondary substations whose age may differ by several decades. The grid has grown additionally at different speeds over time and with different budgets. Looking at a particular MV grid, one may tell the history of the utility and its acquisitions, mergers, different technology stages, deployment strategies...

Another major drawback of the MV distribution grid is that it has usually received a reduced degree of investment, so the minimal enhancements for keeping it up and running have been carried out. Inventory data may be obsolete for some regions, and no supervision or communications may be present at all.

The most important factor which determines the type and requirements for sensors to be used at the time of upgrading the grid to add advanced functionalities is the type of switchgear used in secondary substations. The most popular types are the following ones:

- Masonry switchgear. These are the oldest type, where the switchgear is mounted on masonry constructions. Space is not as restricted as in other types of substations, and different gear can be usually mounted within the MV cells.
- Open-air switchgear. This is an intermediate version, switchgear is mounted on a metallic framed cabinet using air as insulator (the switchgear is visible and can be "touched"). This kind of secondary substations have limited space available and tight requirements on safety isolation spacing.
- Gas insulated switchgear (GIS). In these secondary substations the switchgear is isolated in a closed container filled with SF6 gas (sulphur hexafluoride), which safely contains arc discharges. In these secondary substations space availability is very limited. Sensors must be closely tied to the T-connectors which introduce the MV lines into the switchgear. On the other hand, there are also several types of T connectors with different dimensions.

Each type of secondary substation requires a different sensor solution in order to guarantee a certain precision or performance, and comply with the existing limitations. This requires the development of a set of tailored sensors for every kind of substations, as the following sections will describe.

On the other hand, new switchgear will gradually include preinstalled current and voltage sensors by default, so for new secondary substations installed in the following years, the issue of having available good precision voltage and current readings will be trivial. However, given the rates of secondary substation refurbishment in most electricity utilities, the main complexity for the next coming years lies in upgrading existing MV distribution grids with the required Smartgrid functions.

ADVANCED VOLTAGE SENSORS

Voltage sensors are an indispensable component for properly monitoring a medium voltage network. Careful, precision measurement of voltage magnitudes and phases enables the implementation of advanced functions such as directional fault pass detection and power flow monitoring.

There are two different types of voltage sensors for this application:

- Transformer-based voltage sensors (Voltage Transformers), which are usually heavy, bulky, expensive and difficult to install.
- Resistive or capacitive voltage dividers. These sensors allow an easy adaptation to the different facility locations, depending on the medium voltage switchgear type, as described in the previous section.

As an example, using the space available in the separable T-connector used in GIS switchgear, and replacing the so-called basic plug tap, it is possible to install a voltage divider, either capacitive or resistive. This kind of divider can provide an accuracy of up to class 1, maintaining a reasonable balance between accuracy and price. At the same time it is very simple to install, and requires no extra space in the switchgear, as seen on figure 1.

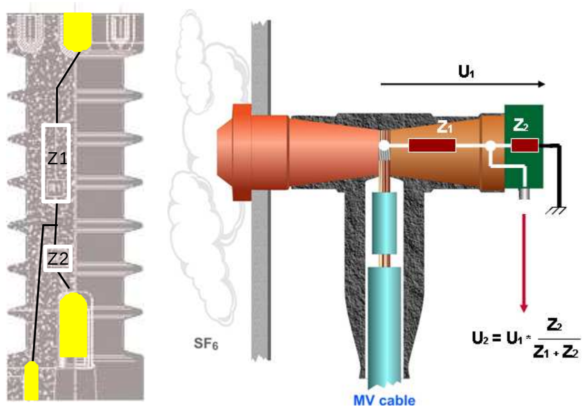

Figure 1. Voltage sensors for MV masonry and gas switchgear

The grounding of the outer semiconductive part of the T-connector in GIS switchgear guarantees that the electric field is confined inside the divider. As a result of this one additional benefit is that the effect of the near adjacent phases over the high impedance of Z1 can be minimized.

In order to guarantee the required system-level accuracy, a strategic choice and placement of the impedance Z1 within the plug tap divider and phase compensation introduced by Z2 could be required to achieve the desired accuracy, both in amplitude and phase, avoiding unwanted parasitic effects. Additionally, individual parameters like exact phase and voltage ratio values can be supplied for every divider, in order to improve the accuracy class of the total system using software based compensation in the electronic device processing the analog readings.

Resistive or capacitive voltage sensors share the following advantages:

- They are not subject to voltage transformer saturation effects, their response being very lineal.
- Their output terminals can be permanently short-circuited with negligible change in the power consumption, which is a great advantage over voltage transformers.

On the other hands, these dividers can show variations with voltage and temperature. Extremely careful divider design is required in order to alleviate this variance which degrades the precision of the divider. The variation with temperature may be internally compensated with proper sensor design.

These voltage sensors can be easily installed in existing MV switchgear, and thus they enable the directional fault indicators and network monitoring systems to do their job with the required accuracy.

ADVANCED CURRENT SENSORS

As with voltage sensors, different types of sensors can be used in medium or low voltage smart grid applications, depending on the available space, the required accuracy, the expected ambient temperature variation and the availability of an external power supply to feed the electronic elements in the sensors (based in Hall Effect, for instance). In addition to this, installation difficulty and cost may have big differences from some solutions to others.

For instance when analyzing the existing SF6 or masonry switchgear, where no external dc power supply is available, Rogowski coils and inductive ferromagnetic current transformers are the most widely used sensors [2]. They are installed directly over the bushings or clamped on the MV cables. The output of the sensors is connected to an external electronic unit which performs the real current calculation based on the analog signal coming from the coils. Usually inductive ferromagnetic transformers provide better accuracy, at the cost of a more difficult installation process, as Rogowski coils are flexible and can be opened.

There are other technologies that may be used, for example current measuring based on the Faraday Effect: the polarisation of light in fibre optics is rotated proportionally to the magnetic field generated by the conductor carrying a current in the vicinity of the fibre [3]. The effect in the phase on the reflected light is measured and transduced into a current value. The installation is very easy, isolation and safety are excellent, and the current can be measured over bare conductors surrounding them with some turns of fibre optics.

ADVANCED COUPLING DEVICES

The mission of a PLC coupler is to provide an access to the network to the communications equipment. In this particular case the network is the MV distribution grid formed by overhead lines, underground cables, transformers and switchgear.

As these couplers must share the installation location and electrical parameters with the aforementioned current and voltage sensors, PLC couplers, which may be of inductive or capacitive type, are subject to the same electrical and safety standards. Dielectric strength, lightning impulse, partial discharges, etc. are electrical parameters that depend directly on the maximum voltage level of the secondary substation.

Frequency, bandwidth and the characteristic impedance of lines and cables play a fundamental role in the performance of couplers.

Capacitive couplers use a HV voltage capacitor in order to pass the high frequency PLC signals over the MV conductor. This capacitor is tuned at the required frequency band, effectively isolating the AC mains frequency.

Pass Band and High Pass are the most common LC coupler filter structures. In all cases the LV side of the coupling capacitor is connected to ground by means of a low value inductance and transient protections like surge arresters, for increased security. An insulating signal transformer is used to match the cable characteristic impedance and the equipment side impedance, and thus maximize the energy transfer. Figure 2 represents a typical LC coupler of this type.

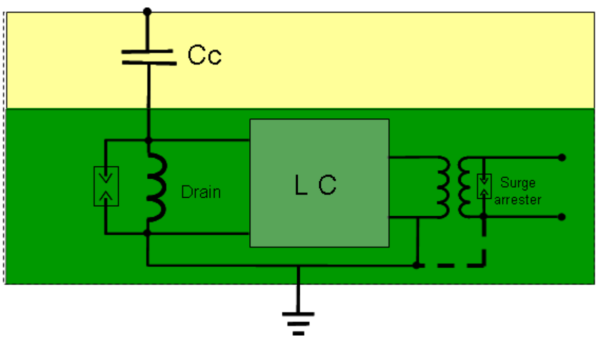

Figure 2. Capacitive coupler schematic example.

Capacitive couplers can be easily installed into the available space of the separable T connector plug tap (in GIS switchgear). This provides a very low loss connection through the MV conductor, and requires no extra space in the switchgear.

Inductive coupling is another coupling method based on current induction on a conductor or on the outer shield screen of underground cables. The installation procedure of the split cores is very easy and the inductive couplers can be a good substitute of capacitive ones, whenever there is no access to the MV plug tap, or it is just simpler to install a core around the existing conductor. Figure 3 represents an inductive coupler.

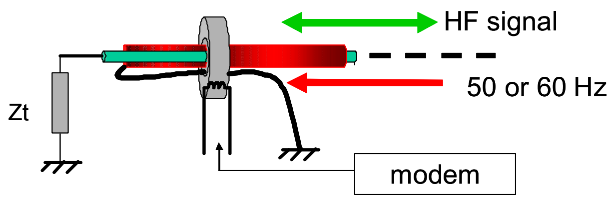

Figure 3. Inductive coupler on the conductor (2MHz to 30MHz range)

The magnetic cores must not saturate with the high values of 50 Hz mains current in order to avoid introducing intermodulation distortion in the HF (in-band) range.

In figure 3 Zt represents the transformer impedance that closes the current loop between both end secondary substations of the PLC link. This impedance consists of the parasitic capacitance of the cable to ground and that of the other two phases' impedances, and it effectively closes the circuit, allowing the communication.

WHEN SPACE RULES: INTEGRATING SENSORS AND FUNCTIONS

One of the main difficulties faced at the time of adding sensors to existing MV switchgear is the lack of space both for the sensors themselves and for an easy and straightforward commissioning. Thus, new sensor solutions are required which provide the best possible integration in minimum space. Sometimes there is space, but not enough to introduce all the required sensors (e.g. voltage sensor and coupling circuit which must be installed into the same separable T connector tap).

Integrated or combined sensors include both the voltage and current sensing functionality in the same device. Sometimes ancillary Smartgrid functions such as power line signal coupling can be also included. The idea of using the high voltage capacitor of the sensor as a means to inject PLC signal into the MV cable is not new, this concept has been used for some years in high voltage substation dividers, in order to carry PLC signals over HV lines. However, the lack of space in existing switchgear adds extra complexity to the capacitor implementation in MV.

However, in many scenarios and types of switchgear space limitations are the main concern, so integrated sensors will be the only solution to enable the introduction of advanced functions in these secondary substations. This may require to replace the separable T connectors or to make minor modifications in the switchgear (replace enclosure covers), in order to make the required interconnections. These additional difficulties underline the need for the utility of a careful analysis on which facilities must be upgraded (adding tailored sensors), and which ones must be refurbished (update the complete secondary substation) if Smartgrid functionality is to be deployed.

CONCLUSIONS

The main conclusions of this work are the following:

- Several different sensor solutions for different applications have been presented. They offer different performance in terms of precision, cost and complexity of installation.
- It is possible, though technically complex, to integrate different sensors into combined units to fit the most space limited applications.
- The Smartgrid will not be a ubiquitous reality unless tailored, highly integrated sensors are introduced to be used in the existing MV distribution grid.
- The diversity of the MV grid requires not a single sensor solution, but a portfolio of different solutions in order to cope with all the types of switchgear.
- Each electricity distribution company must analyze its Smartgrid requirements in order to determine the required precision of the measurements of analog values (voltage and current magnitude and phases), as this precision will ultimately determine the available technical solutions and their cost.

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