SENSOR TECHNOLOGY IN A MEDIUM VOLTAGE SWITCHGEAR FOR THE US MARKET APPLICATIONS

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ABSTRACT

The traditional instrument transformers have limits in various aspects due to their cores made of Ferromagnetic materials, and design requirement to deliver a high power output signal necessary to work with the electro-mechanical relays. Replacing the electromechanical relays with the digital microprocessor based relays without upgrading instrument transformer technology created technological leap but with a set of engineering practices which are sometimes not easy to implement. The more appropriate approach for the digital instruments is reduced input signal levels, which created the opportunity to use voltage and current sensors with low energy output. Examples of such sensors are the Rogowski coil and the voltage divider that can provide not only a better and a more accurate signal, but they are much smaller in overall dimensions, more standardized, safer, and less expensive products. Sensor use is especially appealing in Medium Voltage (MV) applications with limited secondary wiring distance. Over the years, sensor technologies raised to satisfactory performance level and are no longer considered as non-conventional, but are becoming devices of choice. New applications are growing as their use spread around the market, and that leads to an evolution of requirements and rules to be applied. The standardization is in progress but not equally established across the regions. The sensor technology in MV switchgear design for the ANSI market is discussing here.

INTRODUCTION

Modern switchgear designs offer higher power density, better performance, quick deployment, modularity, maintainability, reliability, and all wrapped with the cost reduction. This is particularly the case for MV metal clad and metal enclosed switchgear where the instrument transformers have now become the primary limiting factor preventing further power density improvements. Reducing their size, signal level and making them multifunctional is becoming an area of increased interest. As will be seen from the paper; a full solution to the problem also includes modern communication standards that allow measurement sharing among multiple protection and control devices.

At present, a point-to-point connection is the most common electrical system architecture for ANSI market. That can require multiple instrument transformers at the same location depending on the protection and control scheme involved, see the Figure 1. On the other side, relatively recently introduced IEC 61850 communication standard allows various Intelligent Electronic Devices (IED) to share the data using a single communication bus. Under IEC 61850-9-2 a sole source of a monitored parameter can be distributed among many subscribers, other IEDs, allowing them to accomplish more than one function [4][6]. Moreover, some IEDs can accept a low input signal from the current and voltage sensors.

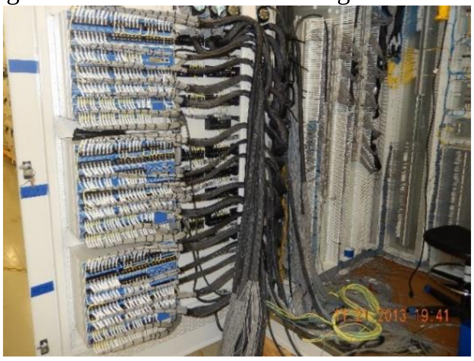

Figure 1 A data center low voltage compartment example showing conventional CT wiring for a bus differential

Benefits of the IEC 61850-9-2 approach are significant but questions naturally arise, and some of them are: sensor redundancy, protection scheme independence (no single point of failure), reliability of the Ethernet network system, speed of communication, and ability to perform differential protection. The hardware reliability of the substation hardened network switches is becoming comparable to the reliability of other IEDs including the protective relays. To further increase the reliability, a redundant optical communicant ring can be used. For differential protection, the paper [1] reports excellent performance even with the SCADA traffic present on the same bus, and with the emerging Software Defined Networking (SDN) technology, a user is given total control over traffic flows and the associated quality of service. Therefore, under new communication scheme in combination with a fast acting arc-flash protection device, the system is ready to take on even most challenging protection systems.

BACKGROUND

If we are to blame someone or something why we still use iron core instrument transformers (ITs) that would be the first generation of the protective relays and the meters, both called here instruments. The protective functions and measurements were created as a combination of the electro-mechanical components such as solenoid based plungers, mechanical levers, inductors, springs, dials, etc. For example, the overcurrent protection function was created by placing the CTs on the power lines so during an overcurrent event the secondary CT output provided enough power to energize a power breaker opening circuit. The tripping value was set by adjusting a retaining spring tension. Metering, voltage measurement, and protective functions were all done similarly. The great advantage of this approach was the ability to operate with no additional sources of power. Systems were self-contained, straightforward and reliable, but limited.

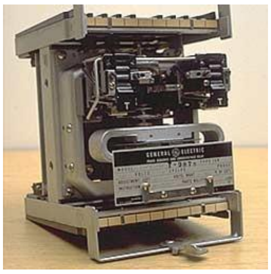

Figure 2 An electromechanical relay

The output from the CTs and the PTs had to have enough energy to run the electro-mechanical devices, and that means overcoming mechanical forces as well as to compensate for the heat loss, saturation, and voltage drops. That is why the secondary current output of the CTs was set to 5A (1A in Europe) with PTs sized to have a substantial surplus of power (0.5 to 2 kVA). Over the years the electro-mechanical instruments were slowly replaced with the digital devices, but we kept using the same instrument transformers.

In today's perspective, the amount of power supplied by the ITs is relatively high. For digital relays, a high-power analog signal from the ITs must be converted into low power signals. Conversion is typically performed by another set of the matching CTs located on an input card of an IED which are another source of limiting factors. Furthermore, matching CTs occupy significant space on the IED's input card, and by using sensor technology that can be improved [2][5].

Finally, modern instruments are without exception externally powered. So the critical question is: why keep providing sometimes hundreds of watts of available signal power level when the instruments are going to use just a fraction of it?

POTENTIAL AND CURRENT TRANSFORMERS

The potential transformer (PT), also called the voltage transformer (VT) in Europe, and the current transformer (CT) have different design and function, but in essence, they share the same principle of operation; they are both an iron core electromagnetic transformers with the copper wound coils. Because of the presence of the Ferrous metals in their cores, the ITs are affected by saturation and Ferro-resonance as the two biggest limiting factors.

Potential Transformers

The PT designs and behavior is well standardized, known by industry, and in service for years. If designed and used correctly, the PT operates at a minimal risk. Furthermore, plenty of meters and relays are available with standardized inputs levels for the PT connections.

However, PTs are large, heavy, and relatively expensive devices prone to failure if not specified, designed, produced or used correctly. To reach desirable accuracy level they need to be appropriately sized and as a final result, they have many times more available power than needed. That takes space in a switchgear and produces additional heat loading.

Figure 3 Different PT designs

The PTs can fail for many reasons: overloading, high voltage transient phenomena, Ferro-resonance, surface contamination, high partial discharge, poor manufacturing, improper grounding, mechanical damage, etc. A switchgear fault due to PT failure can have catastrophic results. Personnel can be endangered, and equipment can be destroyed. The PT primaries are therefore fused, requiring additional space to accommodate the MV fuses.

The PT costs can add up, due to its design and the MV fuses. The biggest cost factor, however, is the switchgear space. The PTs require designated compartments, sometimes a separate section. The maintenance can be expensive, and inventory large due to many ratings and models. Understanding the fact, they are complex devices for providing a simple function-voltage reading, their presence in a modern switchgear is hard to justify. As a result; magnetic PTs are used sparingly, bus PTs providing the main voltage measurement, and feeder PTs for the single-phase synchronizing voltage measurement. This approach leads to custom built switchgear increasing the engineering and real-estate cost for all involved.

Current Transformers

The CTs are robust, offer high reliability, reasonable performance, and low cost, but due to the presence of an iron core have limited dynamic range and need to be appropriately sized for each application, and purpose: protection or metering. Saturation, potential safety hazard, large inventory, physical size, and weight are some of the significant drawbacks.

Figure 4 Different CT designs

The biggest limitation for using a CT for protection is saturation phenomena. Selecting a CT of a higher accuracy or a higher ratio as a mean to overcome saturation, results in a physically larger CT and introduced error. Besides, a higher ratio CT implies lower secondary current; possibly leading to a switch from 5A to 1A secondary, a practice often left unused in ANSI market.

The electromagnetic energy stored in a CT winding is capable of producing thousands of volts if connected to a high impedance load. Induced high voltage levels can permanently destroy the CT and equipment and are well above the safety limits. The shorting blocks are necessary installed adjacent to a relay.

A long cable run between a CT and an instrument can introduce the voltage drop that cannot be overlooked. Increasing a wire size is not the most cost-effective approach, and short cable runs are often not possible because of the distances; particularly the case with centrally located control instruments. Lowering the secondary CT output will improve the design. However, metering equipment is calibrated to 5A.

As an alternative to the 5A CT is transformers with the lower output value: 1A, mA or mV, and the linear coupler. In each of the cases, except the linear coupler, the transformers have an iron core, but with the lower signal level, they offer some advantages [3] but not the entirely new solution. Further optimization is possible by moving the IEDs closer to the high voltage equipment and using digital communications to bridge the required distance.

IT Power Loss

In general, the ITs consume power with losses that can go from a few watts to hundreds of watts depending on models. The losses are due to non-ideal characteristics of the transformers created by winding resistance, core permeability, flux leakage, eddy currents, and hysteresis losses. The IT's power loss is a relatively minor cost but expressed as generated heat can contribute to overall cooling load calculations if a switchgear requires an air conditioned space. Further, for wires and instruments if the power loss is expressed as $R \times I^2$, it is clear that the 1A vs. 5A output will generate 25 times lower loss; and mV output only negligible power loss [4].

VOLTAGE AND CURRENT SENSORS

Some of the main characteristics of the voltage and current sensors are low power signal level, high accuracy, and multipurpose. Also, they are safer than standard ITs and require a lot less space in the switchgear. The main drawback of the low power sensors is their inability to drive multiple devices. This disadvantage can be eliminated by using Sampled Values data sharing following the IEC 61850-9-2 standard.

Voltage Sensor

The VS is a passive device that reduces primary voltage level using resistive and capacitive elements connected as a voltage divider. The VS has a light-weight construction and can weigh several times less than an equivalent PT, for example, 2kg vs. 25kg. If it is encapsulated as stand-off insulator as shown in Figure 5, the VS is commonly used as a bus support. The bus support style VS creates a zero footprint increase for the switchgear. Moreover, it can provide 100% measurement coverage on all switchgear nodes.

Figure 5 Voltage sensors

The VS is operating at a small output voltage level, which is safe for personnel as well as for connected equipment. If the output value is in millivolts, the open secondary doesn't present a danger like from the PT. Internal dielectric stress is typically lower than in the PT, and there is absolutely no Ferro-resonance present.

The main features of the VS are a highly linear ratio and high accuracy characteristic along the wide range of primary voltages. That results in the unique feature, the same VS can serve both: the metering and the protective functions. In proper VS design, a phase displacement error is almost nonexistent, and frequency has a negligible impact. Moreover, the frequency band is wide and can go from DC to several kilohertz.

Some designs are also capable of surviving the DC testing of the cable networks connected to MV switchgear; therefore, there is no need to disconnect the voltage sensors during such tests, and that significantly decreasing cable fault repair time and the associated costs. In a case of the VS internal component failure, the insulating material provides excellent protection against catastrophic events, preventing shrapnel generation and energized part exposure. A small number of elements makes the VS highly reliable and a maintenance free device. The progressive aging can be eliminated by design because few parts of the VS are exposed to primary voltage.

The dual functionality of the Voltage sensor reduces the product portfolio; a few VS models can cover an entire MV product line for both metering and protection, instead of having dozens of PT models. That reduces inventory, simplify logistics, and cuts the cost of manufacturing, service, and maintenance.

The voltage sensors are always configured to measure line to ground voltages, the Y connection scheme. That can be useful in providing ground fault detection and means they need to be sized for full line voltage. The presence of a ground fault can be noticed by monitoring residual voltage calculated out of the three phase-to-ground voltage measurements.

The ANSI-related standard dealing with the voltage sensors can be found in C37.92, and the relevant IEC standard is IEC 60044-7, which is soon to be replaced by IEC 61869-11.

CURRENT SENSOR-ROGOWSKI COIL

The Rogowski coil (RC) is an air-core transformer used for AC measurement with a low power signal output. It offers numerous benefits over an iron core CT due to its air core. It is physically smaller than the CT, doesn't saturate-because air cannot saturate, offers exceptionally wide dynamic range, and gives the secondary output in mV instead of Amps. The RC has traditionally recognized for excellent handling of fault current transients and a broad frequency range.

Figure 6 Different RC designs

The RC measures a rate of change of the electromagnetic field produced by the monitored current carrying conductor [5][7]. The signal as such is integrated and becomes proportional to primary current. The integration is completed either using an analog circuit or by the signal processing algorithms.

Different manufacturers have different standards, but output levels are generally in a range of 150 mV at the rated nominal current level. For example, of the nominal primary current level of 1,200 A, at 50 Hz the secondary output will be 150 mV. The output signal level in mV is below danger threshold level for humans, and the RC can be connected or disconnected from a relay while the monitored conductor is energized; although such practice should not be encouraged.

The RC sensitivity varies widely, with typical universal sensor values in the range of 1 to 2 mV/A at 50 Hz. Due to high linearity and exceptionally wide dynamic range "nominal" current rating loses its meaning. For example; universal RC sensor whose sensitivity is 1.875 mV/A may be rated for 80 A and will produce 150 mV signal at the rated system frequency. During high current fault (i.e. 20 kA) the same sensor will produce 37.5 V. Such output exceeds the levels foreseen by the IEEE C37.92 standard (max. 8 Vrms), but retains full accuracy and is acceptable from the sensor perspective. It does, however, pose a challenge for the IEDs to support the exceptionally wide dynamic range offered by the new sensors.

The Rogowski coil is a multipurpose device, for protection and metering. Properly designed Rogowski coils can achieve meeting accuracy class up to the short-circuit current. Just a few models, mainly driven by a geometry of the window opening, can cover an entire MV product line. That reduces the product inventory and cut the logistic costs.

The guideline for ANSI market can be found under C37.235, driven by the working group WG-I7. Also, there is C37.92. The relevant IEC standard is IEC 60044-8, which is soon to be replaced by IEC 61869-10.

SENSORS APPLICATIONS

The practical limitation of applying sensor technology in ANSI switchgear market at this point, is that very few relay models have the low power signal inputs available. An additional hurdle is a lack of the ANSI relays with the IEC 61850 Sampled Values communication protocol support among the USA manufacturers. Further, the utility companies in ANSI market at present are using 5 A output as a standard value, so the market is limited to commercial and industrial projects such as data centers, microgrids, renewable energy solutions, solar farms, etc.

Additional attention has to be put into the equipment selection so the relays and sensors would have matching specifications. The present lack of standardization of the output signal levels can prevent mixing and matching products among different manufacturers, unless the full compatibility of the devices is ensured. This can be addressed with compliance to C37.92 and the IEC 61869-10, IEC 61869-11 standards which are currently in development.

However, if an application allows an upgrade to sensor technology, in any of the following scenario replacing the

PTs with the voltage sensors would be advisable and keeping the existing CTs until protective relay market becomes ready. To further investigate possible switchgear configurations some recommendations are created:
1) keeping the CTs;
2) replacing the CTs with the low power CTs;
3) replacing the CTs with the current sensors.

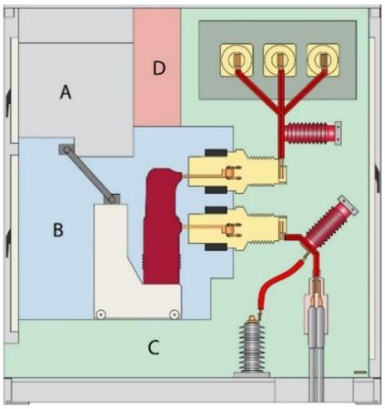

Figure 10 Medium voltage design with the voltage sensors, and standard CTs

1. The biggest design advantage of keeping the existing 5 A output CT and upgrading only the PT with the voltage sensor is that it covers the maximum number of available applications while substantially improving the design. This configuration will allow a wide selection of the relays because the CT output will remain the same and absence of the PTs will provide a clean and open space design, which can lead to footprint reduction and reliability improvements. At present, this solution is probably the most economically feasible for the US market without taking too much of commercial risk. On the other side, a presence of the CT limits further improvements, and measurement performance remains at the current level.

2. Using the low power output CTs such as conventional iron core transformers but with the 1A, mA or mV output would reduce the secondary circuit voltage drop, improve the safety, in addition to already mentioned benefits of using the voltage sensors. This solution has limited application due to the utility metering equipment being calibrated to 5 A.

3. Replacing both: the CT and PT with the current and the voltage sensors, offers the maximum design flexibility and it improves the performance, but it covers a small number of applications; usually limited only to certain commercial and industrial projects. By using sensors, switchgear footprint can be substantially reduced, and cooling, safety and performance improved. Depending on a protection scheme, the communication standard IEC 61850 may have to be used.

CONCLUSION

The sensors should be considered as a valuable replacement of the iron core based transformers. They offer an edge in switchgear design by reducing the footprint, improving safety, and lowering the output signal level. Furthermore, other main benefits are: modularity, multipurpose, an absence of Ferromagnetic materials, lower total cost of ownership [6], smaller size, and the list goes on. To fully utilize advantages of sensor technology the new communication scheme such is IEC 61850 should be applied. However, until utilities accept the low power signal level and IEC 61850 gets a wider presence in ANSI market, a combination of sensor technology with traditional technology, such is the voltage sensor in conjunction with the current transformer, is also valid approach and might offer best from both worlds at this point.

Future Development

The future of the low signal power instrument transformers is in applying an all-digital system, by digitizing the signal starting from the measuring device. The TC38 working group under IEC 61869-13 is working on a standard for stand-alone merging units. A merging unit is capable of accepting the standard analog outputs then digitizing and publishing them through the digital outputs. The all digital systems might sound more distant than a low power analog signal technology, but it might become more adaptable because of easier-digital signal management between various products and among different manufacturers.

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