THE NEXT PHASE IN THE EVOLUTION OF SAFETY BY DESIGN – DIGITAL SWITCHGEAR

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Abstract – Switchgear performance failures are rare but the results can be catastrophic. Digital switchgear enables a safer work environment through design enhancements which also reduce costs for the engineering, manufacturing, commissioning and operation of the system. The digital switchgear solution is increasingly being considered in electrical distribution and is available through multiple vendors' portfolios. It is based on technologies such as current and voltage sensors with low-energy analog outputs, finger-safe digital test switches and IEC 61850 incorporated into modern numerical Intelligent Electronic Devices (IEDs). Due to the increased simplicity and reliability and by reducing the interaction with the equipment by service technicians, operational safety is dramatically increased. In this paper, we contrast the characteristics of digital and conventional switchgear in terms of flexibility, simplicity, ease of use, efficiency and safety. The practical experiences gained from initial projects in the field are presented.

Index Terms – electrical safety, digital switchgear, current sensor, voltage sensor, non-conventional instrument transformers (NCITs), low-energy analog (LEA) inputs, IEC 61850, asset health monitoring.

I. INTRODUCTION

Creating a safer work environment while reducing design and operational costs is the key goal of the users of distribution switchgear [1]. In general, switchgear performance failures are rare but when they occur the results can be catastrophic. There has been a considerable amount of research, resulting in industry standards such as IEEE C37.20.7 [2] and standards for safe work practices such as NFPA 70E [3], to address hazards associated with electrical equipment and how to deal with them. These documents establish or provide guidelines and requirements for the design and application of electrical equipment with operational safety in mind. This has resulted in a number of possible safety enhancements specific to both low and medium voltage switchgear.

Arc resistant construction with an integral plenum has become the most common method of enhancing safety for operations and maintenance personnel in electrical installations [4]. By containing the arc fault products and venting them into a safe area, personnel and nearby equipment are protected from not only the danger of the arc itself but also the arc gasses and debris produced by the fault. This dramatically improves personnel safety as well as reliability of the system through protection of nearby equipment. Another method to improve personnel safety is to employ active arc mitigation protection techniques or devices in the system to reduce the duration of an arcing fault, see [5]. Reducing the duration of the arc fault limits the incident energy level and reduces the damage caused by the fault. A third technique to enhance operational safety is to minimize the need for personnel to interact with or to be near the switchgear during normal and maintenance operations of the equipment. This can be accomplished through features such as remote relay and control panels, remote racking for breakers and auxiliary devices and the use of sensors to monitor hot spots that result from loose connections [6] and partial discharge due to breakdown of insulation.

Digital switchgear focuses on the third element of safety improvements listed above through design enhancements to eliminate or minimize personnel interaction with the equipment. These design enhancements also improve reliability and produce cost savings for buildings, land, engineering, manufacturing, commissioning, operation and maintenance of the system.

In the preamble to 29 CFR 1910 subpart S [7], OSHA suggests that up to 67% of electrical injuries result from inappropriate action of a worker while unsafe equipment and unsafe conditions combined cause the remainder of injuries and incidents. This suggests that by reducing or eliminating the interaction of operations and maintenance personnel with the electrical equipment, the digital switchgear solution will significantly improve the safety of the installation.

II. DIGITAL SWITCHGEAR

The Digital Switchgear concept is increasingly being discussed and used in the electrical distribution industry and it is growing through different vendors' portfolios. We define it as follows:

Digital Switchgear (low or medium voltage) can be defined as an enclosure for circuit switching, *interruption and control devices where all status information, measurements and commands are reliably transferred on a common communication [61850] Ethernet bus.*

Digital Switchgear is based on the combination of technologies such as current and voltage sensors with low-energy analog (LEA) outputs in place of conventional instrument transformers, finger-safe digital test switches and IEC 61850 incorporated into modern numerical Intelligent Electronic Devices (IEDs), i.e., protection and control relays. Nevertheless, as shown in Fig. 1, the basic construction of the digital switchgear is very similar to that of conventional switchgear. Furthermore, when it comes to testing of the switchgear IEDs, meters and instruments during commissioning and operation, the test set-up is also similar to conventional switchgear as shown in Fig. 2.

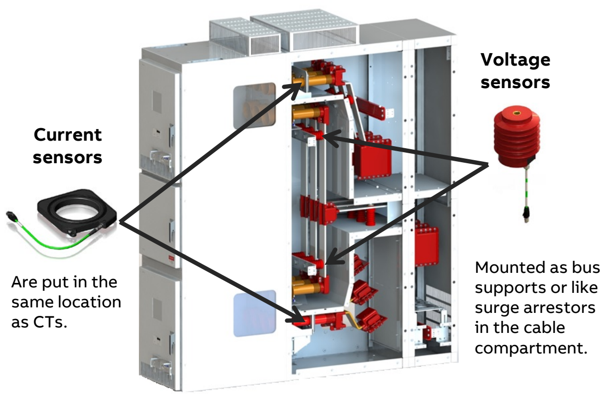


Fig. 1 – Two-high metal-clad medium voltage digital switchgear frame

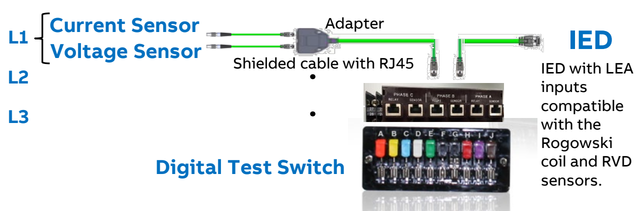
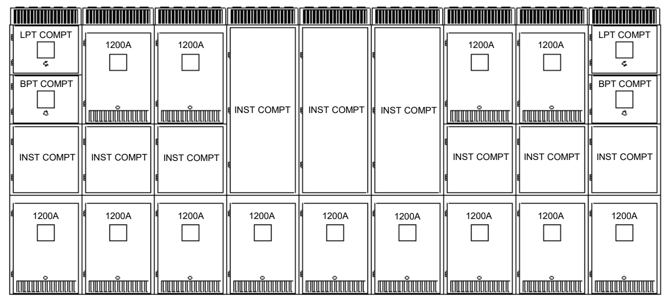


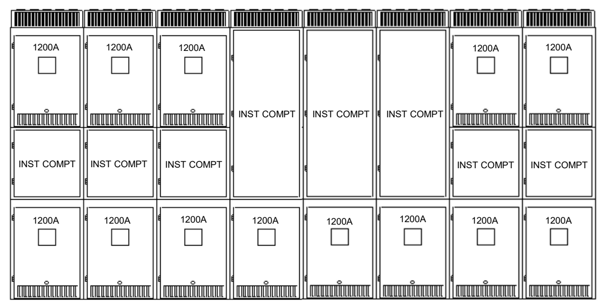
Fig. 2 – Test set-up for sensors and IEDs in digital switchgear

The current sensors are located in the same location as conventional current transformers (CTs) thereby not requiring additional space or mounting provisions. Voltage sensors, on the other hand, are mounted comparable to surge arrestors or in place of bus supports. In this approach, the typical voltage transformer draw-out compartment is eliminated and a space saving is generated through compressing the switchgear layout as illustrated in Fig. 3. In this particular example the overall switchgear frame count has been reduced by 11% resulting not only in a cost savings for the equipment, but also for the costs of the site, building and installation as well.

In order to take full advantage of the digital switchgear design and it's intrinsic benefits, the protection and control system requires the use of IEC 61850. IEC 61850 defines two main communication hierarchies within the substation for information exchange [8]. This is shown in Fig. A-1. The first is between a sensor element and a protection and control device (vertical) and the second between common devices in the primary equipment (horizontal).



Conventional switchgear



Digital switchgear

Fig. 3 – Footprint reduction with digital switchgear: an example

The first communication hierarchy is the process bus as defined in IEC 61850-9-2 for communication between the protection and control-bay-level devices and sensors (also called NCITs, Non-conventional Instrument Transformers) installed at the primary apparatus in the distribution system. The main attributes of IEC 61850-9-2 are the streaming of sampled measure values (SMVs) where the power system current and/or voltage measurements are digitalized into a package of synchronized measurement values communicated to the protection and control devices. The standard does not define the type of sensor or the means for the digital transformation. The mechanism for the digital transformation of the analog sensor measurements is described in [9] where the concept of a standalone merging unit (SAMU) that collects the sensor information and prescribes a standard method to package and communicate the output in introduced. The exchange of sampled values between these sensors and IEDs for protection functions and other purposes allows for the real-time digital information exchange. The interconnection between the sensors and actuators, which are physically connected to the power system process, is the reason the term process bus is used as the interface to the protection and control systems.

For inter-device communication, the station-level bus defined in IEC 61850-8-1 defines necessary requirements for inter-bay and communications to external systems. The station level bus provides a proven means for the common architecture targeting interoperability across vendor platforms providing a platform for standardization that generates efficiency, reliability and reduction in costs [10]. Furthermore, integration of an Ethernet process bus for unsolicited peer-to-peer device communication compared to hard wired communication produces a dramatic reduction in wiring and terminations, see Fig. 4. Also known as Generic Object Oriented Substation Event (GOOSE) messaging, it is based on hardened Ethernet technology usable in the harsh substation environment.

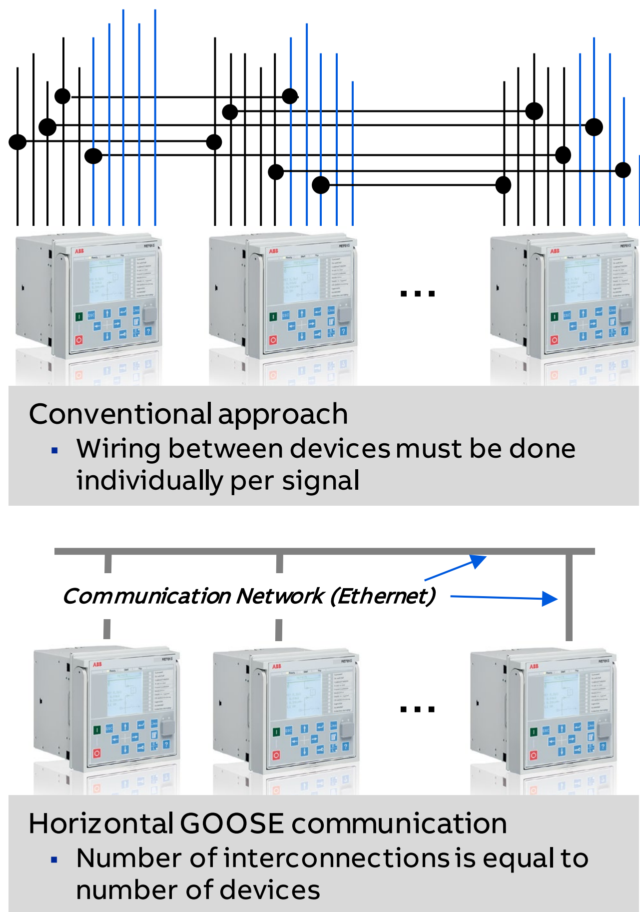


Fig. 4 – Conventional vs. IEC 61850 communication between IEDs

III. SAFETY BY DESIGN

The simplicity and reliability inherent in the digital solution equates to fewer and shorter interventions by operations and service technicians thus dramatically increasing operational safety. The added safety features of digital switchgear are summarized in Table I and discussed in more detail in the following paragraphs.

A. Safety Impact of IEC 61850 with GOOSE

The implementation of sensors and IEDs interconnected with the IEC 61850 process bus produces a significantly simplified control system due to the replacement of conventional wiring and terminations associated with these devices with fiber or Ethernet cable with RJ-45 connections. This reduction in wiring not only reduces the engineering, production, installation and commissioning costs of the equipment but generates a much simpler and highly reliable control system. For operations and maintenance personnel, this equates to a reduction in the amount of time spent in direct contact with the equipment increasing the safety of the installation. The reengineering of a sample switchgear in this fashion is shown previously in Fig. 3 and the major savings are shown in Table II.

TABLE I
ENHANCED SAFETY WITH DIGITAL SWITCHGEAR

	Prevention
Installation & commissioning	• Reduced wiring reduces errors and installation time – Ethernet connectors vs. wire terminal lugs. • Reduced weight of components makes handling of the equipment easier. • LEA outputs of sensors reduce shock hazards during commissioning.
Operation	• Voltage sensor eliminates danger of ferroresonance [11]. • Elimination of primary fuse protection for voltage sensors reduces likelihood of personnel interaction with the equipment. • Sensors have a wide and linear range. Furthermore, current sensors do not saturate. Thus, varying loads can be accommodated without the need to change CTs as in conventional switchgear.
Troubleshooting & Maintenance	• Current sensor eliminates danger of high voltage across the secondary terminal of an open CT. • For the same application, fewer sensors vs. transformers to fail. • Self-supervision & error detection in the relays facilitates troubleshooting. • Minimal control connections that could fail and require repair. • With digital test switches the testing process is same as today with the added safety provided by the sensors with LEA outputs.

B. Safety Impact of Common Communication Bus

Digital switchgear, designed to take advantage of IEC 61850 for protection and control, eliminates the need for a significant amount of point-to-point wiring. Substituting Ethernet cables and RJ-45 connectors for conventional wire and lug terminals for interconnection of devices makes installation of the equipment less complicated at site and also reduces the potential for errors in wiring and shock hazards. Additionally, reducing the number of shipping splits (see Fig. 3 and Table II) that need to be put together at site further decreases the time and effort required by personnel to complete the installation. A picture of the wiring impact is shown in Fig. 5. By reducing the overall number of wiring connections by up to 90% over conventional equipment, the digital switchgear control system is more reliable and reduces potential failures which require operations and maintenance personnel to interact with the equipment.

TABLE II
SAVINGS WITH DIGITAL SWITCHGEAR: EXAMPLE (FIG. 3)

	Conventional Switchgear	Digital Switchgear	Reduction
Length (in)	234	208	11%
Estimated Weight (lbs.)	29100	25182	14%
IT/Sensor Wiring (ft.)	2500	289	88%
IT/Sensor # of Wire Terminations	910	76	92%
Manufacturing (Hours)	135	24	82%
Number of Shipping Splits	3	2	33%

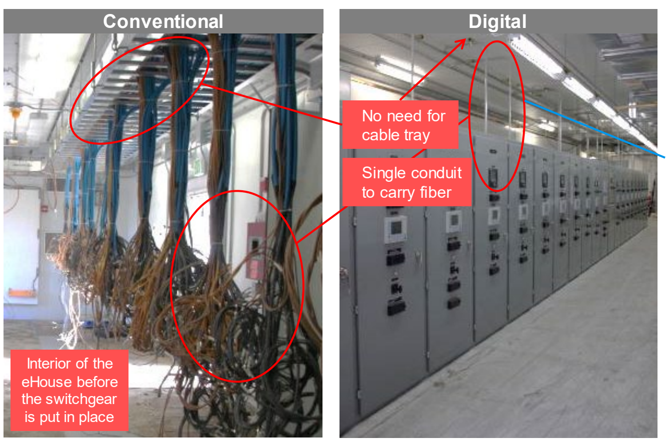


Fig. 5 – Impact of reduced wiring with digital switchgear

To further increase the reliability of the protection and control system, a redundant communication bus can be implemented by simply adding a parallel cable. This simple addition increases the reliability of the system to N-1 redundancy with minimal cost impact. Furthermore, the GOOSE messages are constantly self-checked to verify the health of the connections and devices thus, providing higher reliability and minimizing troubleshooting to locate and correct a failure. These benefits further decrease the amount of time that operations and maintenance personnel may be required to interact with the equipment further enhancing safety.

C. Safety Impact of Current and Voltage Sensors

The use of current and voltage sensors rather than conventional instrument transformers in digital switchgear delivers enhanced safety in addition to weight and space reduction. The advantages are summarized in Table III and discussed next. For medium voltage indoor applications, the most common technologies that are in use today for current measurement are the Rogowski coil or the low energy analog split-core CT. For voltage measurement, it is the Resistive Voltage Dividers (RVDs) or Capacitive Voltage Dividers (CVDs). Irrespective of the technology, the insulation ratings are the same as conventional ITs. These technologies are inherently simpler in construction than traditional instrument transformer technology.

TABLE III
SUMMARY OF SELECTED SAFETY ADVANTAGES OF SENSORS

Current & Voltage Sensors	**Traditional CTs and PTs**
Do not require additional measures for open circuit safety for current measurement devices.	CTs require shorting blocks to avoid potentially fatal voltages if the transformer is energized with the secondary terminals open.
Do not require additional measures for short circuit safety for voltage measurement devices.	PTs present a hazardous condition if the secondary terminals are short circuited with the primary windings energized.
Voltage sensors are non-inductive devices and are not subject to failure from ferroresonance events.	The inductance of PTs may resonate with the capacitance of the line and can result in an overvoltage failure due to ferroresonance.
Simpler construction with fewer internal failure points resulting in higher reliability.	Traditional instrument transformers are more complex with a high number of failure points due to the constrution.
Sensors are low energy devices and generate negligable internal heating resulting in higher reliability.	Traditional instrument transformers may experience thermal aging of the internal insulation system due to excessive load which can lead to premature failure of the device.

To appreciate the safety advantages of sensors over their traditional instrument transformer counterparts requires an understanding of fundamental differences in the technology. Specific design differences and some resulting improvements in safety are as follows:

1) Sensors do not include the large ferromagnetic path known as the core in traditional instrument transformers. By omitting this core, there is no mechanism to couple power from the primary or high voltage circuit of the device to the secondary or low voltage circuit of the device. This results in a low energy output of the device. As a result of this low energy output, an open circuited current sensor cannot produce high voltage on the open secondary terminals when the primary circuit is inductively energized.

Consider that on energized current transformers, especially those with high burden ratings, the open circuit secondary voltage may reach thousands of volts. Thus, there is significant energy available to create a potentially fatal risk to anyone contacting the secondary terminals. The open circuit voltage of a typical current sensor will generally be less than 1 V with less than 50 mW of power output, significantly lower and safer than that of conventional CTs.

2) Likewise, voltage sensors also have low voltage outputs, with low energy due to the above noted lack of a ferromagnetic core. Unlike traditional voltage transformers which can cause dangerous arcs if the secondary terminals are shorted, sensors do not provide the energy necessary for hazardous conditions in this scenario. When the secondary terminals are short circuited on a typical voltage transformer, the transformer will deliver significant energy to the secondary circuit. However, the output power delivered to the secondary of a voltage sensor changes very little in this scenario as there is no ferromagnetic core to drive the power [12]. Consider that a typical medium-voltage sensor has a voltage output of 1 to 8 V versus a typical voltage instrument transformer having a voltage output of 120 V. Likewise, the energy output of a typical medium voltage sensor will be in the milliwatt level whereas a MV voltage transformer will be able to deliver thousands of watts of power. In terms of order of magnitude difference, a typical voltage instrument transformer might provide as much as 25,000 to 100,000 times the power level of a corresponding sensor on the secondary terminals.

3) As stated earlier, voltage sensors do not have an inductive primary winding. This, coupled with the omission of the ferromagnetic core alters the characteristic of the voltage sensor such that it does not act as a large inductive device on the distribution system. If the inductance of the transformer and the capacitance of the line begin to resonate, ferroresonance can occur. This is not possible with voltage sensors. The amount of inductance a voltage transformer introduces into the circuit varies greatly based on the design. For example, a typical 15 kV instrument voltage transformer may have an inductive reactance, contributed by the copper winding as well as the ferromagnetic core, as high as 5,000 to 10,000 Ω at 60 Hz. The medium-voltage sensor by comparison has 0 Ω inductive reactance, not counting any minor inductive reactance that might be introduced by the positioning of the cable in service. Additionally, during ferroresonance events the voltage across the transformer can rise to a level which saturates the core of the voltage transformer. This, in turn, causes a large current in the primary winding which can rapidly overheat and damage the insulation system resulting in a transformer failure. Sensors by their nature are not only incapable of causing ferroresonance but are also not subject to saturation during overvoltage events [12].

4) Both voltage and current sensors are typically simpler in construction than their traditional instrument transformer counterparts. This is especially true in the case of voltage sensors. This inherently simpler construction significantly reduces the failure points, especially as compared to the amount of potential failure points in the traditional instrument voltage transformer. For example, Fig. 6 shows the typical structure of voltage sensors.

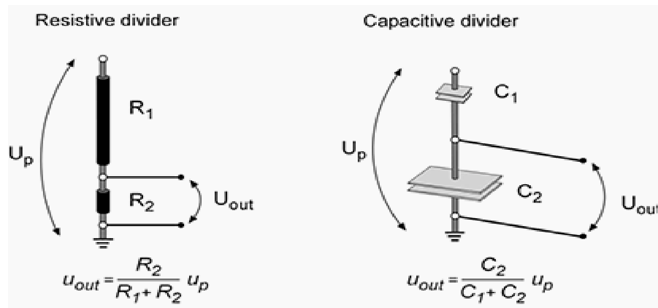


Fig. 6 – Typical internal construction of voltage sensors

To fully appreciate the difference in internal design, consider that a typical 15 kV voltage sensor will have between 2 and 5 internal active parts, including a low voltage PCB with a few components, plus the molding compound. By comparison, a typical 15 kV voltage instrument transformer may have as many as 10,000 turns of up to 2 miles of copper wire and up to 100 layers of wire with insulation between layers. Each turn-to-turn space and layer-to-layer section represents a potential failure point in the high voltage winding. Likewise, whereas a voltage sensor may have a total of 25 to 35 parts, a corresponding voltage transformer would have 250 to 350 individual parts, 10 times as many as the corresponding sensor. On the other hand, these sensors do not provide isolation from line voltage. Nevertheless, the IEDs with LEA inputs that interface with these sensors have a built-in isolation circuit. These circuits are tested to ensure that any transients that are encountered do not cause any damage.

5) Sensors, due to the absence of a ferromagnetic core to provide power transfer, generate less internal heating. This reduces aging of the sensor insulation system and decreases the chance of a potential failure due to insulation breakdown through thermal aging from sustained burden overload on the instrument transformer. As a comparison of the relative heating difference, one particular 15 kV sensor examined is projected to consume over its active life approximately 0.040 kWh of energy whereas its corresponding 15 kV instrument voltage transformer is projected to consume up to 7,500 kWh of energy over the same timeframe. That is a difference of 18,750,000 percent! This reduction in energy consumption saves energy costs

over the lifetime of the equipment. More details on the energy savings can be found in [13].

D. Safety Impact of Health Monitoring Sensors

A fourth method of integration of sensors and digital technology to improve the safety of both low and medium voltage switchgear is through the integration of asset health monitoring. This is typically comprised of cost effective sensor packages for 24x7 monitoring of switchgear health for operational characteristics such as bus temperature and partial discharge. Through constant monitoring of the high current carrying elements within the equipment, catastrophic failures are dramatically reduced or eliminated. As reported in [14] almost 40% of switchgear failures can be accounted for by heat and/or humidity issues while an additional 10% can be attributed to dielectric breakdown [15]. Data logging and monitoring of both temperature and partial discharge characteristics of the system allows for identification of potential problems that could lead to a fault or failure. Maintenance personnel can utilize this information to perform predictive maintenance rather than routine scheduled maintenance. Predictive maintenance programs allow for personnel to access and maintain only the segment or section of the equipment indicating the need for corrective action. This can practically eliminate the overall number of hours required for maintenance in medium-voltage metal-clad switchgear by an average of 4 hours per vertical section annually for routine maintenance required by the manufacturer. By eliminating intervention by maintenance personnel on a routine basis, one of the primary causes of electrical injuries [7] is eliminated thereby creating a safer design.

Predictive maintenance programs also eliminate catastrophic failures through identification and subsequent correction of a problem in the equipment before a failure occurs. Assuring that operations and maintenance personnel have accurate information as to the condition/health of the equipment reduces the risk of faults and failures that could impact equipment and personnel in the surrounding area thus creating a safer and more reliable design.

IV. CONCLUSIONS

Creating a safer work environment while reducing design and operational costs is the key goal of the users of electrical distribution equipment. Digital Switchgear provides a means to realize these requirements while providing a more reliable offering. First, and most importantly, by the simplicity of design and construction. Second, by removing the necessity for operations and maintenance personnel to interact with the equipment. Third, by active monitoring of the performance of that equipment. Thus, faults and failures can be practically eliminated providing a safer and less costly installation.

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VI. VITAE

Dr. Harsh Karandikar has over 30 years of experience in research, engineering and product management of industrial products and services and with a focus in the last decade on technologies for medium voltage electrical power distribution. He currently is the Global Product Manager for Medium Voltage ANSI switchgear and for ANSI Low and Medium Voltage Switchgear Digital Initiatives for ABB’s Distribution Solution business. Harsh holds a Ph.D. from the University of Houston and is a Fellow of the ASME.

Terry Neighbours has over 33 years of experience in the medium and low voltage switchgear and motor control businesses. He has held positions of test engineer, QA manager, project engineer, project manager, manager of project engineering and project management, OEM business manager, and is currently the Global Product Manager for Medium Voltage ANSI metal-clad switchgear. Terry is an IEEE Switchgear Committee member and a member of the IEEE – SA organization. He holds a BS degree in Organizational Management and has an extensive background in electrical engineering, applications, manufacturing and testing of medium voltage switchgear.

Ron Pate is the Global Product Manager for ABB’s ANSI low and medium voltage instrument transformer portfolio. Ron, an electrical engineering honors graduate of North Carolina State University, has extensive experience in the power industry since joining ABB in 1989. He has held a variety of roles including engineering, marketing, product management, and sales and sales management for instrument transformers, power transformers, electricity meters and smart grid systems.

APPENDIX A

COMMUNICATION BETWEEN SENSORS AND IEDs

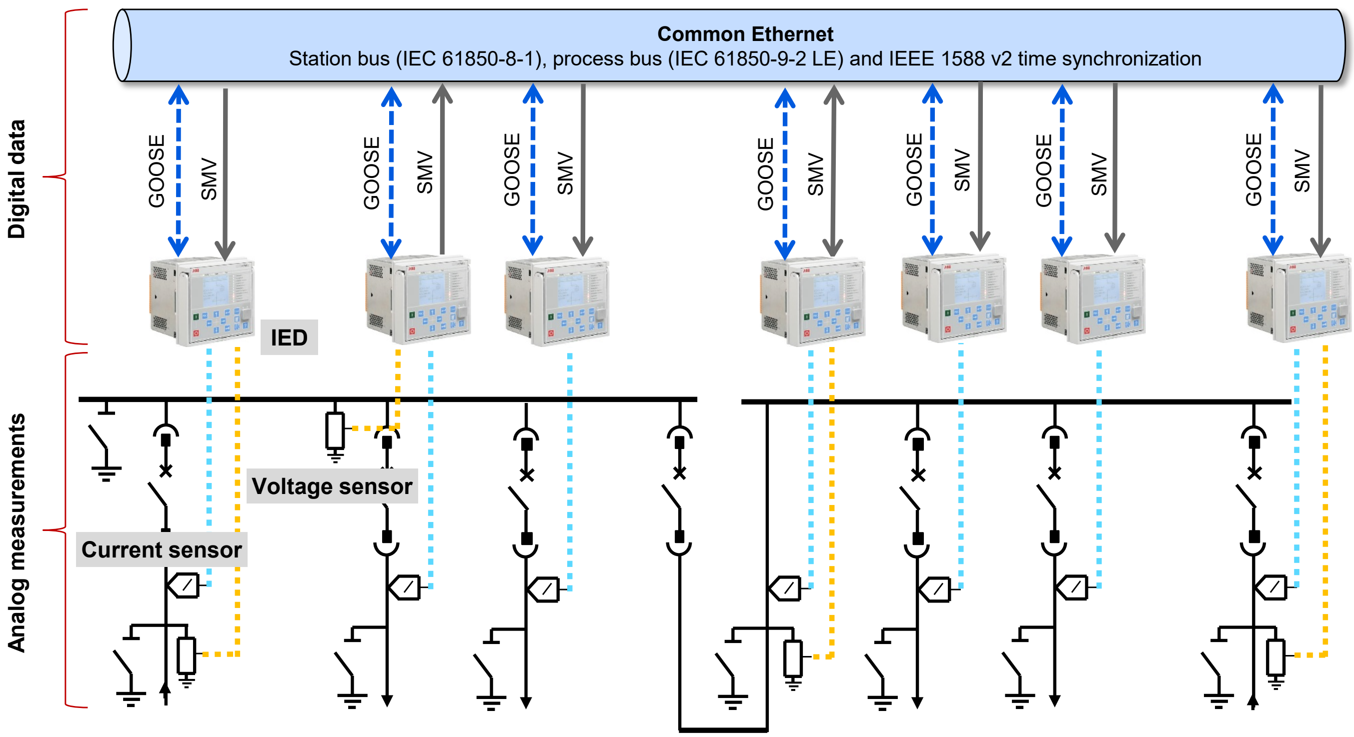

Fig. A-1 – IEC 61850 communication between sensors and IEDs [16]

The IEC 61850 standard distinguishes Station bus IEC 61850-8-1 with vertical and horizontal GOOSE communication (real time communication between the IEDs) and Process bus IEC 61850-9-2 for transmission of Sampled Measured Values (SMV) gathered by measuring devices. The UCA International Users Group created a guideline, commonly referred to as IEC 61850-9-2LE (LE stays for "Lite Edition") that defines an application profile of IEC 61850-9-2 to facilitate implementation and enable interoperability.

The Station and Process busses can be physically separated or they can coexist on the same Ethernet network. The GOOSE and SMV profiles enable designing substation communication for MV switchgear in a novel and flexible way to make the protection relay process data available to all other IEDs in the local network in a real-time manner.