PRACTICAL ASPECTS OF DESIGNING SAFE AND COMPACT MV SWITCHGEAR USING "AIR CORE CT", "RESISTOR VOLTAGE DIVIDER VT" AND MODERN INTELLIGENT MICROPROCESSOR RELAYS

Predrag Milovac
IEM – USA
predrag.milovac@iemfg.com
+1(650) 796-0404

Joemoan I. Xavier
ABB – USA
joemoan.i.xavier@us.abb.com
+1(972) 567-2378

Leslie Holloway
ABB – USA
leslie.holloway@us.abb.com
+1(804) 229-6628

Stevan Davidovich
DRD Lab-USA
stevan@drdlab.com
+1(415) 595-6559

Chenkun Zheng
IEM-USA
chenkun.zheng@iemfg.com
+1(510) 918-8124

ABSTRACT

Advancements in measurement and protection technology lead to the development of low-energy-analog (LEA) output signals in modern medium voltage switchgear design. Traditionally, medium voltage switchgear with rating 5kV-38kV uses iron cores, current transformers, and voltage transformers combined with the protective relays and metering equipment. With the new approach, iron core current transformers are replaced with LEA air-core-current-transformers (aCT), popularly known as Rogowski Coil, and voltage transformers are replaced with capacitive or resistive voltage divider (VD). IEC 61850 GOOSE and Sample Value communication technology available in modern intelligent microprocessor relays further improves the efficiency and reliability of protection and control schemes by better network communication and eliminating most copper wiring within the gear. With the apparent benefits of these advanced technologies, several specific areas of switchgear design improved. This paper discusses practical aspects and advantages of the new technologies and design considerations of an MV switchgear lineup, emphasizing conformance testing.

INTRODUCTION

From a switchgear manufacturer's standpoint, entering the digital communication era brought us dramatic change in design that was not seen in the last century. Only one exception to that was the invention of the vacuum switching technology, but even that invention did not affect general design practice, as is the digitalization of communications.

The latest generation of compact, medium voltage switchgear has several distinguishable differences from the traditional switchgear designs. The footprint is smaller, equipment safer, components are universal, and all modifications for different applications are more software-related than hardware. However, a few would imagine that hardware improvements are result driven by the need to use the better communication network between Intelligent Electronic Devices (IED).

BACKGROUND

Besides the circuit breakers, the voltage and current measurement devices are the switchgear's essential pieces of equipment. Their size, position, and function are significant factors for the overall switchgear design.

The traditional current and voltage transformers have not been changes since the beginning of electrification. The secondary signal levels, 120 V for voltage measurement and 5 A for current measurement, were set hundred years ago and are still in service today. The reason behind these high values is the first electro-mechanical relays that were operated by power from the secondary signal level [1].

However, history tells us that the low-energy-analog output signal device such as the Rogowski coil is built in 1912, and LEA voltage dividers are even older than that. With the introduction of the microprocessor-based relays and better insulating materials in the mid-20th century, one would assume that LEA will come into service, but that did not really happen, mostly due to signal level inability to drive multiple devices and inert industrial practices.

The actual shift in the market happened in the late 1990s, after introducing a set of communication rules wrapped under the IEC 61850 standard. The IEC 61850 standard defined sharing the data among IEDs through Sample Value technology, and the LEA devices become widely accepted in the substations and switchgear lineups [2]. The point-to-point connections that resulted in a forest of wires nowadays resemble modern Internet architecture; any device on the same network can talk to any other device, share data and listen to events on a single bus as an optical cable.

Such an approach started to ease a switchgear design requirement. The footprint becomes increasingly smaller, design open, and minimalistic. Modularity becomes real and quick deployment efficient. The inventory for the measurement devices is reduced to a few models compared to previously hundreds of models, and applications became software-related instead of hardware-related. Wiring time and troubleshooting are reduced by at least 30%, and the cost of ownership decreased.

Manufacturing conformance testing changed as well. Physical wiring and testing the system's automation on the shop floor become virtual wiring inside the software, and relay automation testing is completed on the office desks.

AIR CORE CURRENT TRANSFORMER AND VOLTAGE DIVIDER

The traditional current and voltage transformers (ITs) perform different functions in the switchgear, but they share the same principle of operation. Both generate secondary output signals as electromagnetic transformers using iron-core and copper wound coils.

However, an iron-core due to the presence of ferrous materials bears consequences of saturation and ferro-resonance as the two most significant limiting factors. As a result, the ITs are relatively big, with a limited dynamic range and excessive energy in their potentially hazardous windings. The stringed safety procedure handling these devices, comprehensive catalog selection, coordination with relays and meeters, and heat generated in the coils [2] are additional problems related to traditional ITs.

A viable option to traditional ITs are low energy analog (LEA) transformers. Such devices can come in various forms and secondary signal levels: for current, 1A, mV, or mA, and for voltage measurement in mV. Some LEA transformers come with iron cores, and they do offer improvement but not a complete solution due to the presence of ferro-resonance and saturation. The other group, such as air-core Rogowski coils and voltage dividers, have no ferrous materials present in their cores, and thus they offer advanced features. Some limiting factors, such as the inability to drive multiple devices, are overcome by using Sample Value sharing technology.

Air-Core Current Transformer

The Air-Core current transformers (aCT), or commonly referred to as Rogowski coils, are crafted for the first time a century ago. Since then, they were effectively used in laboratories and high-precision equipment. After introducing IEC 61850, they have become widely acceptable measurement devices used in the industry.

The main characteristic of the aCT is the absence of the iron core; instead, they have an air-core. Because air medium cannot saturate, the key features of aCT are: the absence of saturation, high sensitivity-accuracy, and broad dynamic range. Because of the unique features, aCT serves two purposes: protection and measurement. The design envelope is the same regardless of the primary current; therefore, the inventory is drastically reduced to just a few models.

Also, an aCT is seen as a safe device because the secondary signal is in mV, which is safe to handle. The stored energy in the windings is negligible; therefore, there is no heat and potential hazard.

On the negative side, aCT requires signal integration due to the phase shift, they can measure only AC, and they cannot supply more than one device [4]. However, due to the microprocessor development and shared data using Sample Value technology, all these weaknesses, except the inability to measure DC, are well covered.

Figure 1 Different design of Air-core Current Transformers (aCT), also called Rogowski coils

Voltage Divider (VD)

A voltage divider is probably the oldest electrical device and used on all voltage levels and applications. VD is constructed as a resistive or capacitive divider encapsulated in the hard resin and often installed as bus bar support when used in high voltage applications. The secondary signal level is in mV, which is considered safe to handle. Their full commercialization in the switchgear industry happened only after introducing the IEC 61850 standard due to the inability to drive multiple devices.

The main features of the VD are the absence of ferro-resonance and their small size. The lack of ferrous materials provides a high dynamic range and absence of saturation. Besides, the accuracy is very high.

Figure 2 Different designs of the 15kV voltage dividers

Compared to traditional voltage transformers, VD weighs approximately ten times less, and the size is five times smaller. The VD creates a zero-footprint in the switchgear, which can significantly affect the overall switchgear size and ownership cost.

The VD has no stored energy; therefore, they run cool, and they do not pose a hazard like the traditional voltage transformers.

IEC 61850

IEC 61850 was designed from the ground up to operate over modern networking technologies and delivers an unprecedented amount of functionality that is not available from legacy communication protocols. These unique characteristics of IEC 61850 have a direct and positive impact on the cost to design, build, install, commission, and operate power systems. While traditional protocols on Ethernet enable the substation engineer to do exactly the same thing that was done years ago, IEC 61850 enables fundamental improvements in the substation automation process that is simply not possible with a conventional approach with or without TCI/IP Ethernet. In the context of this paper, some of the key features and the benefits IEC 61850 brings are discussed below.

Standardized data modeling

The core of IEC 61850 is the standard representation of functions and equipment, its attributes, and its location within a system. The basic data model structure defined in the standard is application-independent [5].

The standardized data model enables the user to drastically reduce the cost to configure and commission devices, as IEC 61850 devices do not require as much manual configuration as conventional devices. Client applications no longer need to be manually configured for each point. They can retrieve the points list directly from the device or import it via a Substation Configuration Language (SCL) file. Many applications require nothing more but setting up a network address to establish communications. This results in lowering the commissioning costs.

Peer-to-peer communication

IEC 61850 standard specifies peer-to-peer communication as Generic Object Oriented System Events (GOOSE) data communication. It is a service used to quickly transmit time-critical information like status change, blockings, releases, or trips between various IEDs. Unlike the traditional approach, this is a multicast message which means, more than one device can subscribe to the same set of messages. It can be effectively utilized to build smart protection and control schemes like faster bus bar protection, coordinated arc protection, breaker failure schemes, bus transfer schemes and other interlocking schemes.

Traditionally, the signal paths between protection and control devices have been hardwired. In these schemes, the response time is constrained by the auxiliary relay on/off the sending device's delay and correspondingly by the input filtering on the receiving device. Both these delays can be avoided using GOOSE. Furthermore, with a hardwired system, it is not possible to know if a wire is connected and working. In contrast, all GOOSE connections are monitored continuously, and any anomalies are reported to the substation automation system. Thus, the receiving device can take corresponding actions, such as shifting into the fail-safe mode or blocking some functionality.

Additionally, protection and control devices often have a limited number of binary inputs and outputs due to cost and space constraints. With GOOSE, a higher number of virtual inputs and outputs can be used without additional device or wiring costs. This significantly reduces wiring costs and construction costs by reducing the need for trenching, ducts, conduits, etc.

The station bus may be configured in a ring topology with ring redundancy, a redundant star for IEDs with dual-port redundancy or any solutions which fulfill the requested performance and reliability requirements. The process bus may also adopt a ring or even a star topology. IEC 61850 supports Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy protocol (HSR) to ensure high availability with zero-switchover time.

The station and process buses

The station bus connects the IEDs for protection, control, and monitoring with station-level devices like the station computer with HMI and the gateway to the network communication center (NCC) using whatever services are required by the applications.

The process bus connects the IEDs with the process switchyard/switchgear devices like current transformers, voltage transformers, and switching devices like breakers. The communication of status information, commands, and bus trips are the same as for the station bus.

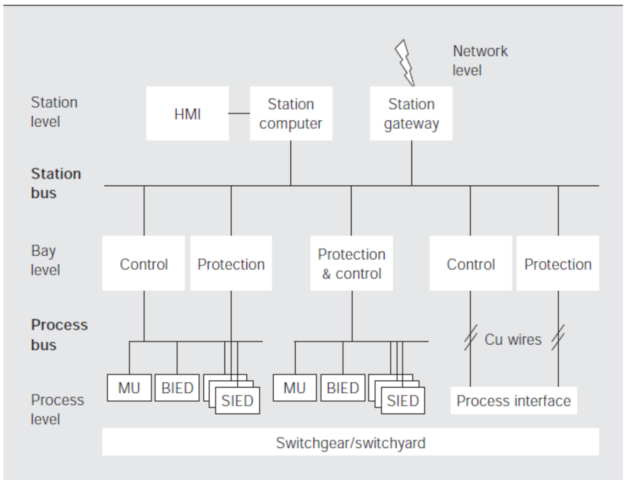

Figure 3 Station and process bus connectivity under IEC 61850

The conversion of proprietary signals from non-conventional instrument transformers for current and voltage or analog values from conventional instrument transformers to IEC 61850 Sampled Value (SV) is done using an IED called a merging unit (MU). A MU merges the 3-phase currents and voltages, including the zero-sequence components of one bay high-precision time-synchronized by definition. The process bus functionality for the switchgear is provided by protection IED with integrated MU functionality.

The communication stack and mapping

IEC 61850 has selected mainstream technology for the communication stack, i.e., a stack structure according to the ISO/OSI layers consisting of Ethernet (layers 1 and 2), TCP/IP (layers 3 and 4) and manufacturing messaging specification, MMS, (layers 5 to 7). The object model and its services are mapped to the MMS application layer (layer 7). Only time-critical services, such as SV and GOOSE are mapped directly to the Ethernet 2 link layer (layer 2) [6].

Multi-vendor interoperability

Interoperability requires the standardization of not only the data objects but also access to them. For this reason, IEC 61850 also includes standardized abstract services. The most common services are read, write, control, reporting, logging, get directory, file transfer, GOOSE messaging, sample value sharing. The language spoken by all IEC 61850 devices, irrespective of who makes it, is the same – descriptive, unique words. This gives real power to the users as they are no longer stuck with devices that speak proprietary languages. Since IEC 61850 defines more of the devices' externally visible aspects besides just the encoding of data on the wire, the cost for equipment migration is minimized. All devices share the same naming conventions minimizing the reconfiguration of client applications when those devices are changed [7] [8].

SWITCHGEAR DESIGN APPROACH

The absence of the voltage transformer reduces the individual switchgear section footprint by approximately 20%. Further footprint reduction becomes more apparent with each additional measuring node. Digital switchgear can have a voltage measuring node at a desirable location with zero footprint increase. In comparison, traditional switchgear would require a separate compartment and sometimes an entire section. Additionally, the high voltage cable management becomes increasingly better, providing an option for fully front-accessible switchgear.

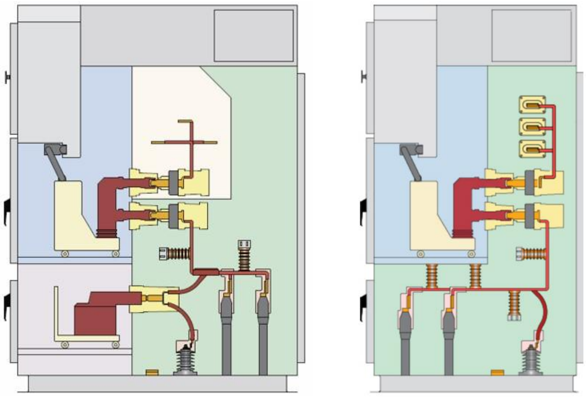

Figure 4 Comparison of the switchgear with the traditional voltage transformer (left), and "digital" switchgear with voltage sensors embedded in the stand-off insulators (right)

Replacement of the current transformers with aCT offers space savings and better high voltage insulation protection. It is expected that multiple current transformers are placed on the same current measurement node in traditional design. That increases the length of the mounting bushing and, as a final result, increases switchgear size. Contrary to that, a digital switchgear accomplishing the same task with a single aCT by sharing data to multiple subscribers using IEC 61850.

The wiring of digital switchgear offers a significant improvement as the complexity of a job increases. A single section's internal wiring reduces wiring time by about 30% and the number of wires by 50% for a simple configuration. However, saving on wiring increases significantly more as the wiring between the sections increases. For example, in traditional design and point-to-point wiring scheme, with multiple CTs placed on the same node, each CT had multiple wire runs to protective relays, sometimes located in different electrical rooms. The number of wires pulled between the sections is count in dozens. The section's wire bundles were measured in several inches, and heavy wire trays were needed to carry them. On the other hand, in digital switchgear, wiring between the sections is accomplished with just two optical cables, and the wire trays were replaced with a small-diameter electrical conduit.

CONFORMANCE TESTING

The conformance testing of the traditional switchgear design is never an easy task. This type of testing is performed to expose automation logic and check components' functionality for early error detection. Conformance testing should not be confused with the device accuracy tests or standard acceptance tests.

The conformance testing of the traditional switchgear is rarely completed under nominal current levels unless the load banks are present, but high voltage nominal levels are standard. Because of that, the conformance testing is completed in segments and on the completed switchgear lineup under the high voltage staff's monitoring due to risk factors, such as open CT secondary or residual high voltage charge.

The troubleshooting involves tracing the wiring diagrams and physically locating faulty wire or connection among dozens or hundreds of other wires.

On the other hand, testing the application under IEC 61850 communication and using LEA signal output is much different. The relay automation testing could be done away from the assembly floor and completed at the time of relay programming. The signal injection measured in mV is provided to simulate current and voltage measurement in the office-like environment, a feature not readily available for the traditional signal levels. Upon passing the logic tests, the relays are assembled in the switchgear lineup, assured that automation is inspected. This ability offers a significant step in conformance testing and reduction of production time because the automation could be inspected in parallel or even before the switchgear is assembled.

Designing a Demo Unit

The authors re-created the medium voltage Main-Tie-Main scheme to demonstrate easy conformance testing, the communication ability over IEC 61850, and other digital switchgear features. The demo unit consisted of three protective relays, HMI, industrial computer, ethernet switches, and the signal generator.

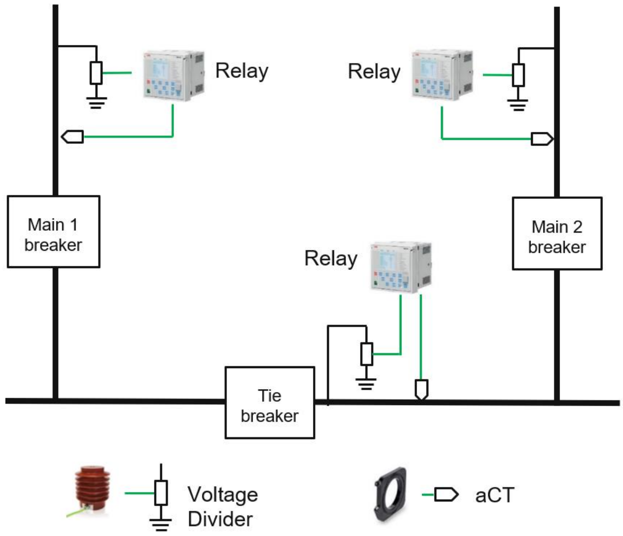

Figure 5 Main-Tie-Main scheme with the Voltage Dividers (VD) and Air-core Current Transformers (aCT) locations

The Main-Tie-Main configuration is arranged in star, PRP topology. The ability to use a ring topology, HSR arrangement, was also a viable option. The authors selected PRP topology for the demo unit because they wanted to explore the system with the possibility of a greater number of connected relays, typical for complex applications.

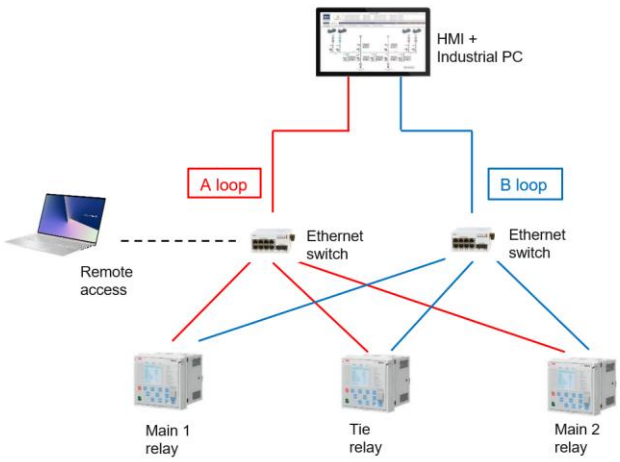

Figure 6 The Parallel Redundancy Protocol (PRP) network arrangements

In the figure above, the PRP network arrangement is shown. Two parallel loops A, and B, create redundant communication paths and thus provide zero-time switching in case of a loss of one loop. The protective relays are star-connected into the industrial network switches and optical cables connected to the industrial PC, which is embedded under HMI. Using stand-alone industrial computers such as COM 600 was the first choice, but authors also explored using a widely available industrial computer with integrated HMI. The remote access to the IEDs is available on either ethernet switch, A or B.

The M-T-M demo unit's biggest challenge was providing the voltage and current signals from aCT and VD. The system's primary current is 1,000 A and voltage level 12 kV. Based on the primary voltage and current levels, the signal levels expected from aCT and VD are 1.2 V and 0.75 V, respectively. Generating the primary nominal voltage and current to extract mV signals was not a practical option, so the authors decided to create the secondary signal using a field-programmable gate array (FPGA) signal generator. The hardware of choice was National Instruments Compact RIO hardware and associated software running on a laptop.

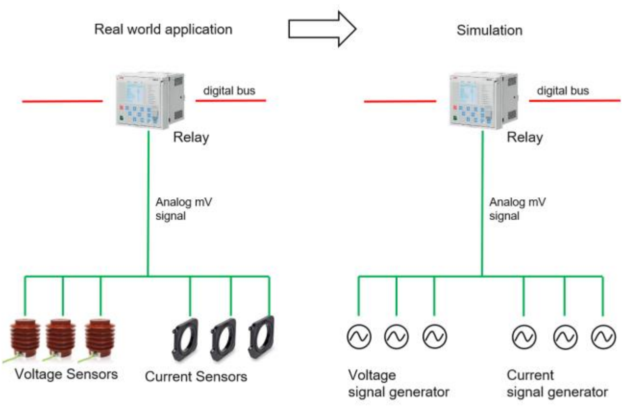

Figure 7 Schematic of simulation of the signal generation

The Compact RIO contained an FPGA fabric that generated the emulated 3-Phase signals for either 50 or 60 Hz. It updated each sinusoid every single degree in a 360-degree cycle. The real focus turned to a program on the laptop that provided the FPGA Compact RIO parameters for the emulated waveforms.

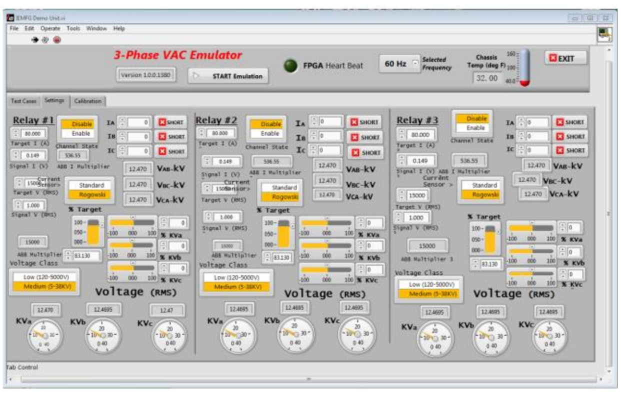

Figure 8 Main window for setting desirable voltage and current levels

The program operated on a laptop and provided the operator with a menu of both nominal and a half dozen fault conditions. It became clear that if the test device was connected to the IEC 61850 network, it could obtain in real-time the relay-switch status and update its emulation accordingly. The software has a toolkit for software developers to implement IEC 61850 communications, but this was beyond the demonstration tool's original tasking scope.

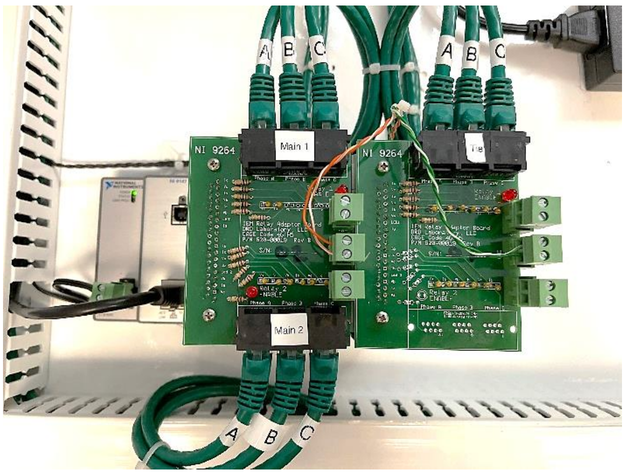

Figure 9 The custom relay adaptor board, connected to Compact RIO NI chassis; providing mV simulated aCT and VD signals to the protective relays

The Demo Unit In Operation

The demo unit is programmed to simulate several scenarios: loss of power (under-voltage,) three-phase short circuit (overcurrent,) and phase to ground short circuit (overcurrent). The scenario selection is button-operated through the GUI.

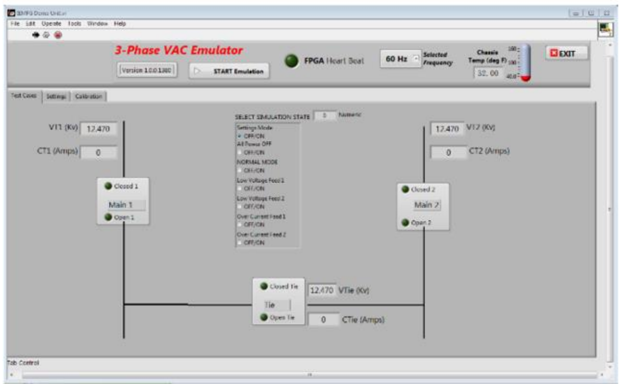

Figure 10 Main-Tie-Main scheme screen with available conformance scenarios selectors

The threshold values for triggering events are set in the relays and the system's calibration through the using the manufacturer's aCT and VD calibration coefficients. The loss of power is programmed to perform open-transition (the close-transition was also possible).

The open transition sequence was the following: upon a loss of power of either source A or B, the main breaker on the same branch open, then Tie breaker close. The user can control the return of the power over GUI. After establishing healthy voltage on the previously failed source, manual restitution is required. Upon giving the manual permission, the Tie breaker will open, and finally, the Main breaker will close, which completes the simulation of the real-life event.

Similar scenarios are created and demonstrated for the overcurrent events for three-phase fault or phase to ground fault.

Figure 11 The demo unit in Main-Tie-Main arrangement with illuminated schematic and breaker position (red close, green open), performing a simulation of loss of power on one of the sources, front view

The Demo unit's benefit is that the system component operated on full-scale voltage and current values, which was a compelling demonstration for the potential customers and owners. The demo unit has illuminated mimic busbars and the breaker position, operated by the relays, which provides a great visual effect of the system's automation. Furthermore, the authors showed all the advantages of using IEC 61850, such as easy wiring, connectivity, safety features, system redundancy, etc.

Continuous development of the conformance testing setup will include developing the specialty hardware for easy programming and connectivity of the desired number of IEDs. Such equipment will provide a safe environment to test an entire switchgear lineup's automation and on the desirable system current and voltage values.

Figure 12 The rear view of the demo unit, on top: relays, HMI and network switches, bottom: signal generator

CONCLUSION

Using air-core current transformers and voltage dividers with IEC 61850 offers great switchgear design features such as footprint reduction, manufacturing cost reduction, less wiring, increased measurement accuracy, safety, and modularity. Further, a great benefit of digital switchgear is improved conformance testing, shifting design, testing, and error tracing from physical to virtual environments. The simulated mV signal levels from aCT and VD proved to be adaptable for modeling and manipulation using conventional tools such as FPGA circuits. Also, such an approach is highly scalable, supporting of IEC 61850 library, and cost-effective.

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