

IEC 61850-9 Process Bus Line Protection Performance Test and Comparative Methodology

Camilo Esteban López.; Juan David Garcia.
Control and Protection Engineering Area
HMV Engineers
celopez@h-mv.com ; jgarcia@h-mv.com

Abstract – In 2015, San Miguel Hydroelectric Power Plant (44 MW) started operations, and in its 110 kV outgoing transmission line bay a protection system was installed, based on the Process Bus concept in compliance with IEC 61850 9-2LE standard, being the first application in Colombia with this technology and one of the first ones in Latin America. The project was initially named “Digital MK” [1]. In addition to it, since it was a pilot project, a parallel hardwired conventional protection system was installed on the same transmission line, in order to have an operation comparison between both systems.

In early 2017, El Molino Hydroelectric Power Plant (20 MW) started operations, and in its 110 kV outgoing transmission line bay two additional protection and control systems were installed also based on the Process Bus concept in compliance with IEC61850-9-1 and IEC 61850-9-2LE standards, respectively.

These three protection and control systems based on a process bus have given HMV the possibility to gather experience and performance data from different manufacturers to define the minimum requirements and conditions for a reliable implementation of the technology.

This paper provides examples of the application of the IEC 61850-9 Process Bus technology for Control and Protection of High Voltage Substations, its conceptual and detail development, parametrization, programming, testing, and commissioning methodology for different types of architectures. It also presents the performance experience of three Process Bus-based systems that have been in operation for several years already.

Keywords: IEC61850, process bus, station bus, IED, FAT tests, SAT tests, Sampled Values, Goose

Introduction

Conventional control and protection systems of substations have been replaced by digital technology that take advantage of the benefits of communications under IEC 61850 “Communication networks and systems for power utility automation” which establishes communications systems conditions under the digital substation control and protection scheme [5]. On the other hand, IEC 61850-9 section defines the

communication network (known as Process Bus) for transmission of analog signals between Data Acquisition devices in the substation yard (Merging Units) to the protection and control IED’s (Intelligent Electronic Devices). Process bus manages data packages with Generic Object-Oriented Substation Events (GOOSE) for binary type signals and Sampled Values (SV) data packages for current and voltage measurement information.

In substations with conventional Control & Protection system, signals among IED’s are hardwired, generating low flexibility for the signals exchange, higher copper wiring costs, and greater space requirements.

This Paper also presents performance experiences of Process Bus applications in factory acceptance tests (FAT) and onsite acceptance tests (SAT), from the experience gained by HMV Engineers in the implementation of three process bus systems with different manufacturers, in compliance with IEC 61850-9.

Project Description

HMV Engineers constructed, under turnkey scheme or EPC (Engineering, Procurement, Construction), the San Miguel Hydroelectric Power Plant (44 MW) and El Molino Hydroelectric Power Plant (20 MW), including the 110 kV lines to interconnect each power plant to the San Lorenzo substation (property of the local grid operator).

Both projects included the installation of control and protection systems under process bus technology in compliance with IEC 61850-9 standard, for the 110 kV outgoing line.

Protections for the San Miguel - San Lorenzo (SMG-SLO) transmission line included two independent systems; a main system under the process bus concept in compliance with IEC 61850-9-2LE standard, replacing the hardwiring for optical fiber between the switchyard equipment and the control and protection IED’s, and a back-up system with the conventional concept, using hardwiring for analog and digital signals. The conventional system was implemented in order to have an operation comparative and a back-up for the protections system based on process bus.

For El Molino – San Lorenzo (MOL-SLO) transmission line the design included two process bus systems according to IEC61850-9-1 standard and a third system with switched network technology (IEC61850-9-2LE).

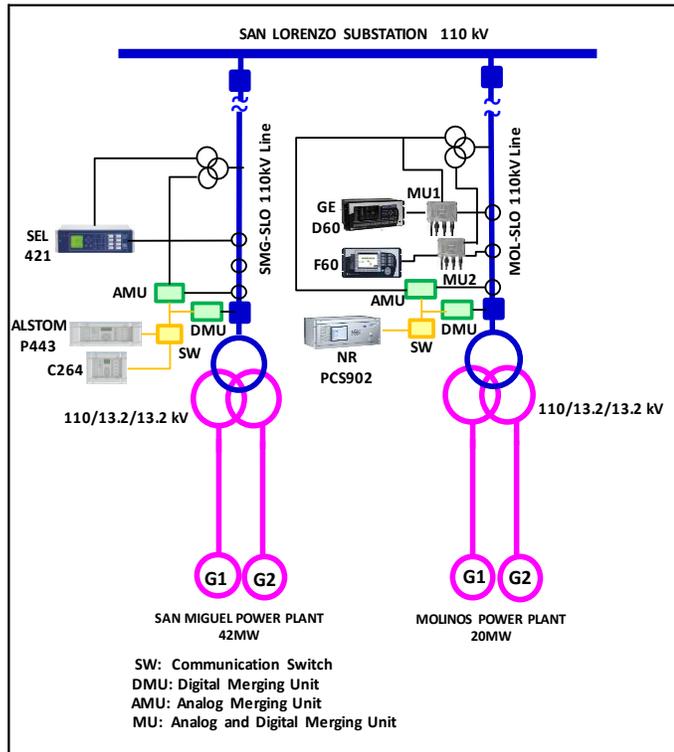


Figure 1: Line protection with process and conventional bus

Protection systems with process bus installed under standard IEC 61850-9-2 LE are made up by an (former) ALSTOM P446 distance multifunctional protection, for San Miguel Power Plant line, and an NR PCS 902 distance multifunctional protection for El Molino Power Plant line; both protection relays acquire the signals from the switchyard analog and digital Merging Units (see Figure 1). Connections at process bus level for these systems are an independent switched network, single star, with a single link among Network Switches, Merging Units and Protection Relays. [3]

The process bus system under IEC61850-9-1 is made up by a GE D60 distance multifunctional protection that receives the switchyard equipment signals from an analog/digital combined Merging Unit, through an optical fiber point-to-point connection.

The conventional protection system is made up by an SEL 421 relay that receives switchyard signals by copper wiring.

One of the main elements present in process bus systems are Merging Units (MU) which process analog and digital signals and transmit them via fiber optics communication, using switched or point-to-point networks, to the different IED's; these MU are designed

to be installed as close as possible to the primary high voltage equipment as it is hardwired to the instrument transformers and switching equipment for both the analog and digital signals acquisition.

In addition to that, and in order to monitor and compare the process bus system operation with the conventional system, at the San Miguel Power Plant a REASON fault recorder was installed to record analog, digital, and sampled values signals, as well as GOOSE messages.

Substations at both projects have three hierarchical control levels:

- Level 0: Switchyard equipment such as circuit breakers, disconnecting switches, power transformers, CT's, VT's, and Merging Units.
- Level 1: Protection and control IED's.
- Level 2: Local SCADA system of the 110 kV bay and Generation Power Plant.

Conventional System vs. Process Bus

In the conventional protection system, the relay analog inputs module becomes the interface between voltage and current transformers and the relay processing cards. These hardwired analog signals are frequency filtered in the relay before the analog/digital conversion stage, and then the sampled data is processed in the protection module. Any tripping or alarm commands are issued via the digital output modules. Sampled data are a set amount of data per cycle. [8]

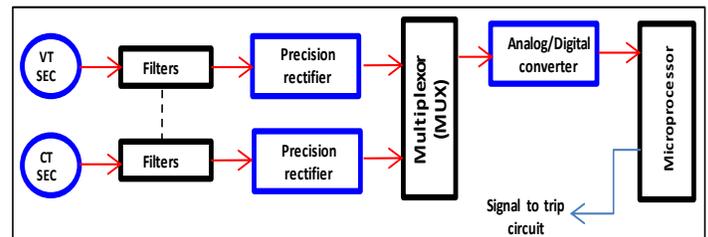


Figure 2: Conventional signal system processing [13]

In the process bus solution control and protection system IED's do not receive hardwired current and voltage analog signals from the instrument transformers nor switchyard equipment digital signals, required for the logics of the operation. In this case all signals are received via fiber optics from Merging Unit (MU) devices, which are the interfaces for the instrument transformers, switches, breakers, power transformers and any other bay devices.

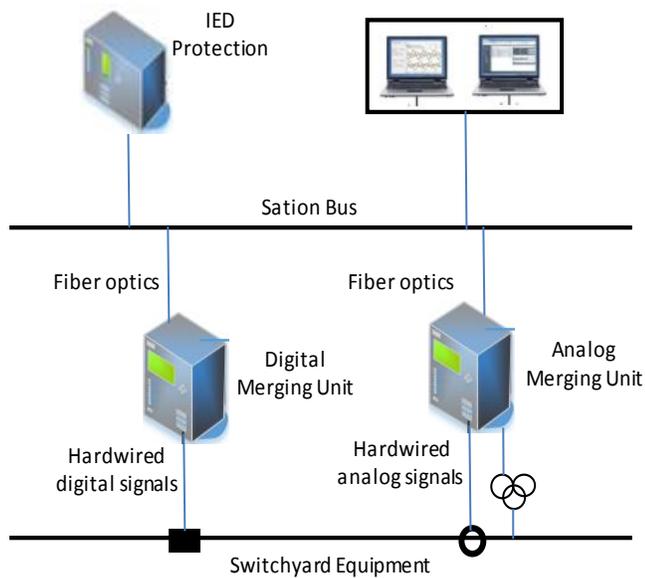


Figure 3: Process bus system, signal processing [2]

For both systems, process bus and conventional, HMV Engineers performed Factory Acceptance Test (FAT), Site Acceptance Test (SAT), and the commissioning, using new testing tools for the injection of analog and digital signals and software tools for diagnosis.

Time Synchronizing

One of the biggest challenges for the implementation of the process bus is the high reliability required by the communication system [9]; but in addition to that, the time synchronization of IED's takes a very high importance, especially in switched systems, as according to IEC 61850-9-2LE at the moment of the analog signal conversion into sampled values, voltage and current sine waves must be synchronized in time in order to allow control and protection IED's to properly reproduce phasor information [3], and avoid incorrect operations. Process bus applications require 1 μ s or less sampling accuracy to guarantee analog signal correct sampling [10].

This requirement leads to the fact that for time synchronization on switched network process bus systems, according to IEC 61850-9-2LE, it is advisable to have redundant satellite master clock (GPS), and to try to use high accuracy protocols like PTP (Precision Time Protocol) [3]. In point-to-point network process bus systems according to IEC 61850-9-1, time synchronization dependency is not as critical as IED's synchronize MU through the point-to-point network.

Process Bus System IED Tests

The objective of the process bus system tests is to verify interoperability among different devices and correct functionality of IED's before commissioning [4]. All process bus system are factory tested and may be classified into three types:

- IED communication verification test
- Interoperability between devices test
- IED device operation tests

Communications verification tests determine if IED's perform according to Standard IEC 61850 specifications; this is performed connecting the devices to the LAN network of the process bus or station bus and simulating GOOSE-like messages, publishing and subscribing, for the station bus, and sampled values readings for the process bus. [4]

Device interoperability tests are performed connecting two or more IED's from different manufacturers to the LAN network. Performing these tests sometimes comes with a series of challenges that the engineer must take care of in order for the devices to share information in both directions.

To guarantee the correct publication of the messages and network traffic, software tools like IEC 61850 analyzers are used.

The device operational tests assess the relay performance/response according to the behavior of the power system through the secondary injection of current and voltage signals.

Process bus IED's in point-to-point networks (IEC 61850-9-1) and switched networks (IEC 61850-9-2LE), must be fully tested, requiring to important changes in methodology between comparison tests and conventional systems, not only at concept level of the tests to be conducted, but also in the execution procedure using new tools that allow the achievement of integral tests of the system.

For IED tests in point-to-point communication systems, an analog/digital merging unit is required, just like the one to be used under normal operating conditions. These merging units shall be injected through traditional test equipment; likewise the test equipment receives hardwired digital signals to verify the digital MU output activation [3]. Merging units communicate point-to-point (directly) through optical fiber to the IED that is to be tested

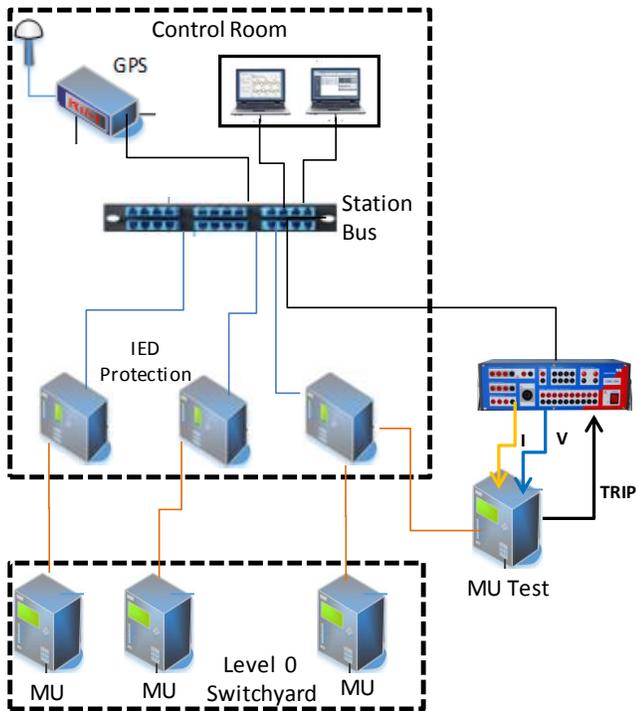


Figure 4: Connection of the protection test equipment in a point-to-point process bus (IEC 61850-9-1)

For the process bus IED's, in switched networks, current and voltage simulations are carried-out through the communication network; that is, the test equipment is a merging unit simulator able to generate sampled values defined under standard IEC61850-9-2LE; likewise the report of the relay output, such as tripping commands, pick-up, and other signaling, take place as GOOSE messages received by the test equipment.

In switched process bus networks in star topology or PRP (Parallel Redundancy Protocol) topology, only one connection to the network switches is required to integrate the merging unit simulator, as illustrated in Figure 5.

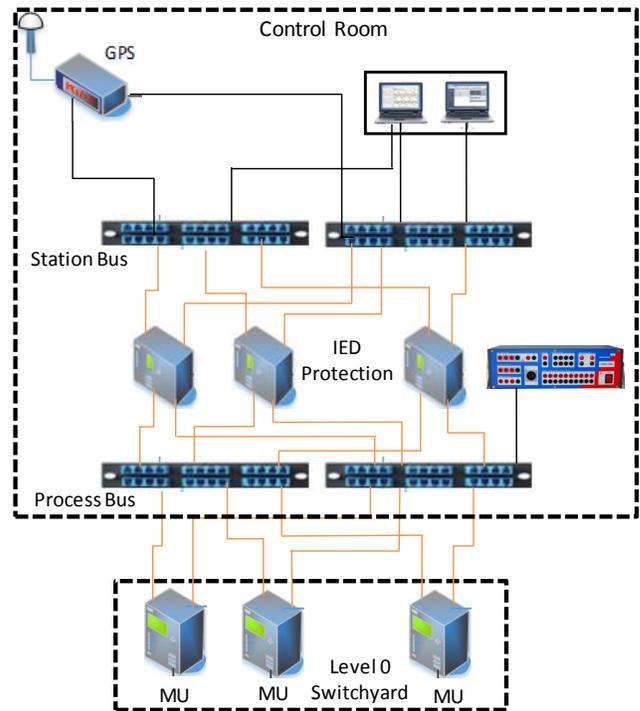


Figure 5: Connection of the protection test equipment in a switched process bus with star or PRP topology (IEC 61850-9-2LE)

For switched process bus networks in ring and HSR (High Availability Seamless Redundancy) topology, the merging unit simulator connection to the network must be done through a Red Box (Redundancy Box) device which is part of the HSR ring, as shown in Figure 6.

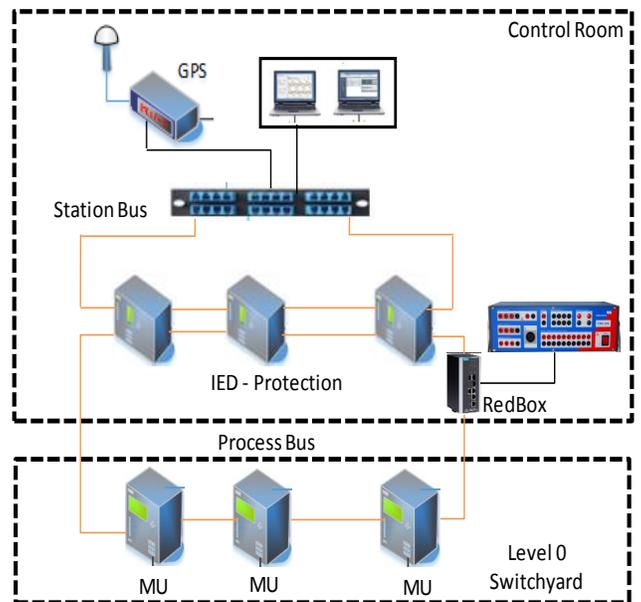


Figure 6: Connection of the protection test equipment in a switched process bus under ring topology with HSR redundancy (IEC 61850-9-2LE)

For some protection functions it is necessary that the test equipment also simulates GOOSE messages in order to publish them over the network; that is the case of the reclosing function (79) that requires simulating breaker position to verify a full operation cycle. [2]

The recommended method to perform tests on point-to-point systems includes, at least, the following verifications [1]:

- Tests on individual components, related to IEC61850 communications.
- Tests on Merging Units.

For switched process bus systems, additional to the fore-mentioned verifications, the following must be included:

- Tests on distributed applications at bay level.
- Tests on distributed applications at station level.

Tests on IED's with switched process (IEC 61850-9-2LE), require additional software tools to help data network diagnosis that indicates if sampled values and GOOSE messages are being correctly sent. In point-to-point communication process bus (IEC 61850-9-1), the software of the IED and MU manufacturer is used to guarantee that analog variables and digital signals are sent correctly to their destination IED.

Some tools commonly used for IED tests on switched network process bus are:

- *Software tools for checking of configuration files under IEC61850:* Currently there are applications in the market from different manufacturers that allow reading **.CID** files that contain the configuration of the equipment enabling to perform detailed tests of each element.
- *Analog signals simulation tool:* This tool generates current and voltage values making available for the testing engineer the required conditions for the detailed verification of device functions.
- *Merging Unit simulator:* Unlike the commonly used tool to simulate the power system, where analog signals are connected to the IED terminals, this software allows simulation of sampled values over the data network as defined under standard IEC61850-9-2LE .
- *IED simulator:* Allows the simulation of control/protection devices in which the most important functionality is publishing and subscription to GOOSE messages enabling integral tests of the configured functions in the control and protection devices.

In addition to a continuous monitoring of the status of the system, it is recommended the use of the following tools that, although not used in the projects

implemented by H MV, provide useful elements for the system maintenance and follow up, in general:

- Assessment tool for the monitoring of elements integrated to the data network, performing a permanent monitoring of them.
- Tool for the permanent generation of detailed tests to be performed to network devices.

Replacement of Traditional Protection Test Blocks

With the acquisition of analog and digital signal information under the process bus communication network, it becomes unnecessary the use of traditional protection test blocks that allow physically isolating every analog and digital connection of the IED, through the insertion of a test plug. Using simulation tools that comply with IEC 61850 standard, different modes of operation are identified allowing the IED to recognize the type of activity being performed and hence operate according to what is expected (normal operation or test mode).

These operation modes are identified as flags that tag messages sent by the simulation tools or IED's depending on the device that publishes them, and allows the subscriber IED to process them, send operation pertinent indications, and block wired contacts that would send commands to the switchyard equipment.

Factory Acceptance Tests (FAT's)

During the commissioning of the conventional process bus and hardwired line protection systems at San Miguel and El Molino projects, different fault conditions were simulated to verify operation times in every protection and perform a comparative analysis between systems.

For the performance of the tests, an OMICRON CMC356 equipment was used to simulate sampled values and GOOSE packages and network analysis software to control these network packages.

OMICRON CMC356 was configured to generate three voltages and three currents as sampled value signals and to receive, through GOOSE messages, protection relay trip commands. Through these signals, IED trigger and operation times were measured.

The main parameters of the transmission line that were configured in the protection relays are shown in Table 1 and Table 2:

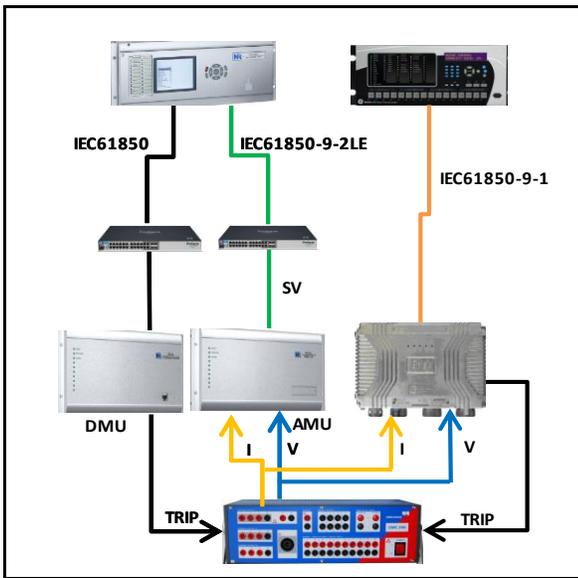


Figure 8: Switched network (IEC61850-9-2LE) and point-to-point process bus (IEC61850-9-1) process bus line protection FAT test connection scheme

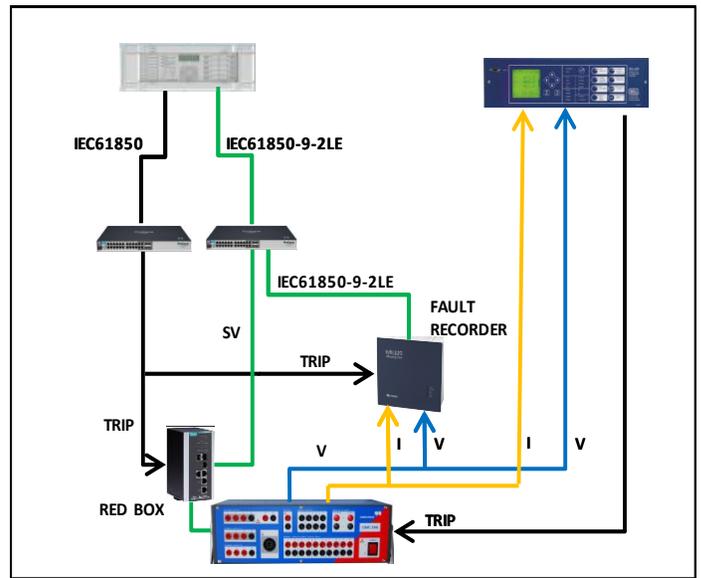


Figure 9: Switched network (IEC61850-9-2LE) and conventional wiring process bus line protection SAT test connection scheme

Site Acceptance Tests (SAT's):

The purpose of SAT is to inspect the system in its final location to guarantee a flawless commissioning and to verify the equipment complies with all performance requirements compared to the conventional systems.

The commissioning of the process bus system at the project site comprises:

- MU setup with the high voltage primary equipment.
- Hard-wiring between primary equipment and MU functional tests.
- Connection of the fibers optics that are part of the process bus LAN network, between MU and control room.
- IED operating tests and verification of the signals between MU and IED's.

For SAT tests it is not possible to have the Merging Unit near the communication equipment; therefore signal simulation for the switched network process bus system is directly performed from the communication switches; that is, the test equipment is directly connected to the substation LAN network and for the point-to-point communication process bus system a reserve Merging Unit must be available to be placed near the relay.

The connection performed for SAT tests is shown in Figures 9 and 10:

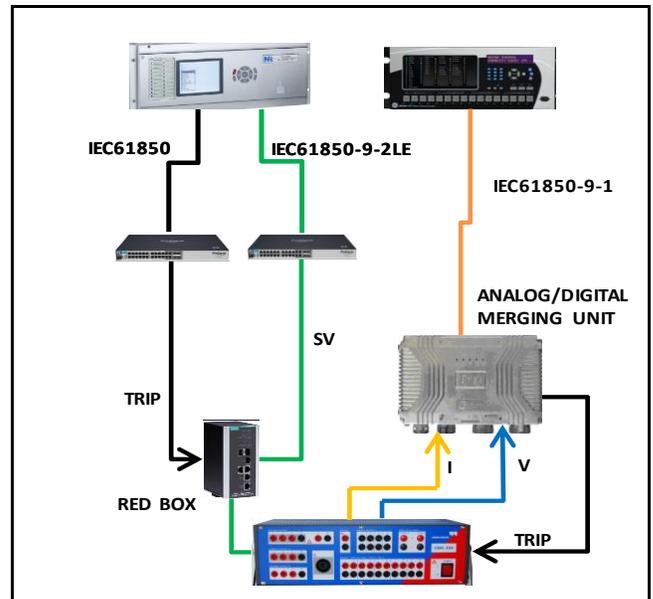


Figure 10: Switched network (IEC61850-9-2LE) and point-to-point (IEC61850-9-1) process bus line protection FAT test connection scheme

Conventional Wired and Process Bus Line Protection, Comparative Performance

Measurement Comparison

In order to make a comparison between analog measures and sampled values, an angle and magnitude profile was recorded in a REASON fault recorder

indicating analog signals as SMG110kV and sample valued signals as AMU_V_110kV.



Figure 11: Process bus and conventional system bus angular behavior.

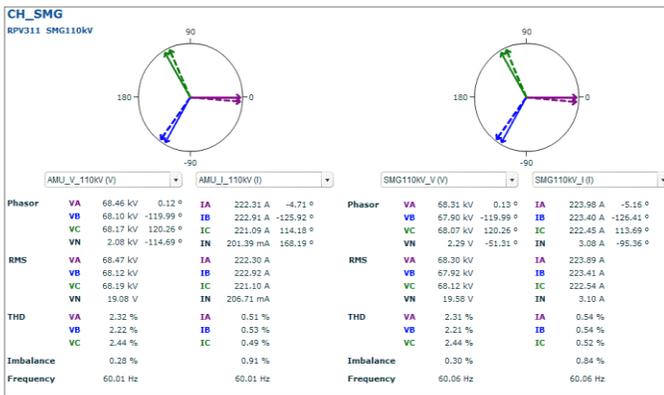


Figure 12: SMG analog measures and AMU sampled value measures.

The assessment of the measurement at the same time instant indicates that, effectively, analog Merging Units are publishing data packages that reflect analog values from instrument transformers. This comparison indicates that both relays, process bus and conventional wired, measure the same phasor magnitudes and angles of the voltage and current magnitudes.

Protection Scheme Operating Times

Different types of protection relay faults were simulated during the tests; tripping time in the test equipment was recorded both for the process bus protection and for the conventional protection.

The results of the tests are shown in Table 5 and Table 6.

Type of fault	Z2 (P-G)		Z2 (P-G) PUTT		Z2 (P-P)		Z2 (P-P) PUTT		67N
Nom. oper. Time (ms)	300		0		300		0		3267
Relay	ALSTOM	SEL	ALSTOM	SEL	ALSTOM	SEL	ALSTOM	SEL	ALSTOM
Oper. time GOOSE (ms)	317.7	NA	24.9	NA	317.3	NA	24.6	NA	3330
Oper. time. Dig. output (ms)	322.4	323	29.7	26,3	321.9	321.4	29.2	24,5	3335

Table 5: Process bus IEC 61850-9-2LE (switched network) vs. conventional protection relay operation times.

Type of fault	Z2 (P-G)		Z2 (P-G) PUTT		Z2 (P-P)		Z2 (P-P) PUTT	
Nom. oper. Time (ms)	300		0		300		0	
Relay	GE D60	NARI	GE D60	NARI	GE D60	NARI	GE D60	NARI
Oper. time. Dig. output (ms)	328.1	337.7	30.8	38.1	326.4	336.9	30.2	38.1

Table 6: Process bus IEC 61850-9-2LE (switched network) vs. IEC 61850-9-1 (point-to-point) protection relay operation times.

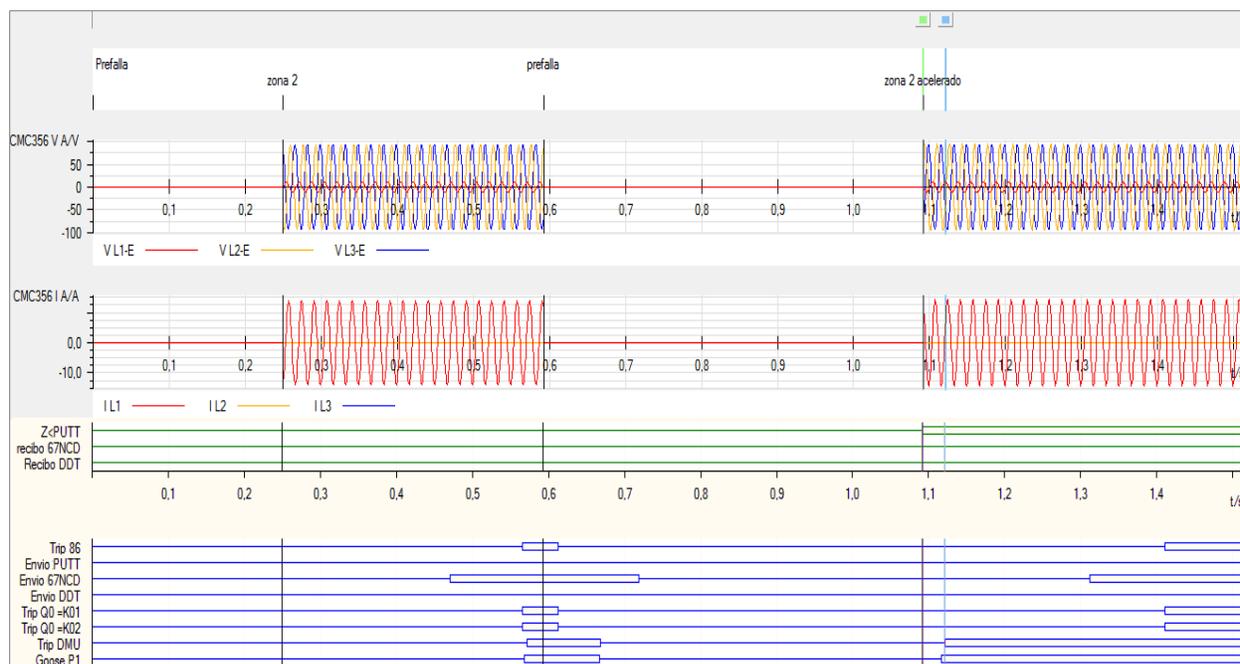


Figure 13: Process bus IEC 61850-9-2LE system secondary injection test.

In the fault cases analyzed and comparing the process bus line protection through a switched network vs. the conventional line protection, both systems performed very similarly in terms of operation time, being the conventional system a little faster for instantaneous tripping cases. The fault recorder was also able to compare simulated fault waves from sampled values which were equal to the conventional system. It is important to take into account that, in the implemented networks, sampled values were managed by an independent network from digital signals (GOOSE), due to the high traffic of information sampled values required in the network.

In the comparative of a switched network through process bus line protection vs. process bus through point-to-point network line protection, there were also similar performances by both systems with acceptable operation times, and in all cases being a little faster the point-to-point protection. Due to the differences of the compared relay brands and also different algorithms, it is

not necessarily attributable to the type of process network.

Events During Operation

As of the publication date of this paper, the process bus system installed at San Miguel 110 kV substation has been operating correctly for over two years, with similar performance as the conventional system.

During this period of time, several high voltage system faults have occurred and the process bus-based line protection has operated correctly, detecting the fault conditions and acting with times very close to the conventional system.

Below, an event that took place in San Miguel – San Lorenzo 110 kV line on August 13, 2016. The record was taken from the fault recorder installed at the substation which gets the signals both through conventional wiring and 61850 process bus.

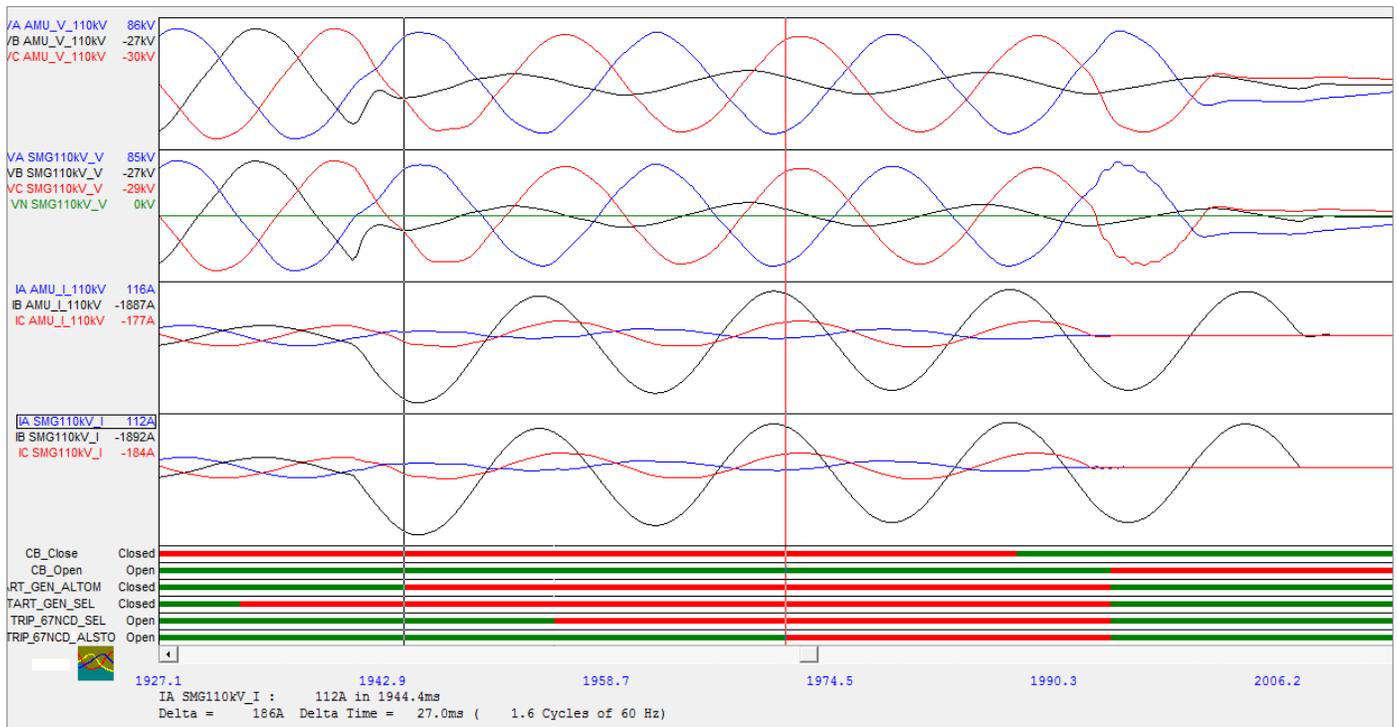


Figure 13: Real event oscillography, San Miguel – San Lorenzo 110 kV line

The event shown in Figure 13 is a single phase fault on line San Miguel – San Lorenzo 110 kV, S phase, which triggers the ground directional over current function in a directional comparison scheme (67NDC). On the oscillography taken from the REASON event recorder, analog measures (VA SMG110 kV, I SMG110 kV) and sampled values taken from the switched network, delivered by the Merging Unit (AMU_V_110kV, AMU_I_110 kV), may be compared; additionally, pick-up and trigger operation times of the conventional and process bus protections were recorded.

In this case, the conventional relay operated faster than the process bus relay with differences in the 67N function of 11.5 ms; likewise, the trigger operating difference was 16.2 ms, being equally faster the conventional system.

Conclusions

Digital substations based on standard IEC 61850 have been replacing conventional control and protection systems taking advantage of communication systems to reduce conventional hardwiring, associated civil infrastructure, and taking advantage of operation and maintenance benefits.

Standard IEC 61850 allows implementing control and protection systems by process bus with switched communication technology (IEC 60850-9-2LE) and

point-to-point communication (IEC 60850-9-1). Each one implies migrating to new techniques for the performance of FAT and SAT tests, whereby protection staff must use new testing methods and equipment other than the ones used for traditional tests and systems.

Comparatively, during the analysis it was noticed that the operation of a process bus line protection with point-to-point communication technology and conventional hardwiring had very similar results in terms of operation times with some differences originated in the algorithms used by each manufacturer for the protection functions; these results allow to conclude that the protection systems performed adequately under the functional tests carried out and under real fault events, so that the process bus IED operated correctly and similarly to the conventional relay in terms of fault detection and performance of the protection function.

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AUTHORS

Camilo E. López: Electrical Engineer graduated from Universidad Nacional de Colombia, Medellin Campus in 2004, specialized in Industrial Energetic Management from Instituto Tecnológico Metropolitano (ITM) in 2009. Started his career in industrial automation programming and design with PLC equipment; in addition to it, in industrial system maintenance before joining HVM Ingenieros. In his seven years at HVM, he has performed in design, setup, tests, and commissioning, in different countries, of control and protection systems associated to medium and high voltage and power plants. Currently, he performs as a specialized engineer in the control and protection area. **celopez@h-mv.com**

Juan David Garcia: Electrical engineer graduated from Universidad Pontificia Bolivariana in 1994; started his career in substation maintenance and power plant design before joining HVM Ingenieros. In his 22 years at HVM, he has performed in design, tests, and direction of projects associated to medium and high voltage and power plants. Currently, he performs as director of the control and protection area and as control, protection, and low voltage system manufacturing and procurement leader. **jpgarcia@h-mv.com**