Ethernet-Based Protection and Control System for the Tabasco Substation: Design Concepts, Testing, and Field Performance

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***Abstract*—This paper describes the application of Ethernet-based protection signaling (IEC 61850 GOOSE messaging) to implement the complete protection and control system of the Tabasco 400/230 kV substation. This new substation, located close to Villahermosa, Tabasco, Mexico, belongs to the Southeastern Transmission Area of Comisión Federal de Electricidad, the national Mexican electric utility. The paper describes the system architecture and the protection and control design concepts. It provides information on the design documentation—an important consideration in applications where programmable logic replaces a large number of hard-wired connections. Finally, the paper describes the system factory testing and shows the system operation for actual fault cases.**

I. Introduction

The IEC 61850 standard provides methods of developing best engineering practices for substation protection, control, monitoring, integration, and testing [1] [2] [3]. Comisión Federal de Electricidad (CFE), the national Mexican electric utility, became interested in IEC 61850 because of interoperability and interchangeability.

CFE has a substation automation specification known as SICLE [4]. SICLE is the Spanish acronym for Substation Local Information and Control System. This specification addresses network topology, functionality, and device characteristics. Initially, the specification mandated the use of serial networks (with DNP3 and other protocols) in substation networks. In 2000, the SICLE specification migrated to Ethernet networks.

CFE also developed a specification on the general characteristics of substation automation systems (SASs) based on the IEC 61850 standard [5]. This specification includes requirements resulting from CFE best design practices that are not addressed by IEC 61850. Currently, CFE is developing specifications for IEC 61850-based distribution substation automation.

In 2008, CFE placed an IEC 61850 system in service at the La Venta II wind farm [6]. This was the first IEC 61850 project with equipment from multiple manufacturers. The lessons learned in this project were applied to other CFE substation automation projects for transmission substations (400 kV, 230 kV, 138 kV, and 115 kV) [7].

This paper describes the IEC 61850-based protection and control system of the Tabasco 400/230 kV substation. The system architecture and design concepts are illustrated, information on the design documentation package is provided, the system factory testing is described, and the system operation for actual fault cases is shown.

II. Project Background

The Tabasco 400/230 kV substation (Fig. 1) is a new air-insulated substation located close to Villahermosa, Tabasco, Mexico. It belongs to the CFE Southeastern Transmission Area. This substation is an important node linking the CFE Yucatán Peninsula Transmission Electric Grid with the rest of the Mexican Interconnected System.

Fig. 1. View of the Tabasco 400/230 kV substation.

This substation (Fig. 2) includes the following:

- Four 400 kV lines connected to a bus with a breaker-and-a-half arrangement. These lines connect the Tabasco substation with the Escárcega and Malpaso II substations.
- Four 230 kV lines connected to a bus with main and auxiliary bus arrangements. These lines connect the Tabasco substation with the Macuspana II, Villahermosa Norte, and Kilómetro 20 substations.
- Two 400/230/34.5 kV, 375 MVA autotransformer banks, composed of single-phase autotransformers.
- Two 34.5 kV, 30 MVAR reactors.

For this project, CFE specified the protection, control, and monitoring (PCM) panels to comply with IEC 61850. The PCM system uses Generic Object-Oriented Substation Event (GOOSE) messaging for tripping and interlocking signals and manufacturing message specification (MMS) messaging for reporting to higher-level systems.

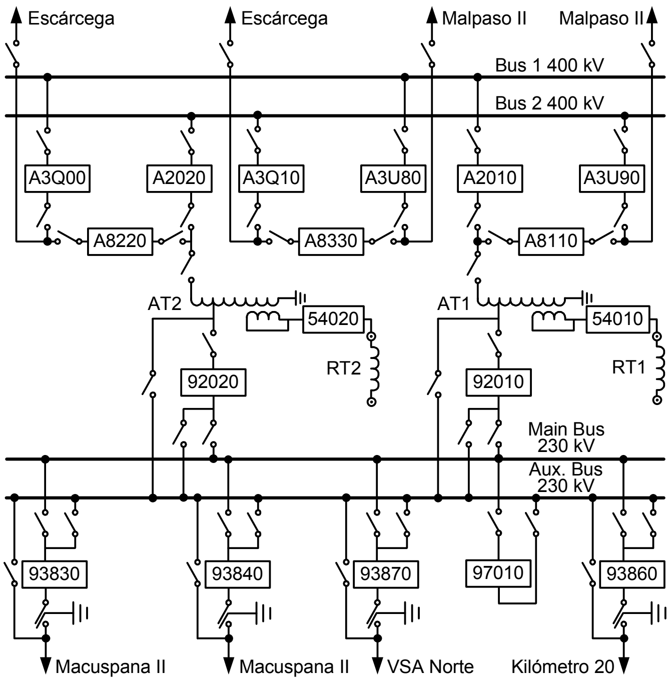

Fig. 2. Single-line diagram of the Tabasco 400/230 kV substation.

III. Design Objectives

The project design objectives included the following:

- Achieve a redundant, flexible, robust, fault-tolerant design by:
  - Eliminating single points of failure using redundant logic for high dependability.
  - Eliminating auxiliary relays, lockout relays, and disconnect switches.
  - Providing a redundant, robust communications system with self-test abilities.
  - Designing the communications network to accept IEC 61850-compliant equipment from different manufacturers.
  - Providing flexibility for future system functionality improvements by modifying logic programming with no need for wiring changes.
- Achieve high quality and reliability and reduce cost by:
  - Reducing field wiring.
  - Reducing panel wiring to save panel space and reduce the number of panels.
  - Designing the communications network to facilitate system testing to reduce factory testing and commissioning work.
- Improve operation and safety by:
  - Maximizing the use of protection, control, monitoring, and communications functions available in microprocessor-based relays.
  - Using device logic programming to implement tripping logic and control interlocking.
  - Implementing economical, safe, and reliable protection schemes using modern relays and field I/O modules with high mean time between failures (MTBF) that are able to process logic information in harsh environments.
  - Providing a modular solution, which should be manufacturer-independent, flexible, expandable, and compliant with end-user specifications.
  - Designing to achieve IEC 61850-based communication inside the substation and communicate with the remote control center using other protocols, such as DNP3, DNP3 IP, Modbus®, Modbus IP, Harris 5000/6000, and so on.
  - Developing an intuitive and user-friendly human-machine interface (HMI).
  - Providing modern tools for data recording, storing, and management, including historic event and alarming data, to facilitate operation, disturbance analysis, and asset management.
  - Providing appropriate design documentation for operation and troubleshooting.

IV. Network Architecture

The Tabasco substation has a centralized control enclosure that houses all the PCM panels and the supervisory control and data acquisition (SCADA) panel. Outdoor cabinets placed in the yard close to the substation equipment house remote I/O (RIO) modules. Fiber-optic links connect the intelligent electronic devices (IEDs) in the control enclosure with the RIO modules. Copper cables connect the RIO modules with the breakers and disconnect switches.

Fig. 3 depicts the network architecture, which consists of an Ethernet ring with redundant Ethernet switches in a main and backup configuration. Fiber-optic 1000BASE-SX links provide communication among Ethernet switches. Following CFE specifications, the system has one Ethernet switch per panel. The ability of the fiber-optic ring to be automatically reconfigured after a failure, achieved by the use of Spanning Tree Protocol (STP) among the Ethernet switches, provides reliable recovery after network failure. However, IED redundancy is necessary for high reliability of high-speed protection applications because of the inherent delays in STP network reconfiguration.

Two sets of IEDs (IED 1 and IED 2 in Fig. 3) provide full application, not just communications, redundancy for the critical protection and control functions. They are connected in a redundant star configuration: each set of IEDs communicates with two Ethernet switches using independent ports and separate 10/100BASE-T copper cable links. Each IED is connected to the Ethernet switch on the IED's own panel and the Ethernet switch on an adjacent IED panel.

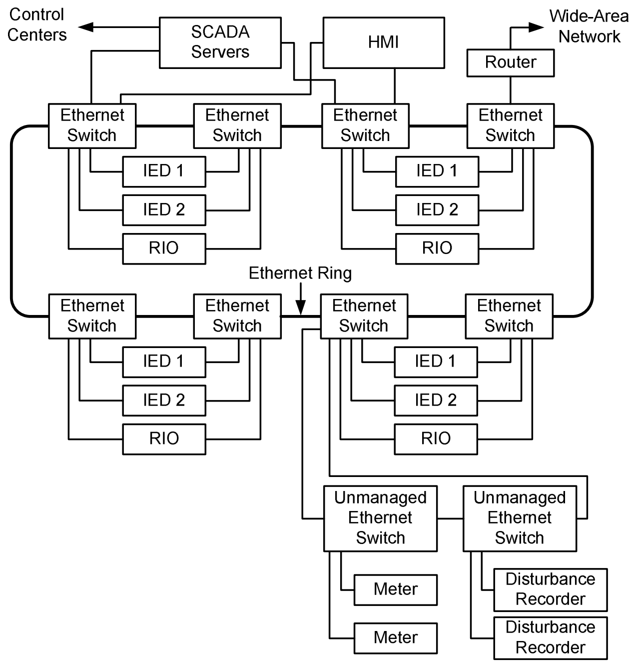

Fig. 3. The Tabasco substation network architecture includes an Ethernet ring with redundant Ethernet switches. Redundant star networks connect the IEDs and RIO modules with the Ethernet switches.

The RIO modules also communicate with two Ethernet switches in a redundant star network, as Fig. 3 shows. Rugged 12-strand fiber-optic cables provide the connection between the Ethernet switches placed in the control enclosure and the RIO modules located in outdoor cabinets.

The meters and disturbance recorders do not use IEC 61850 MMS or GOOSE messaging. They are connected through unmanaged Ethernet switches in a ring network that connects to the main Ethernet ring (Fig. 3). This network uses 10/100BASE-T copper cable links. The system accesses these IEDs using their proprietary protocols that coexist on the Ethernet network, which also supports IEC 61850 protocols.

The system uses GOOSE messaging for the protection and control IED data exchange, including communication with the RIO modules to perform the following:

- Breaker tripping.
- Manual breaker and disconnect switch closing and opening.
- Interlocking.
- Alarming.

The system uses IEC 61850 MMS reporting to send data to the SCADA and HMI systems and File Transfer Protocol (FTP) and Telnet for engineering access.

V. Protection System Design

The protection and control system uses a dual-system architecture that provides very high dependability. Redundant functionality includes the following:

- Fault detection in the System 1 and System 2 relays.
- Fault interruption in the System 1 breakers and System 2 breaker failure schemes.
- Control, status, and alarms in the System 1 local HMI and System 2 remote SCADA.
- Tripping and interlocking in the System 1 and System 2 logic processors.

The system includes the PCM functions listed in Table I.

TABLE I
PCM FUNCTIONS

Protection Scheme	400 kV and 230 kV Buses	400 kV Lines	400/230/34.5 kV Autotransformers	230 kV Lines	230 kV Bus Tie	34.5 kV Reactors	RIO Modules
Functions	87B 86B	85L 1 (POTT) 85L 2 (POTT) 67N 27 59 60 50BF 86BF 25/27 79 DTT	87T1, 87T2 51H1, 51H2 51L1, 51L2 51T1, 51T2 64N1, 64N2 51NT 86T 25/27 60 50BF 86BF	85L 1 (POTT) 85L 2 (POTT) 67N 27 59 60 50BF 86BF 25/27 79 DTT	50BF 86BF 25/27	87R 51R 51RN 86R 50BF 86BF	Breaker tripping Breaker opening and closing Disconnect switch opening and closing Breaker Trip Coil 1 monitoring Sudden pressure and Buchholz signals Oil and winding temperatures Tap position
	Metering, breaker status and alarms, disconnect switch status and alarms, local commands, remote (SCADA) commands, sequential event reporting, and oscillography						

The PCM system was designed to comply with the following requirements, identified within CFE best engineering practice guidelines resulting from previous IEC 61850 substation successes:

- The system must include RIO modules mounted close to the primary equipment and perform data exchange between protection and control IEDs and primary equipment via fiber-optic links and the RIO modules. This data exchange includes tripping signals sent to Breaker Trip Coil 1, manual breaker and disconnect switch closing and opening signals, status signaling, and alarming.
- The system must use GOOSE messaging for protection and control IED data exchange to perform interlocking, signaling, and alarming.
- The system must use copper control cables for current and voltage signals, tripping signals sent to Breaker Trip Coil 2, and disconnect switch status information for bus differential protection.
- The system should not include any auxiliary relays for protection and control functions.
- Breaker failure schemes should use relay output contacts for tripping and initiation.
- The system should not include dedicated lockout (86) relays. The hand-reset lockout function must be implemented in protective relays with control pushbuttons on the front.
- The breaker automatic reclosing selector should be implemented in the control and data acquisition module (CDAM), which has control pushbuttons on the front. The CDAM performs bay control and data acquisition functions according to the SICLE specification [4].
- The system should include one RIO module per breaker and associated disconnect switches.
- The RIO modules should perform breaker trip coil monitoring functions.
- The RIO modules associated with autotransformers and reactors should receive the signals corresponding to oil and winding temperatures and tap position.
- Autotransformer alarm signals should be sent on a per-phase basis via the RIO modules to the corresponding protection and control IEDs in the control enclosure.
- For autotransformers, the tripping signals from System 1 relays, System 2 relays, sudden pressure relays, and Buchholz relays should be sent simultaneously to the breaker trip coil and the relay performing the lockout (86) function.
- Tripping signals from sudden pressure, Buchholz, and temperature relays should be sent on a per-phase basis via copper cables to autotransformer System 1 and System 2 relays. Sudden pressure and temperature relays should connect with System 1 relays, and Buchholz relays should connect with System 2 relays.
- The protection system operating time, measured from a fault inception to the closure of the RIO module contact that energizes the breaker trip coil, should be:
  - Less than 32 milliseconds for System 1, 400 kV protection.
  - Less than 37 milliseconds for System 2, 400 kV protection.
  - Less than 37 milliseconds for System 1 and System 2, 230 kV protection.
- The system should perform continuous relay monitoring. To this end, relay self-test fail contacts should be wired to the CDAMs or other IEDs.
- The system should perform continuous dc circuit monitoring.

The physical design of the system includes the following indoor panels and outdoor cabinets:

- For PCM IEDs, swing-rack indoor NEMA 12 panels with 900 mm x 800 mm x 2300 mm dimensions.
- For RIO modules, swing-rack outdoor NEMA 4X cabinets with 800 mm x 400 mm x 900 mm dimensions.

VI. Control System Design

As discussed in Section IV, the communications network includes an Ethernet ring with redundant switches. Each PCM panel includes an Ethernet switch. Each IED connects via copper cables to the switch located on its panel and to the switch placed on the adjacent panel, as Fig. 4 shows. This arrangement complies with the CFE SAS specification, which allows the use of copper communications connections inside the panels and with adjacent panels [5]. Fig. 4 also shows the connections between the IEDs on the PCM panels and the RIO modules in the outdoor cabinets. These connections use rugged 12-strand fiber-optic cables.

The Ethernet ring and redundant switches provide a fully redundant communications system. Any IED can communicate with any other IED via GOOSE messaging, even if a section of the Ethernet ring or a switch fails.

The RIO modules collect alarm and status data from the neighboring breakers and disconnect switches. Using the IEC 61850 Substation Configuration Language (SCL) methods, each RIO module labels and organizes the measured and calculated information into data models defined by the standard. Each RIO module sends these data via GOOSE messaging to the CDAM corresponding to its bay. In order to meet specification, each CDAM converts locally created alarm and status data, as well as data received from the RIO module, into custom data models, specified and defined by CFE, and publishes this information in GOOSE messaging, as well as IEC 61850 MMS reports. The CDAMs and relays use the information to make interlocking decisions.

When a fault occurs, the relays that operate publish their tripping signal as a GOOSE message. The RIO module of the corresponding breaker subscribes to this message and generates the contact closing action required to trip the breaker.

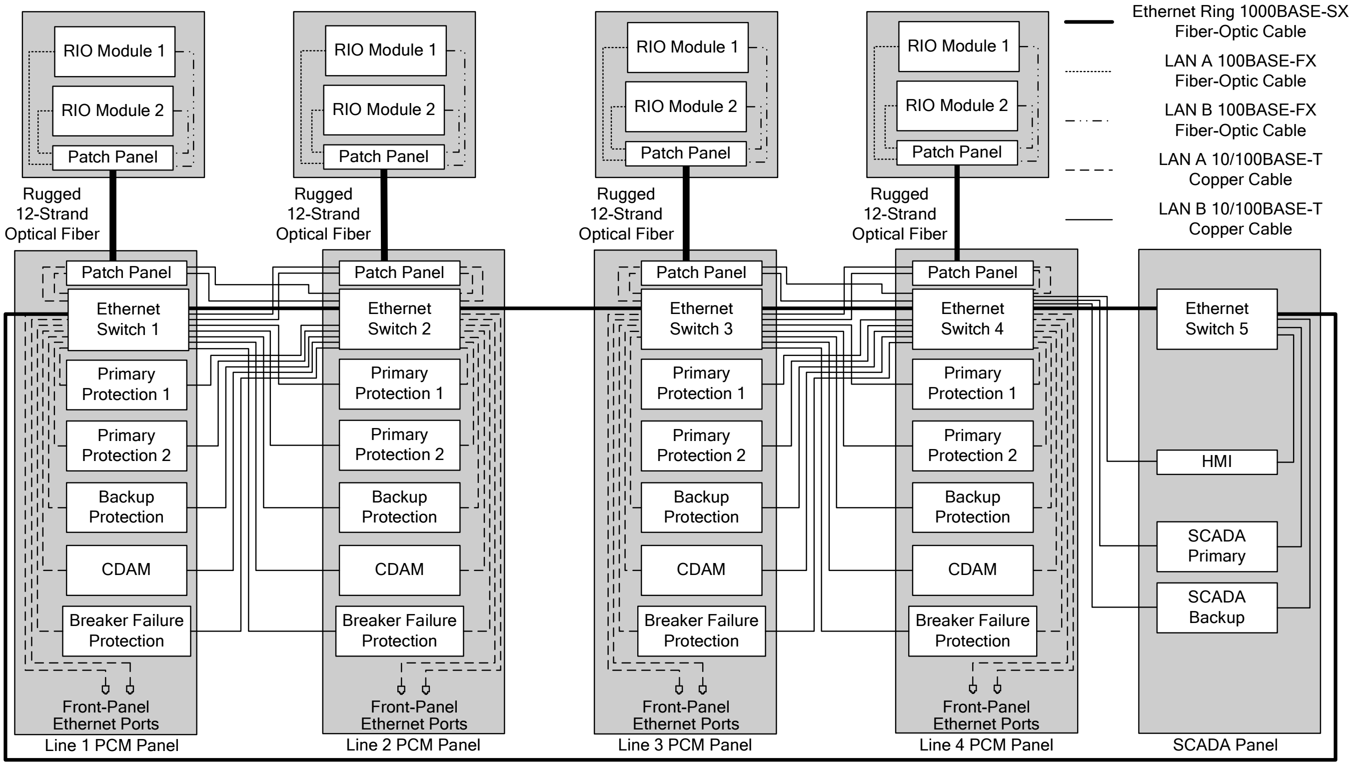

Fig. 4. Each IED connects to the Ethernet switch located on its own panel and to the Ethernet switch mounted on an adjacent panel.

The system includes a local HMI, a main SCADA server, and a backup SCADA server. The SCADA servers communicate with two remote control centers via DNP3 serial links.

All the relays and CDAMs report to the HMI and SCADA servers using the IEC 61850 data model defined by the CFE SAS specification (Fig. 5). Four identical buffered reports are configured in each IED. Each one of the three clients subscribes to a buffered report; a fourth report is available for a future client (a simulator, for example).

The SCADA servers provide the following functions:

- Breaker control and monitoring.
- Disconnect switch monitoring.
- Display of measurements of voltages, currents, active and reactive power, frequency, power factor, transformer oil and winding temperatures, and tap position.
- Display of the location and measured currents for the most recent fault.
- Display of relay operation information.
- Display of ac and dc system failure information.

The system HMI provides these functions:

- Breaker control and monitoring.
- Disconnect switch control and monitoring.
- Transformer tap changer control.
- Reclosing enabling and blocking.
- Direct transfer trip (DTT) enabling and blocking.
- Display of measurements of voltages, currents, active and reactive power, frequency, power factor, transformer oil and winding temperatures, and tap position.
- Display of the location and measured currents for the most recent fault.
- Local/remote indication for each breaker and disconnect switch.
- Local/remote and testing mode indication for each CDAM.
- Display of the status of each IED communication.
- Display of alarms in real time.
- Display of historic alarm information, including the last 10,000 events.
- Creation and display of a trend graphic for each bay for the last 30 days, which includes information on voltages, currents, and active and reactive power.

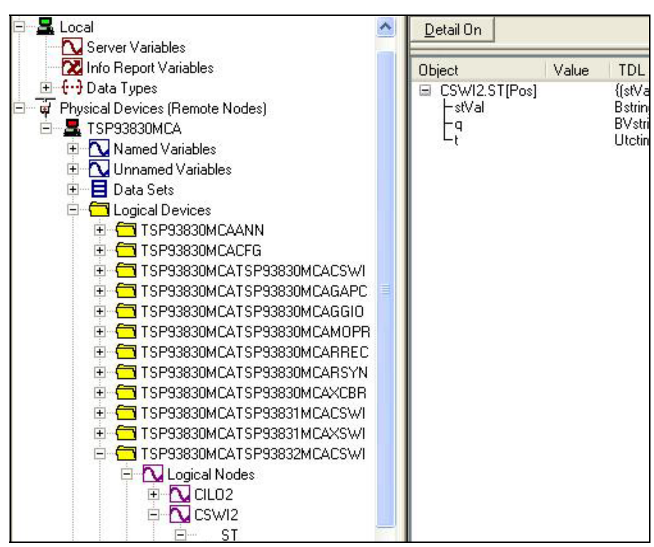

Fig. 5. Example of a data model as defined by the CFE SAS specification.

The HMI application contains the following screens:

- Substation single-line diagram (Fig. 6).
- Bay single-line diagrams.
- Communications network diagram (Fig. 7).
- Real-time alarm reports.
- Historic alarm reports.
- Trend graphics.
- Buttons that allow access to the configuration software of any IED.
- Buttons that allow access to applications to visualize digital and analog variables.
- Buttons that allow access to the instruction manual of any IED.

The control system design fulfills the following project goals, defined by CFE:

- Interoperability. The system allows relays from different manufacturers to communicate via GOOSE messaging.
- Open protocols. The system uses the IEC 61850 suite of protocols for communication between devices; these protocols are open, supported by clear and concise information, and available from multiple manufacturers. The system uses open access Ethernet protocols for engineering access, command line interface, and file transfer for configuration, diagnostics, and maintenance.
- Manufacturer independence. The system allows the selection, based on IED features and performance, of IEDs from different manufacturers for replacement or future expansion. Some manufacturers support communications among devices via the IEC 61850 protocols but often use manufacturer-specific Ethernet transport methods for IED configuration, diagnostics, and maintenance. This results in a hybrid network of open protocols for real-time and near real-time messaging among devices and a combination of open access and manufacturer-specific engineering access.
- Robust system architecture. The Ethernet ring with redundant switches and redundant IEDs provides a failure-tolerant network.
- Modular system. The standard designs for the different bay types allow for seamless future growth of the system.
- Intuitive and user-friendly HMI.
- Robust communication with the control centers. Redundant SCADA servers provide for failure-tolerant communication with the remote centers.
- Cybersecurity. A router controls and restricts access to the local-area network (LAN) from outside.

VII. Design Documentation

Designing a PCM system involves developing a complete design documentation package, which provides detailed information for physical construction of the system [8]. The package must also document the functions of the system so that the designer can verify design accuracy and maintenance personnel can test, commission, and troubleshoot the system. The package should also provide information for operations personnel.

A. Design Documentation Package

The design documentation package for the Tabasco substation PCM system includes:

- Schematic (elementary) diagrams:
  - Single-line diagrams.
  - AC schematic diagrams.
  - DC schematic diagrams.
  - Logic diagrams.
- Wiring diagrams:
  - Panel wiring diagrams.
  - Switchyard equipment wiring diagrams.
  - AC and dc distribution wiring diagrams.
  - Cabling schedules.
- Communications diagrams:
  - Ethernet ring network.
  - IED connections to the Ethernet switches.
  - Time-synchronization network.
  - GOOSE message table, which identifies the source data within the IEDs, the data set the source data are packaged within, the description of the GOOSE message and network navigation settings used to publish the source data (including GOOSE reference, IEEE 802.1p priority, IEEE 802.1Q virtual local-area network [VLAN] identifier, application identifier, media access control [MAC] address, and GOOSE identifier), and the logical point destination within each IED receiving the GOOSE payload.
  - Cabling schedules.
- Physical diagrams:
  - Panel layouts.
  - Bills of material.
  - Substation control enclosure plan and elevation view layouts.
- PCM device settings files:
  - Particular IED settings.
  - Settings related to GOOSE messaging.

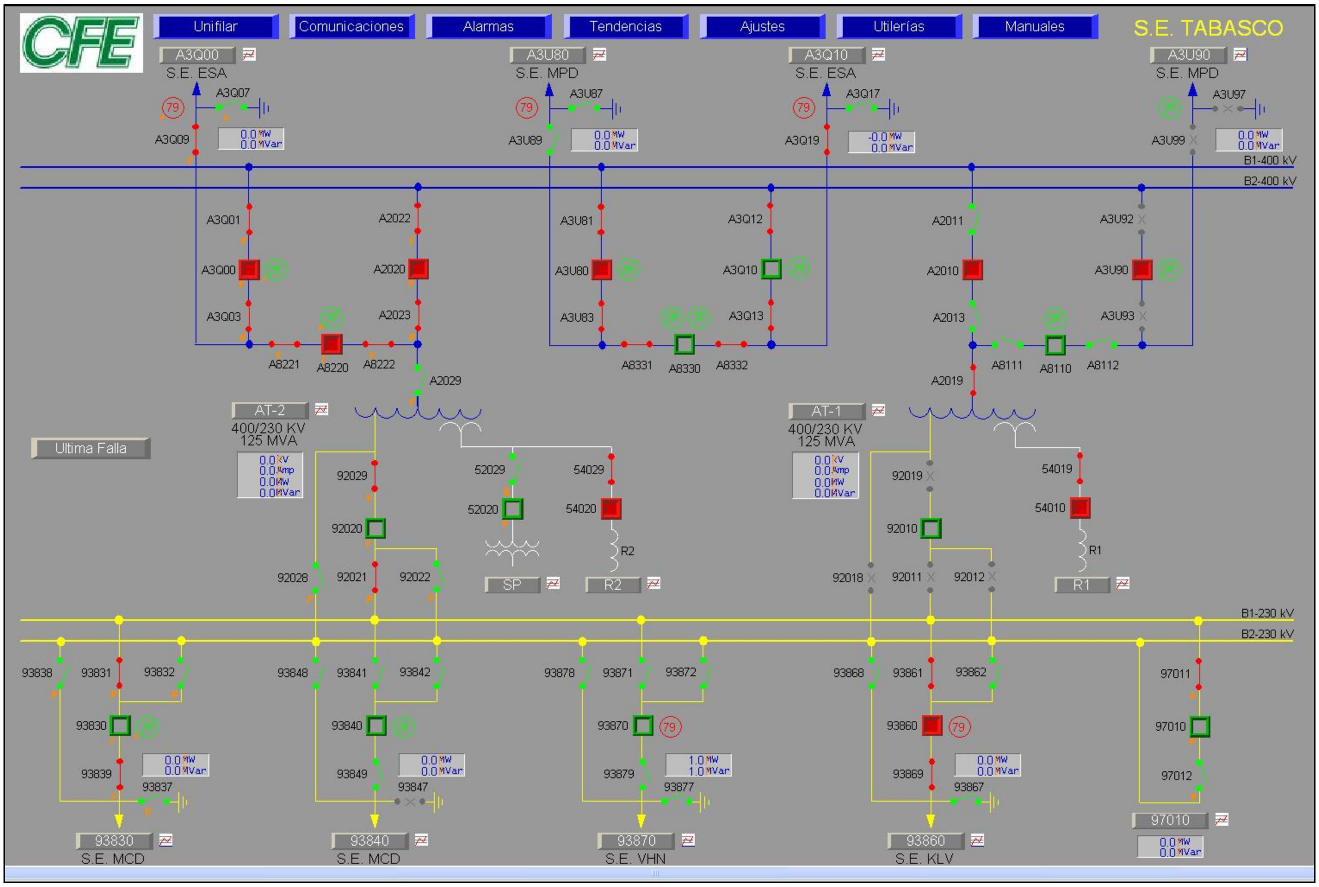

Fig. 6. Example of a substation single-line diagram screen.

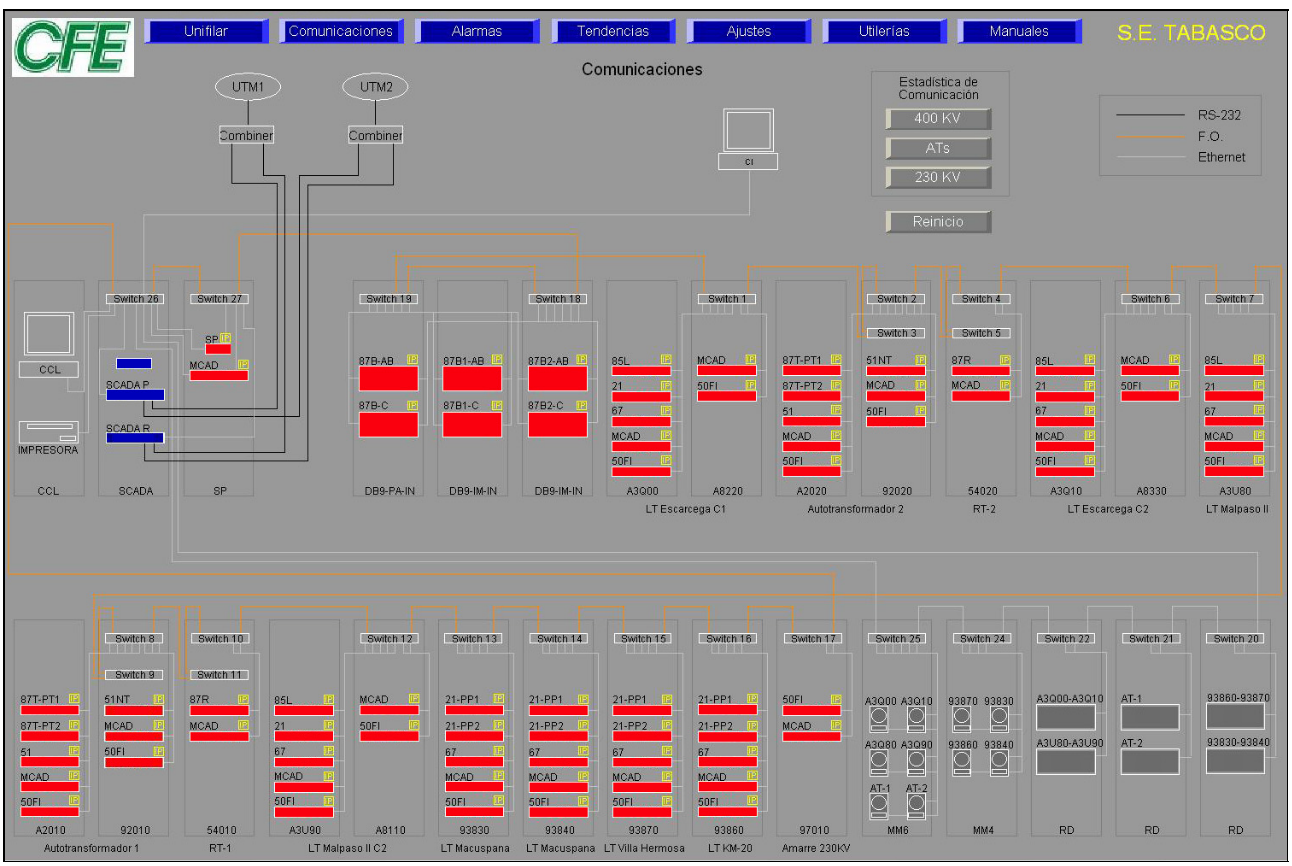

Fig. 7. Example of a communications network diagram screen.

B. AC and DC Schematic Diagrams

Schematic diagrams show the arrangement and logic of the circuits, describing how the system works. They provide the following information:

- Single-line diagrams provide a summarized view of the system.
- AC and dc schematic diagrams show a detailed view of the circuits.
- Logic diagrams supplement the dc schematic diagram to show the functions programmed in the IEDs. Logic diagrams are essential in a modern system that uses programmable PCM devices.

The ac and dc schematic diagrams for the Tabasco substation PCM system include the following:

- AC diagrams showing the connections of the current and voltage transformers with the relays, CDAMs, meters, and disturbance recorders.
- DC circuit for Breaker Trip Coil 2.
- DC power supply circuits for all IEDs.
- 50BF dc tripping circuits.

The ac and dc schematic diagrams are complemented with IED programming tables (Fig. 8). These tables provide information on the device type, its function, and the functions assigned to each input and output. The IED programming tables are valuable for system designers and end users. The designer can use them to configure the IEDs at the factory and test the system, for example. End users refer to the tables for system operation and troubleshooting.

Tabla de Programación 85L			
Entrada	**Función**	**Salida**	**Función**
IN101	Disponible	OUT101	Disparo Bobina 2 Fase A Int. A3U80
IN102	Disponible	OUT102	Disparo Bobina 2 Fase B Int. A3U80
IN103	Disponible	OUT103	Disparo Bobina 2 Fase C Int. A3U80
IN104	Disponible	OUT104	Arranque 50FI-B
IN105	Disponible	OUT105	Arranque 50FI-M
IN106	Recepción POTT (Fibra)	OUT106	Disponible
IN107	Recepción POTT (OPLAT)	OUT107	Disponible
⋮	⋮	⋮	⋮

Fig. 8. Example of an IED programming table.

Modern PCM devices have a large number of inputs and outputs that must be documented. Because these inputs and outputs are typically isolated, they can be located in many different circuits, which can be on several different drawings. The Tabasco substation PCM system documentation package includes cross-reference diagrams that provide the coordinates of all I/O contacts to facilitate finding them in the multiple diagrams. As an example, Fig. 9 depicts the diagram for 50BF initiation from 87B protection and for bus tripping from 50BF operation via 86BF lockout relay. This diagram includes the cross-references with other diagrams of the panels involved.

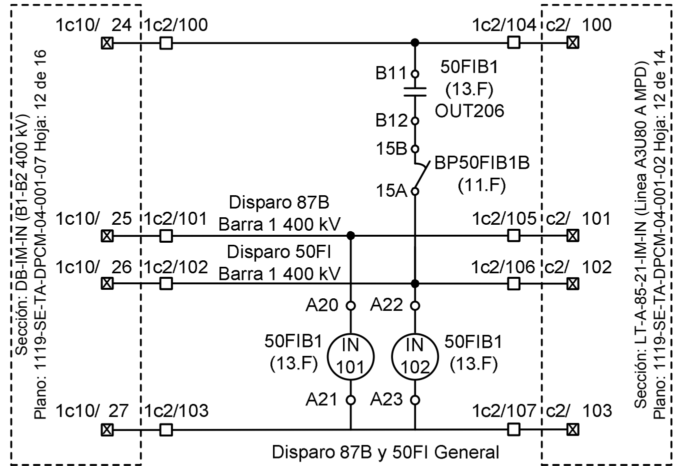

Fig. 9. Example of a cross-reference diagram.

C. Logic Diagrams

Designs that use advanced programmable relays require logic diagrams that show the functions programmed in the IEDs. Logic diagrams are an extension of schematic diagrams. Understanding the functioning of the logic from the IED settings equations alone is almost impossible. Logic diagrams solve this problem—they provide information on how the system works.

In the Tabasco substation PCM system, the functionality is mostly in programmable logic. In addition, this logic works through the Ethernet communications network. The logic diagrams integrate IED logic settings, logic variables, data transmission variables (GOOSE messages), and the physical I/O represented in the schematic diagrams. The logic diagrams provide the following:

- Cross-referencing between logic functions inside each IED.
- Cross-referencing between logic functions of different IEDs located in the same panel.
- Cross-referencing between logic functions of IEDs located in different panels.
- Cross-referencing between IED logic functions and schematic diagrams, including physical I/O.

Fig. 10 is a partial view of a logic diagram that shows the cross-referencing between the logic functions and other logic functions external to the diagram.

Logic diagrams should only include the logic programmed by the user. IED logic functions are described in the manufacturer documentation, so they are represented as boxes with inputs and outputs in the diagrams. Fig. 10, for example, shows the breaker closing logic, a function available in the relay, represented as a dotted-line box. In some cases, logic functions created with programmable logic by the user are also represented as boxes in higher-level logic diagrams. For example, Fig. 11 shows the logic diagram of the current unbalance function created with programmable logic that is represented as a box in a higher-level 50BF logic diagram (not shown).

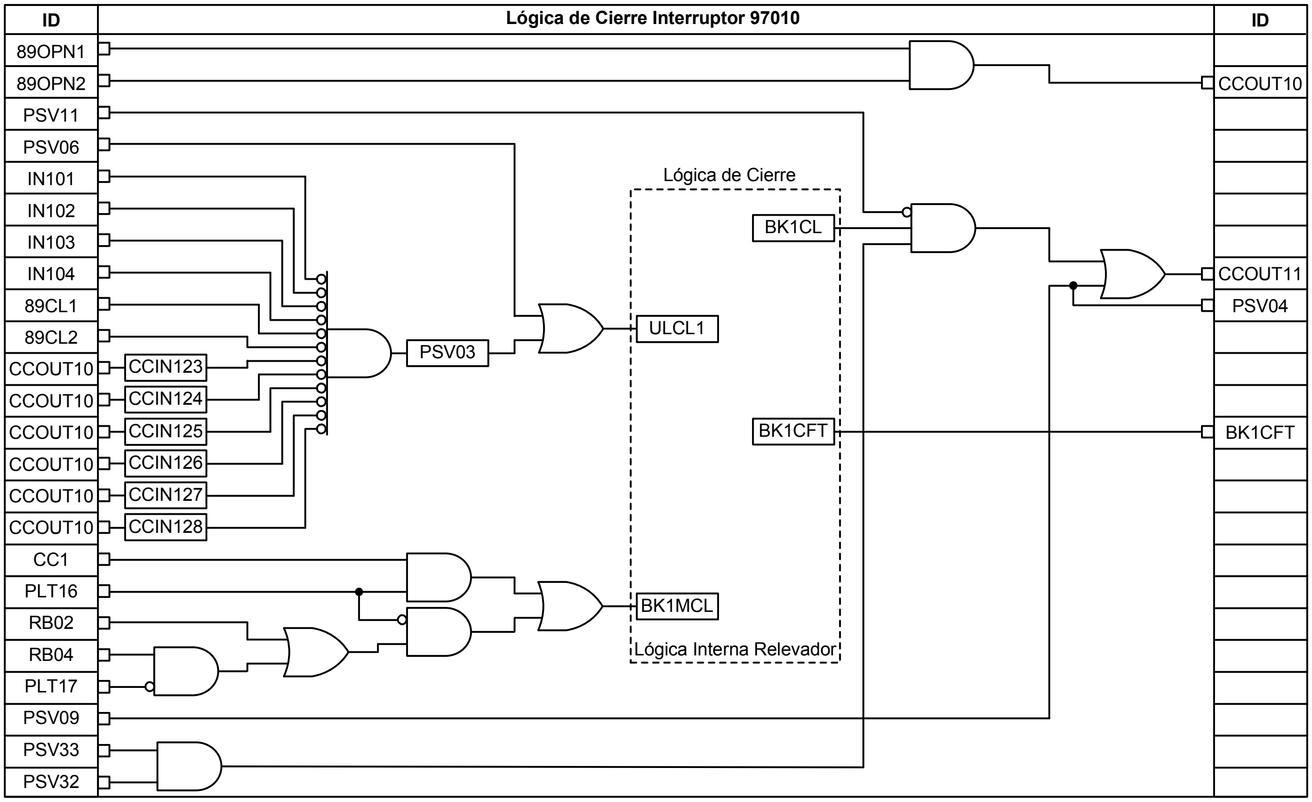

Fig. 10. Partial view of a logic diagram showing cross-referencing between logic functions and including a box that represents an IED logic function.

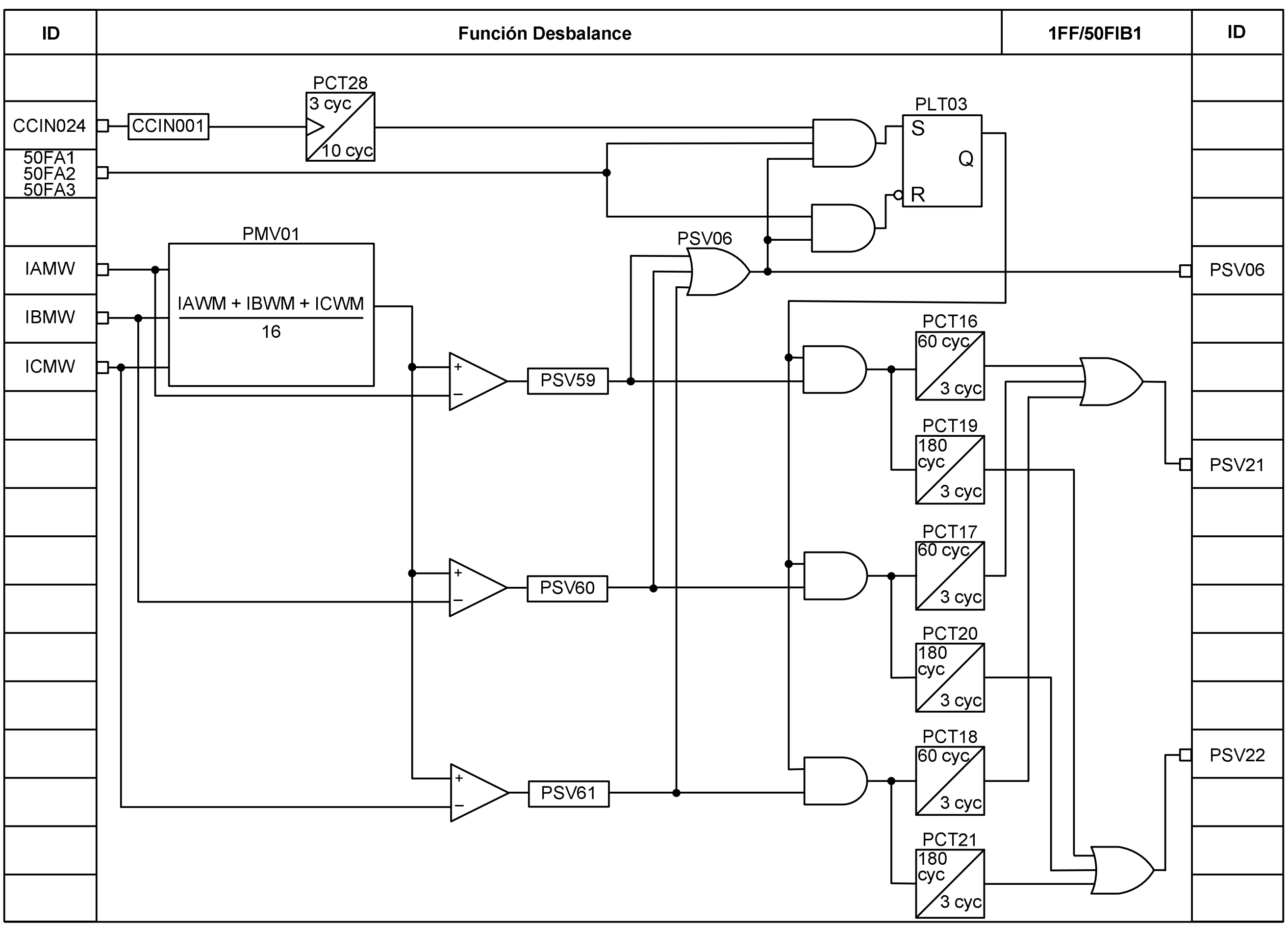

Fig. 11. Example of a logic function created with programmable logic that can be represented as a box in a higher-level logic diagram.

D. Communications Diagrams

In an integrated system design, many of the control circuits connect via communications cables. The routing of these communications links must be shown on a diagram. The communications diagram of the Tabasco substation PCM system is a detailed version of the network architecture diagram shown in Fig. 3. As mentioned previously, at a minimum, this diagram must include the following information:

- Ethernet ring network topology.
- Connections of the IEDs to the Ethernet switches.
- IRIG-B time-synchronization network.

The process for developing the documentation package in an IEC 61850 project requires creating a master list of Internet Protocol (IP) addresses for all the IEDs, including relays, meters, communications data concentrators, and Ethernet switches. Documentation that helps to understand how the GOOSE messages travel among the IEDs is crucial for system testing, commissioning, and troubleshooting. In the Tabasco substation PCM project, this information was provided in GOOSE message lists, which are tables that document GOOSE messaging transmissions.

Fig. 12 shows the Microsoft® Excel® version of a GOOSE message table obtained from the IEDs. The first column is the list of subscriber IEDs. The second column lists the virtual control inputs in the receiving IED that mirror the values of the GOOSE message data items received. The value that is mapped to the virtual control input from the incoming GOOSE message is identified in the third column ("Subscribed Data Item"). These messages are published by the IEDs listed in the fourth column ("Publisher IED Name"). The last column, "Observaciones," contains information on the function and properties of the GOOSE messages. The other columns of the table list network parameters. These network parameters include the GOOSE reference as part of the subscribed data item, IEEE 802.1p priority, IEEE 802.1Q VLAN identifier, application identifier, MAC address, and GOOSE identifier.

The GOOSE message tables must faithfully reflect IED programming. CFE used an IEC 61850 configuration software package from one of the IED manufacturers to document the GOOSE tables. Fig. 12 shows a GOOSE message table view within this configuration software. Though there are no third-party standardized tools for this purpose, this software works with any IED IEC 61850 configuration file from any manufacturer. Fig. 13 shows one of the configuration screens of this particular multivendor IEC 61850 configuration software. This tool also exports the information to other standard software tools, such as an Excel spreadsheet.

Subscriber IED	Control Input	Subscribed Data Item	Publisher IED Name	Multicast MAC	App ID	VLAN ID	VLAN Priority	GOOSE ID	Observaciones
TSPA3Q00PP1	CCIN001	TSPA3QPPMCA.A3Q00MCA_GOOSE04.ANN.CCOUTGGIO21.Ind01.stVal bit 0	TSPA3Q00MCA	01-0C-CD-01-00-06	0006	006	1	GOOSE04	EDO INT PROPIO FA
TSPA3Q00PP1	CCIN002	TSPA3QPPMCA.A3Q00MCA_GOOSE04.ANN.CCOUTGGIO21.Ind02.stVal bit 0	TSPA3Q00MCA	01-0C-CD-01-00-06	0006	006	1	GOOSE04	EDO INT PROPIO FB
TSPA3Q00PP1	CCIN003	TSPA3QPPMCA.A3Q00MCA_GOOSE04.ANN.CCOUTGGIO21.Ind03.stVal bit 0	TSPA3Q00MCA	01-0C-CD-01-00-06	0006	006	1	GOOSE04	EDO INT PROPIO FC
TSPA3Q00PP1	CCIN004	TSPA8220MCA.A8220MCA_GOOSE06.ANN.CCOUTGGIO21.Ind01.stVal bit 0	TSPA8220MCA	01-0C-CD-01-00-08	0008	008	1	Sub1Bay3	EDO INT MEDIO FA
TSPA3Q00PP1	CCIN005	TSPA8220MCA.A2880MCA_GOOSE06.ANN.CCOUTGGIO21.Ind02.stVal bit 0	TSPA8220MCA	01-0C-CD-01-00-08	0008	008	1	Sub1Bay3	EDO INT MEDIO FB
TSPA3Q00PP1	CCIN006	TSPA8220MCA.A2880MCA_GOOSE06.ANN.CCOUTGGIO21.Ind03.stVal bit 0	TSPA8220MCA	01-0C-CD-01-00-08	0008	008	1	Sub1Bay3	EDO INT MEDIO FC

Fig. 12. Example of a GOOSE message table.

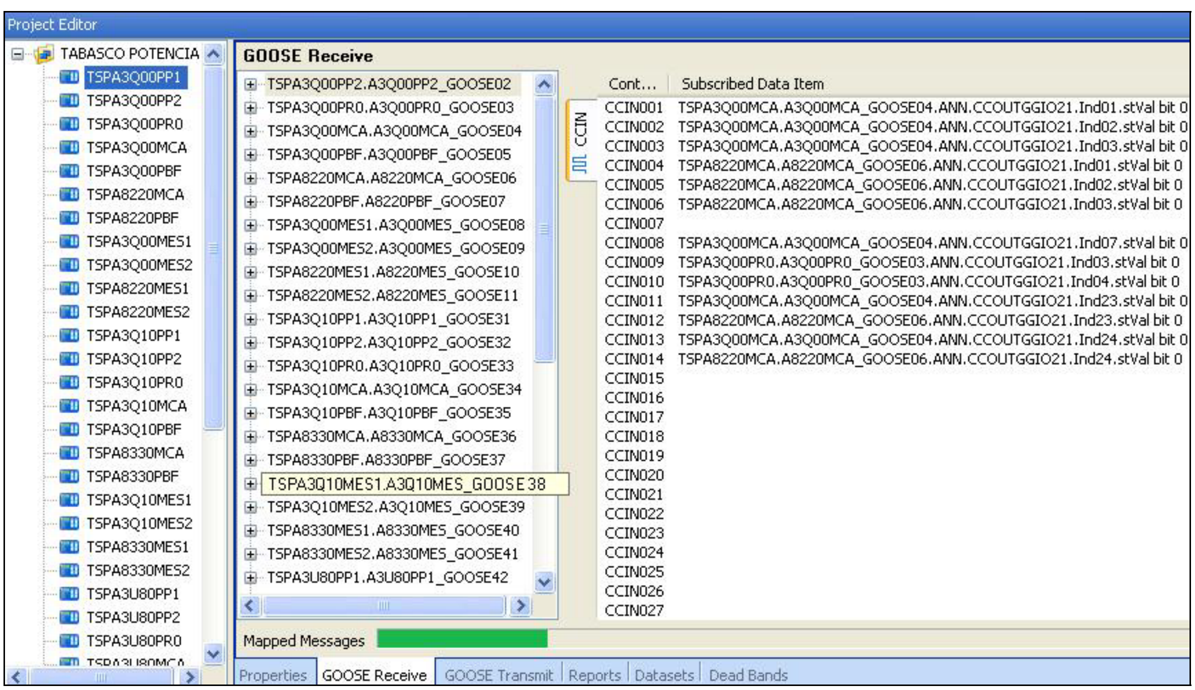

Fig. 13. Screen of the software tool used to create GOOSE message tables.

A major challenge in IEC 61850 projects is the lack of standard tools to generate a complete documentation package [7]. In this project, several tools, such as OpenSCLConfigurator, were used. In particular, creating a comprehensive Substation Configuration Description (SCD) file is a challenging and demanding activity. The SCD file describes a complete substation communications system, including communications network topology, client and server data sources, and IED and client data and control requirements. The file format is standardized to be created using Extensible Markup Language (XML). SCD files are modified using XML text editors, such as the Notepad++ editor used for this task in this project. Fig. 14 shows a sample of the SCD file content using the Notepad++ editor.

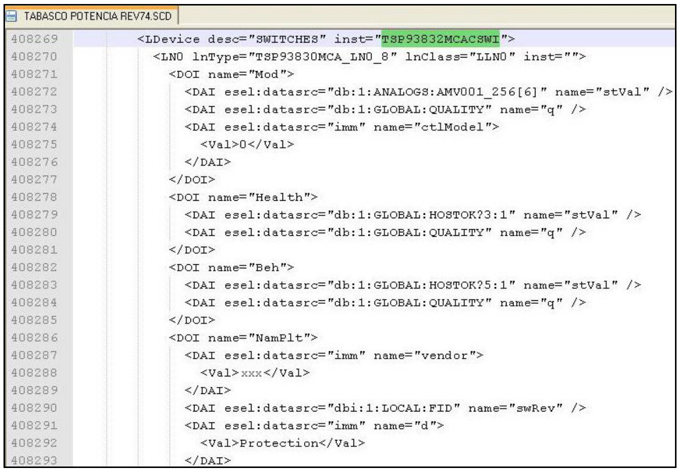

Fig. 14. SCD file edition using Notepad++ editor.

VIII. System Factory Testing

System factory testing included operational tests, functional tests, and integrated system tests. All the tests were witnessed and approved by engineers of the CFE Southeastern Transmission Area and the CFE Mexican Laboratory for Electrical Testing (the Spanish acronym is LAPEM).

We used the following documentation for testing:

- Schematic PCM diagrams.
- Logic diagrams.
- General panel layout diagrams.
- Cabling schedules.
- Communications network diagram.
- GOOSE message lists.
- Logic and communications settings.
- HMI application information.

A. Operational Tests

The objective of the operational tests was to verify the circuits of the PCM panels and the RIO cabinets. These tests included the following activities:

- Visual inspection. A check of the physical condition of the panels and cabinets and a verification of the physical equipment layout with the corresponding general layout diagrams were performed. The inspection included a review of the following:
  - General status of equipment and materials.
  - Process plan updating.
  - Design documentation.
  - IED instruction manuals.
- Continuity tests. Point-to-point wiring continuity checks for all panel circuits were performed. The terminal types, the quality of terminal crimping, and the wire sizes, colors, and labeling were checked.
- DC circuit tests. Each dc panel circuit was energized. Proper IED startup, the polarity and independence of dc circuits, and the continuity of the positive and negative dc circuit buses were verified.
- AC circuit tests. Analog voltage and current signals were applied to each panel ac circuit. Signal phasing and polarity at the input of each relay, CDAM, meter, and disturbance recorder were checked.
- IED configuration. IED settings files specific to the Tabasco substation protection and control system were loaded and verified in the IEDs.

B. Functional Tests

The objective of the functional tests was to validate the logic settings applied to the IEDs of each panel. These tests required injecting three-phase ac signals using a relay test set and also applying logic input signals using a custom-built substation simulator. The ultimate goal was to verify the proper performance of the protection and control system, as seen from the terminal blocks of each panel.

The substation simulator was designed and built using logic processors with programmable logic controller (PLC) abilities. The simulator allows the generation of manual control commands from a connected laptop. The simulator was programmed to emulate the Tabasco substation. It applied logic signals to the panel terminal blocks and applied control commands for different substation operating conditions. The logic signals included breaker and disconnect switch status, transformer oil and winding temperatures, and tap position.

Using only the substation simulator, we tested the following:

- Control:
  - Manual breaker opening and closing.
  - Manual disconnect switch opening and closing.
  - Manual transformer tap changer control.
  - Interlocking.
- Alarming:
  - Breaker status.
  - Disconnect switch status.

The operation of the protection and control system was verified using a test set to inject ac signals and the simulator to apply logic signals to the panel test blocks. These tests included the following:

- Three-pole tripping (via GOOSE messaging and copper cables).
- Single-pole tripping (SPT) (via GOOSE messaging and copper cables).
- Permissive overreaching transfer trip (POTT) scheme operation.
- 50BF retripping and tripping.
- DTT automatic reclosing.
- Synchronism-checking supervision of manual breaker closing.

C. Integrated System Tests

The objective of the integrated system tests was to validate the proper operation of the whole protection and control system. These tests required interconnecting all the system panels the same way that they would be connected in the substation, using fiber-optic and copper cables as required. These tests included the following:

- Communications tests. The objective was to check all the system communications links. Hardware and software tools were used to check the integrity of the communications devices (ports, cables, transceivers, and so on) and to check the message exchange between the IEDs.
- HMI tests. The objective was to check the HMI functionality. Visual inspections of each screen and manual tests were performed, including:
  - Manual control of breakers, disconnect switches, and transformer tap changers.
  - Analog measurement displays.
  - Digital signal displays (status and alarm).
  - Sequential event report displays.
  - Engineering access.
  - Oscillographic event retrieval.
  - Report creation and display.

IX. Operation for Actual Faults

A. Fault on the TBS-93870-VHN 230 kV Line

The TBS-93870-VHN 230 kV line connects the Tabasco (TBS) and Villahermosa Norte (VHN) substations. The line length is 45 kilometers. The line protection includes redundant POTT directional comparison schemes with SPT logic. On October 14, 2010, when the line was carrying a load current of 165 A, a permanent A-phase-to-ground fault occurred. The fault current measured at the Tabasco end was 5,423 A. The fault location was 11.63 kilometers away from the Tabasco line end. This location was within the reach of the Zone 1 elements at both line ends. Fig. 15 shows the A-phase voltages and currents and some of the digital quantities recorded by a relay at the Tabasco substation. Fig. 15 shows the fault, which was cleared by an SPT at the Tabasco end. After the single-pole-open (SPO) period, the A-phase pole of the breaker reclosed against the permanent fault. Then the SPT scheme tripped all three breaker poles to clear the fault and blocked reclosing.

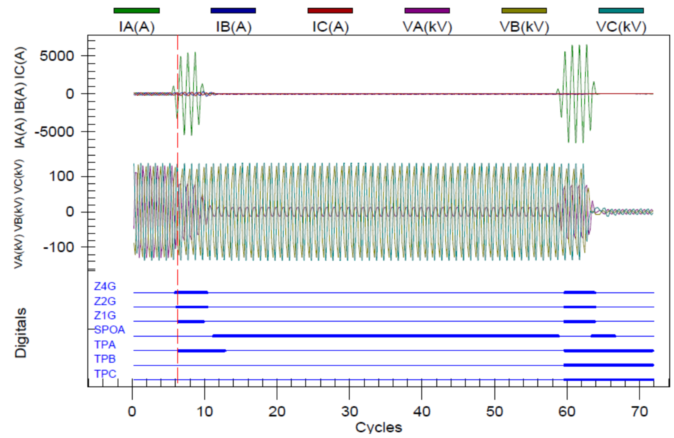

Fig. 15. Oscillogram recorded at the Tabasco end of the TBS-93870-VHN line.

From Fig. 15, we conclude the following:

- The fault started at 15:43:53.067 hours.
- The ground distance fault detection element Z4G operated at 15:43:53.072 hours. The operating time was 5 milliseconds.
- The ground distance element Z2G (overreaching zone) operated at 15:43:53.075 hours. The ground distance element Z1G (Zone 1) operated at 15:43:53.079 hours. The operating times of these elements were 8 and 12 milliseconds, respectively.
- The Z1G assertion initiated tripping of the A-phase pole of the local breaker (bit TPA asserted).
- The A-phase pole of the local breaker opened to clear the fault at 15:43:53.159 hours. The total fault-clearing time was 92 milliseconds.
- Bit SPOA asserted to declare the breaker SPO condition.
- The local breaker successfully reclosed at 15:43:53.955 hours (0.888 seconds after the fault inception).
- The local ground fault detection (Z4G), distance Zone 1 (Z1G), and distance Zone 2 (Z2G) elements operated again at 15:43:53.968 hours, indicating a permanent fault. The operating time of these elements was 13 milliseconds.
- The Z1G assertion initiated three-pole tripping of the local breaker (bits TPA, TPB, and TPC asserted).
- The local breaker opened to clear the fault at 15:43:54.031 hours. The total fault-clearing time was 76 milliseconds.

Fig. 16 shows part of the sequential event report from the CDAM corresponding to this line. From this report, we conclude the following:

- The CDAM received the reclosing initiate signal (bit 79CY3 asserted).
- The CDAM confirmed that Breaker Trip Coil 2 received an A-phase pole tripping signal (bit APER2 ACIDE FA 93870 changed to ALARMA).
- The CDAM confirmed that Breaker Trip Coil 1 received an A-phase pole tripping signal (bit APER1 ACIDE FA 93870 changed to ALARMA).
- The CDAM confirmed the breaker A-phase pole opened (bit EDO 52a FA INT 93870 changed to ABIERTO).

```
=>SER 10/14/2010

MCAD 93870                        Date: 06/06/2011  Time: 13:55
Tabasco Bcos. 1 y 2 + MVAR        Serial Number: 2009189355

FID=xxx-xxx-4-R122-V0-Z011011-D20090526

#      DATE         TIME            ELEMENT              STATE
705  10/14/2010  15:43:53.093   79CY3                    ASSERTED
704  10/14/2010  15:43:53.112   APER2 ACIDE FA 93870     ALARMA
703  10/14/2010  15:43:53.118   APER1 ACIDE FA 93870     ALARMA
702  10/14/2010  15:43:53.128   EDO 52a FA INT 93870     ABIERTO
```

Fig. 16. Part of the CDAM sequential event report.

Fig. 17 shows part of the sequential event report from the RIO module corresponding to this breaker. From this report, we conclude the following:

- The RIO module received the breaker tripping signal (bit VB001 asserted) and closed its output contact (bit OUT105 asserted).
- The RIO module received confirmation of the breaker A-phase pole opening (bit IN201, corresponding to the breaker 52a contact, deasserted).
- The RIO module received confirmation that the 21G element was reset (bit VB001 deasserted).

```
SER 10/14/2010

MES938701                                Date: 06/06/2011   Time: 14:01:48
TABASCO

Serial No = 2009187109      FID = XXX-XXXX-R104-V0-Z002002-D20090716
CID = F01D

 #       DATE          TIME             ELEMENT                   STATE
485  10/14/2010  15:43:52.860900  OUT105                        Asserted
484  10/14/2010  15:43:52.860900  VB001                         Asserted
483  10/14/2010  15:43:52.864400  IN313                         Asserted
482  10/14/2010  15:43:52.874400  VB004                         Asserted
481  10/14/2010  15:43:52.875400  IN310                         Asserted
480  10/14/2010  15:43:52.875400  IN302                         Deasserted
479  10/14/2010  15:43:52.886400  IN201                         Deasserted
478  10/14/2010  15:43:52.903400  IN202                         Asserted
477  10/14/2010  15:43:52.966400  VB001                         Deasserted
476  10/14/2010  15:43:52.978900  OUT105                        Deasserted
475  10/14/2010  15:43:52.978900  VB004                         Deasserted
```

Fig. 17. Part of the RIO module sequential event report.

B. Fault on the TBS-A3Q00-ESA 400 kV Line

The TBS-A3Q00-ESA 400 kV line connects the Tabasco and Escárcega (ESA) substations. The line length is 297 kilometers. The line protection includes redundant POTT directional comparison schemes with SPT logic. On June 5, 2011, when the line was carrying a load current of 199 A, a temporary C-phase-to-ground fault occurred. The fault current measured at the Tabasco end was 1,446 A. The fault location was 208.9 kilometers from the Tabasco line end. This location was out of the reach of the Zone 1 high-speed elements at the Tabasco end. Fig. 18 shows the C-phase voltages and currents and some of the digital quantities recorded by a relay at the Tabasco substation. Fig. 18 shows the fault, which was cleared by an SPT at the Tabasco end. After the SPO period, the C-phase pole of the breaker successfully reclosed at the Escárcega end (the C-phase voltage was restored to its normal value). Later, the C-phase pole of the breaker successfully reclosed at the Tabasco end to restore normal line operation (not shown in the oscillogram).

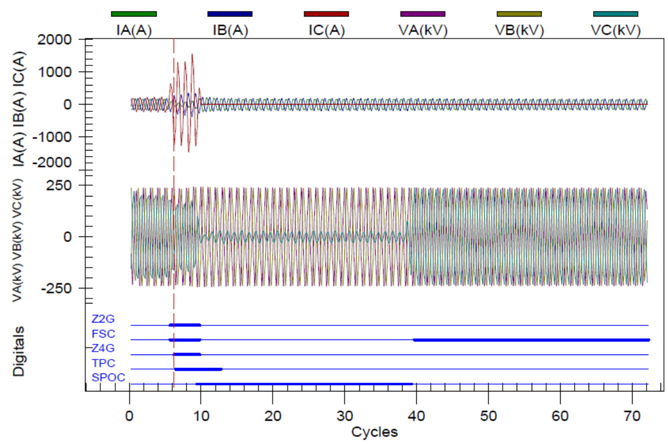

Fig. 18. Oscillogram recorded at the Tabasco end of the TBS-A3Q00-ESA line.

From Fig. 18, we conclude the following:

- The fault started at 19:16:28.099 hours.
- The high-speed ground distance element Z2G (overreaching zone) operated at 19:16:28.107 hours. Output FSC of the high-speed faulted phase selection logic also asserted at 19:16:28.107 hours. The operating time of these elements was 8 milliseconds.
- The ground distance fault detection element Z4G operated at 19:16:28.115 hours.
- The assertion of Z2G and reception of the transfer trip signal from the remote end initiated tripping of the C-phase pole of the local breaker (bit TPC asserted at 19:16:28.116 hours). The operating time of the POTT scheme was 17 milliseconds.
- The C-phase pole of the local breaker opened to clear the fault at 19:16:28.168 hours. The total fault-clearing time was 69 milliseconds.
- Bit SPOC asserted to declare the breaker SPO condition.
- The remote breaker (Escárcega substation) successfully reclosed at 19:16:28.673 hours (0.674 seconds after the fault inception). Escárcega is the line end with the weakest source.
- Later, the local breaker closed the C-phase pole to normalize the line (not shown in the oscillogram).

Fig. 19 shows part of the sequential event report from the CDAM corresponding to this line. From this report, we conclude the following:

- The CDAM confirmed that Breaker Trip Coil 2 received a C-phase pole tripping signal (bit APER 2 MAN FC A3Q00 changed to ALARMA).
- The CDAM confirmed that Breaker Trip Coil 1 received a C-phase pole tripping signal (bit APER 1 MAN FC A3Q00 changed to ALARMA).
- The CDAM confirmed that the breaker C-phase pole opened (bit EDO 52a FC INT A3Q00 changed to ABIERTO).
- The CDAM confirmed that the breaker C-phase pole reclosed (bit EDO 52a FC INT A3Q00 changed to CERRADO).

```
FE/MCADB1                           Date: 06/06/2011  Time: 12:31:16.177
TABASCO                             Serial Number: 2009189349

FID=xxx-xxx-4-R122-V0-Z011011-D20090526

#      DATE         TIME            ELEMENT               STATE

12   06/05/2011   19:16:28.152    APER 2 MAN FC A3Q00   ALARMA
11   06/05/2011   19:16:28.165    APER 1 MAN FC A3Q00   ALARMA
10   06/05/2011   19:16:28.175    EDO 52a FC INT A3Q00  ABIERTO
9    06/05/2011   19:16:28.194    EST TRIF INT A3Q00    ABIERTO
8    06/05/2011   19:16:28.275    APER 2 MAN FC A3Q00   NORMAL
7    06/05/2011   19:16:28.279    APER 1 MAN FC A3Q00   NORMAL
6    06/05/2011   19:16:29.167    OPERO REC INT-A3Q00   OPERADO
5    06/05/2011   19:16:29.201    BLOQ 79 INT-A3Q00     BLOQUEADO
4    06/05/2011   19:16:29.244    EDO 52a FC INT A3Q00  CERRADO
3    06/05/2011   19:16:29.246    EST TRIF INT A3Q00    CERRADO
2    06/05/2011   19:16:29.284    OPERO REC INT-A3Q00   NORMAL
1    06/05/2011   19:16:40.487    BLOQ 79 INT-A3Q00     HABILITADO
```

Fig. 19. Part of the CDAM sequential event report.

Fig. 20 shows part of the sequential event report from the RIO module corresponding to the breaker. From this report, we conclude the following:

- The RIO module closed its output contact (bit OUT107 asserted) to trip the breaker C-phase pole.
- The RIO module received confirmation of the breaker C-phase pole opening (bit IN205, corresponding to the breaker 52a contact, deasserted).
- The RIO module received further confirmation of the breaker C-phase pole opening (bit IN206, corresponding to the breaker 52b contact, asserted).

```
MES A3Q001                                  Date: 06/06/2011   Time: 12:47:38
TABASCO

Serial No = 2009187113       FID = xxx-xxxx-R104-V0-Z002002-D20090716
CID = F01D

#      DATE          TIME              ELEMENT                      STATE

24   06/05/2011   19:16:28.010800   OUT107                       Asserted
23   06/05/2011   19:16:28.014300   IN315                        Asserted
22   06/05/2011   19:16:28.024800   IN312                        Asserted
21   06/05/2011   19:16:28.025300   IN306                        Deasserted
20   06/05/2011   19:16:28.037300   IN205                        Deasserted
19   06/05/2011   19:16:28.053300   IN305                        Asserted
18   06/05/2011   19:16:28.055300   IN206                        Asserted
```

Fig. 20. Part of the RIO module sequential event report.

X. Conclusion

CFE engineers have learned many lessons since the first IEC 61850-based project. The CFE SAS specifications have been improved to reflect the experience gained in many projects. These specifications address the requirements for new substation automation projects, including the requirements for system factory testing and on-site commissioning. CFE decided to use IEC 61850 for present and future projects, including new installations and substation retrofits.

Future designs will make further use of the available IEEE and other methods of Ethernet traffic navigation. These methods are used to configure Ethernet switches to prioritize, segregate, and filter messages to improve the performance of information transfer via digital messaging. These include the following:

- IEEE 802.1p priority
- IEEE 802.1Q VLAN identifier
- MAC

Numerous enhancements have been made to Ethernet over the last decade but still cannot prevent packet loss during failure, reconfiguration, or bandwidth saturation. Therefore, application redundancy via dual primary IEDs remains the only reliable method for mission-critical reliability of protection and control.

The Tabasco substation system includes PCM panels in a centralized control enclosure and RIO modules in outdoor cabinets placed close to the primary equipment. The system architecture includes the following:

- An Ethernet ring with 1000BASE-SX links.
- Redundant Ethernet switches.
- Redundant star networks connecting the IEDs to the switches.

The system fully complies with CFE specifications and is reflected in a comprehensive documentation package that includes all the information required for system testing, commissioning, troubleshooting, and operation. The system factory tests and operations during actual faults confirmed good system performance.

Some economic benefits of this project, as compared with traditional substation automation projects, are as follows:

- Cost reduction by replacing copper control cables with fiber-optic links.
- Smaller trenches and cable raceways.
- Maintenance cost reduction by using multifunction IEDs with self-testing and event reporting abilities.
- Reduction of the number of panels (because of the multifunction IEDs) and the size of the control enclosure.
- Reduction of commissioning time and cost because of comprehensive factory testing. CFE has experienced up to a 50 percent commissioning time reduction [7].

XI. References

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XII. Biographies

Nicolás Erasmo Juárez Tobías received his BS degree in electric and industrial engineering from the Saltillo Technological Institute in 1982. From 1983 to 1984, he was a protection engineer in the electric department of the Ingenio Azucarero Tambaca, a sugar cane refinery. In 1985, he joined Comisión Federal de Electricidad (CFE). From 1986 to 1992, he was the head of the protection office of the Angel Albino Corzo (Peñitas) hydroelectric power plant. From 1992 to 2010, Mr. Juárez was the head of the electric grid analysis department of the CFE Southeastern Transmission Region (SRT). Since 2010, he has been the regional protection manager of CFE SRT. His areas of interest are power system analysis, protection and control, and synchronized phasor measurement applications.

Eduardo Ramón Ortega Zavaleta received his BS in electrical engineering from Oaxaca Technological Institute in 2001. From 2001 until 2005, he worked as a protection engineer for Servicios Especializados de Ingeniería de Protecciones Eléctricas (SEIPE), a consulting company in Oaxaca. From 2006 until 2007, Mr. Ortega was a construction supervisor in the Southeastern Distribution Division of Comisión Federal de Electricidad (CFE). From 2007 to 2010, he was the head of the protection and metering office of the CFE Transmission and Transformation Subarea (TTS) in Villahermosa, Mexico. Since 2010, Mr. Ortega has been the head of the protection, control, and metering department of the CFE TTS in Villahermosa. He has participated in many substation modernization projects and commissioning activities.

Santos López Aguilar received his BSEE degree from Tuxtla Gutiérrez Technological Institute in 1991. He attended a set of graduate courses jointly taught by the University of Guanajuato, Mexico, and General Electric Company in 1997. Mr. López joined Comisión Federal de Electricidad (CFE) in 1991, where he is currently head of the protection, control, and metering department of the Southeastern Transmission Region. During this time, he has performed relay setting calculations and protection scheme commissioning, including single-pole tripping schemes, in many transmission and subtransmission substations. He commissioned the substations of the Mexico-Guatemala interconnection. Mr. López has been a leader in the introduction of digital technology and optical fiber links in CFE substations. He is currently involved in substation integration projects based on the IEC 61850 standard. Mr. López has been a member of the CFE Permanent Protection Engineers Committee since 2008.

Jorge Juárez Mejía received his BSEE degree from Oaxaca Technological Institute in 1996. From 1997 until 1998, he worked for Servicios Especializados de Ingeniería de Protecciones Eléctricas (SEIPE), a consulting company in Oaxaca, as a protection technician. In 1999, he was the head of the protection, control, and metering department in the Southeastern Distribution Division (SDD) of Comisión Federal de Electricidad (CFE) in Palenque, Mexico. From 2000 to 2004, he was the head of the protection, control, and metering department in the SDD of CFE in Tapachula, Mexico. During this time, he was engaged in supervision, maintenance, improvement, and commissioning of protection, control, and metering system activities. In October 2004, Mr. Juárez joined Schweitzer Engineering Laboratories, Inc. (SEL). He is currently a senior protection engineer in San Luis Potosí, Mexico. His activities include protection, control, and metering system design and commissioning of SEL products for utilities and industrial plants.

José Luis Torres Pérez received his BS in electronic engineering from Instituto Tecnológico de la Laguna in 2005. After his graduation, he worked for SENSA Control Digital as a commissioning engineer. In December 2006, he joined Schweitzer Engineering Laboratories, Inc. as a testing and quality assurance engineer, responsible for internal and customer testing for protection, control, and metering systems. In 2009, he was promoted to senior automation engineer. Since then, Mr. Torres has been an automation project leader, and his duties include management, engineering design, and commissioning of substation integration projects.

Manuel Santiago Esquivel received his BSEE degree in electrical engineering from the National University of Rosario, Argentina, in 1994. From 1995 until 1996, he worked for Compañía Administradora del Mercado Mayorista Eléctrico, S.A., where he performed tasks related to the operation and control of the Argentinian power system. From 1997 until 2002, he worked in the Patagonia Subarea protection department of TRANSPA, S.A. (an electric utility in Argentina). From 2002 until 2005, he was an independent consultant in Argentina. From 2006 until 2009, he worked as a protection engineer for ABB México. In 2009, Mr. Santiago joined Schweitzer Engineering Laboratories, Inc., where he is currently an engineering leader in San Luis Potosí, Mexico.

Eliseo Alcázar Ramírez received his BSEE degree from the Oaxaca Technological Institute in 1998. From 1999 until 2001, he was the head of the protection, control, and metering department in the Southeastern Distribution Division (SDD) of Comisión Federal de Electricidad (CFE) in Tehuantepec, Mexico. From 2001 until 2004, he was head of the protection office of the CFE SDD. During this time, he was engaged in activities of supervision, maintenance, improvement, and commissioning of protection, control, and metering systems. In April 2004, Mr. Alcázar joined Schweitzer Engineering Laboratories, Inc. (SEL), where he is currently a protection engineering supervisor in San Luis Potosí, Mexico. His activities include protection, control, and metering system design and commissioning, as well as technical support and training on SEL products for engineers from utilities and industrial plants. His expertise includes fault analysis, short-circuit studies, protection coordination, and protection system design.

Héctor J. Altuve Ferrer received his BSEE degree in 1969 from the Central University of Las Villas in Santa Clara, Cuba, and his Ph.D. in 1981 from Kiev Polytechnic Institute in Kiev, Ukraine. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School at the Central University of Las Villas. From 1993 to 2000, he served as professor of the Graduate Doctoral Program in the Mechanical and Electrical Engineering School at the Autonomous University of Nuevo León in Monterrey, Mexico. In 1999 through 2000, he was the Schweitzer Visiting Professor in the Department of Electrical Engineering at Washington State University. Dr. Altuve joined Schweitzer Engineering Laboratories, Inc. in January 2001, where he is currently a distinguished engineer and director of technology for Latin America. He has authored and coauthored more than 100 technical papers and several books and holds four patents. His main research interests are in power system protection, control, and monitoring. Dr. Altuve is an IEEE senior member.

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