Fault-Tolerant Integrated Protection and Control System for KM20 Substation Modernization Project

Michael J. Thompson, Manglio López, and David González
Schweitzer Engineering Laboratories, Inc.

Joaquín Ayala, Nicolás Juárez, Gerardo Pérez, and Juan Villaverde
Comisión Federal de Electricidad

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Michael J. Thompson, Manglio López, and David González, *Schweitzer Engineering Laboratories, Inc.*, Pullman, WA, USA
Joaquín Ayala and Nicolás Juárez, *Comisión Federal de Electricidad,* Tuxtla Gutiérrez, Chiapas, MEXICO
Gerardo Pérez and Juan Villaverde, *Comisión Federal de Electricidad,* Villahermosa, Tabasco, MEXICO

***Abstract*--CFE's Kilómetro 20 (KLV) substation is a major 230/115 kV transmission switching station near Villahermosa, Tabasco, Mexico. This important substation had some of the oldest protection and control equipment in the region and was in need of modernization. To accomplish the modernization for the least amount of cost, CFE installed a drop-in control house. The design exploited the synergies of modern protection and control technologies to make the project feasible. A completely pretested control system improves quality and reduces expensive onsite commissioning work. The fully integrated architecture of the design allowed the system to be built in a house that was small enough to be easily transported. Extensive use of remote I/O modules located in the yard near the substation equipment and logic processors further reduced the space required for cabling and eliminated problem prone auxiliary relays for interlocking. The integrated system provides local HMI and SCADA functionality. The use of remote I/O modules also reduced the cost of recabling this large substation yard and improved reliability by replacing many copper circuits with continuously monitored links that are immune from radiated and induced interference. This paper describes the key features of this unique project.**

I. INTRODUCTION

In 2002, Comisión Federal De Electricidad (CFE) began planning for the modernization of the Kilómetro 20 (KLV) substation near Villahermosa, Tabasco, Mexico. This substation is a major switching station for the 115 kV and 230 kV transmission system in Southern Mexico. A request for proposals for a complete, factory fabricated, and tested protection and control system was issued in the fall of 2002.

The project commenced in 2003 with initial energization of circuits on the new system occurring in October 2003. At this writing, the process of transferring all circuits to the new protection and control system is ongoing.

The design exploited the synergies of modern protection and control technologies to make the project feasible. One of the important features of the design was to extend the concept of continuous self-test features of microprocessor-based relays to encompass the entire protection and control system. The project involved supplying a factory-tested, drop-in control house, connected to the substation equipment using remote I/O modules via fiber-optic links. This paper describes the execution and important design features of the project.

II. BACKGROUND

The KLV substation was built in 1978. It began operations in 1979 and, at that time, included one 230 kV line, one 225 MVA transformer, and five 115 kV lines. The protection, control, and metering (PCM) panels were duplex cabinets with single-function electromechanical relays.

The KLV substation is located in southeast Mexico, 20 kilometers from Villahermosa, state of Tabasco, on the Villahermosa–Teapa motorway.

The KLV substation plays an important role in the electric system in Mexico because 1) it acts as the main link between the Peninsular Transmission electric grid and Mexico's interconnected electric system, and 2) it provides most of the 115 kV lines for the Tabasco electric grid.

In its first ten years of operation, KLV grew to its present configuration of five 230 kV lines, one 225 MVA transformer with one 25 MVAR reactor on its tertiary, and eight 115 kV lines. Over the years, KLV has been partially updated with static relays and then with microprocessor-based relays. However, the KLV substation was in need of total modernization.

A. *KLV Substation*

The KLV substation configuration (see Fig. 1) includes:

- For the 230 kV side, two busbars and one tie breaker (Bus 1 and Bus 2). This configuration provides a highly reliable electric system, because in case of busbar failure, a backup busbar will still be in service. There is a third busbar—the transfer busbar—with a normally open transfer breaker.
- For the 115 kV side, one busbar and one transfer busbar.

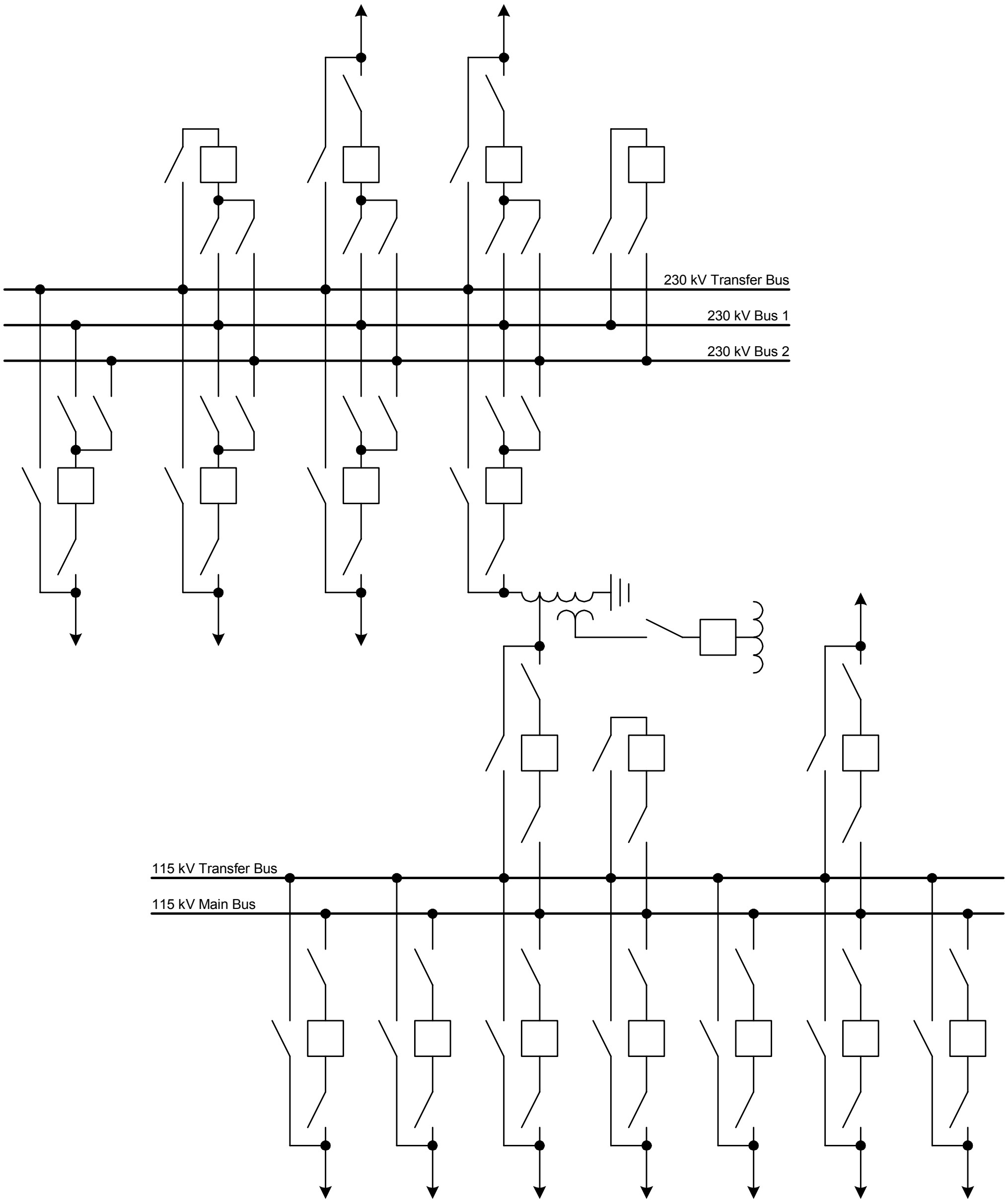


Fig. 1. Single-Line Diagram, KLV—115 kV and 230 kV

B. Project Justification

CFE planned to completely modernize the KLV substation, based on the following considerations:

- The substation needed space for new PCM panels.
- All the trenches were full of copper control cables, and CFE wanted to replace them with fiber optics.
- Villahermosa weather and the cable paths from the substation yard to the PCM cabinets caused PCM duplex cabinet humidity.

CFE searched the market for the best option to accomplish this modernization. They spent several months considering various alternatives for completing this project, including:

- Building a new control house.
- Expanding the existing control house.
- Enabling distributed control on a per bay basis, installing small PCM cabinets in the substation yard.
- Acquiring a drop-in control house with state-of-the-art PCM cabinets included.

CFE decided to specify and bid a drop-in control house for several reasons, including:

Economics. The cost of installing a drop-in control house is much less than that for building a new control house, and it is even less expensive than enlarging the existing control house. The drop-in control house provides 40% savings for the overall project compared to the traditional solution. The new control house includes one battery bank, ten PCM panels, one local HMI panel, remote I/O cabinets, fiber optics, and associated services.

Space. Traditional PCM panels include a lot of accessories and auxiliary relays, so they need more space, they are more expensive, and they are more prone to fail. Eliminating those accessories and auxiliary relays reduced the space needed for the PCM panels.

Technology. Using state-of-the-art technology, it is possible to reduce the copper wiring for alarms and controls. Instead of copper control cables, we specified fiber-optic links and remote I/O equipment, reducing interferences and their associated problems. Inside the control house, most of the links use digital communications channels to exchange information, and all these links are continuously monitored.

Commissioning. Because the KLV substation is already in operation, the amount of time required to commission the system was a critical matter to consider. One of the reasons CFE selected the drop-in control house was that it would reduce about 50% of the labor time.

III. DESIGN GOALS

The project team had several design goals for the project:

- Achieve a robust, fault-tolerant design:
  - Eliminate any single point of failure
  - Eliminate, wherever possible, problem prone auxiliary relays and switches
  - Design in continuous self-test features
- Improve quality and reduce cost:
  - Reduce field wiring
  - Completely test the system before leaving the factory
  - Reduce expensive onsite commissioning work
- Improve safety and operation:
  - Install extensive control interlocking
  - Develop an intuitive user interface
  - Provide better data recording and alarm annunciation for analysis
  - Include better design documentation for operation and troubleshooting

The balance of this paper describes how the project team achieved these goals.

IV. CONTROL HOUSE DESIGN DETAILS

A fundamental aspect of this project was to improve the quality and cost by having the system completely factory fabricated and tested prior to arrival on site. Factory testing of the circuitry, programmable logic, communications links, computer HMI system, etc. can be accomplished much more thoroughly and economically in a factory environment than in the field. This can significantly improve quality, cost, and schedule aspects of the project.

A. Control House

A fundamental challenge to the project was to fit all of the protection and control systems for such a large substation into a control house small enough to be easily transported. The new control house dimensions are nominally 3 m x 10 m. The house included a main control room and a separately accessed battery room. Each room has a separate HVAC system. Fig. 2 shows the layout of the control house. Photos of the old and new panels, as well as the new control house are in Fig. 3, Fig. 4, and Fig. 5.

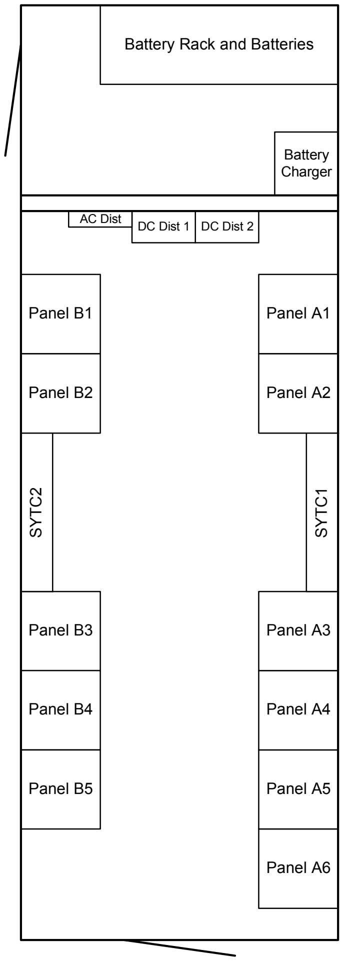


Fig. 2. Basic Drop-In Control House Layout

Fig. 3. KLV Old PCM Panels

Fig. 4. KLV New Panels

Fig. 5. New KLV Control House

B. *Panels*

To make the best use of interior space, closed back/swing front cabinets, lined up along each wall, were specified for the protection and control panels. The relaying and metering equipment is mounted in the door with wiring terminations along the interior left and rear walls of the cabinets. Cabling between the switchyard termination cabinets (SYTCs) is via an overhead cable tray. There were some initial concerns about ease of access for maintenance and troubleshooting with closed back panels such as these, so the cabinet design used on this project was large enough to make it easy to step inside to take readings, check fuses, trace wiring, etc. The overhead cable entrance allowed a flat floor with no obstacles, making it easy to stand inside the cabinet as required. All in all, the design was quite easy to work with.

The SYTCs provide a clean line of demarcation between the control house and the substation yard equipment. Two were provided—one each for the 115 kV and 230 kV portions of the station. In retrospect, the use of fiber-optic links reduced the number of circuits to such an extent that the SYTC cabinets could have been much smaller than those used on this project. During factory testing, the SYTC cabinets made connecting the substation simulation signals to the protection and control system extremely easy. Breaker trip and close signals, current and voltage sensing, and power are the only signals connected to the yard via copper circuits. All other status and control signals are connected to the yard via remote I/O modules and fiber-optic links. During testing, logic processors were used to simulate the signals coming into the system from remote I/O modules.

Using a computer HMI system for local control, metering, and annunciation made it possible to eliminate much of the equipment that would otherwise have to be mounted on the panels. Using powerful microprocessor-based relays and meters also minimized the space requirements.

Four basic types of panels were used:

- Three 230 kV line panels (two lines per panel)
- Four 115 kV line panels (two lines per panel)
- Three transformer/reactor/lockout relay panels
- One HMI panel

The scope of this project did not include upgrading the 115 kV or 230 kV busbar protection systems. The layout allowed space for one additional panel to be added in the future as required.

C. *Auxiliary Power Supply Systems*

A single ac distribution panel supplies the control house habitation systems and battery charger. All of the substation equipment ac auxiliary circuits continue to be fed through the distribution panels in the original control building.

The dc power distribution system is fully redundant. Two dc distribution panels supply System 1 and System 2 protection and control systems. One is fed from the station battery located in the battery room, and the other is fed from a battery bank located in the existing control building. A tie breaker in each cabinet allows a great deal of flexibility for cross feeding the circuits should there be a failure or maintenance required on one of the dc supplies. To eliminate single points of failure, the protection and control circuits were carefully allocated between the System 1 and System 2 dc distribution panels.

V. PROTECTION SYSTEM DESIGN DETAILS

The protection and control system uses dual-system architecture. Including a fully redundant System 1 and System 2 throughout the design made possible many of the features that make this integrated protection and control system robust and fault tolerant, with continuous self-test features. Fig. 6 shows the overall system architecture.

- Fault Detection
  - System 1 Relay
  - System 2 Relay
- Fault Interruption
  - System 1 Circuit Breaker
  - System 2 Redundant Breaker Failure Systems
- Control, Status, Alarms
  - System 1 Local HMI
  - System 2 Remote SCADA
- Lockout Tripping and Interlocking
  - System 1 Logic Processors
  - System 2 Logic Processors

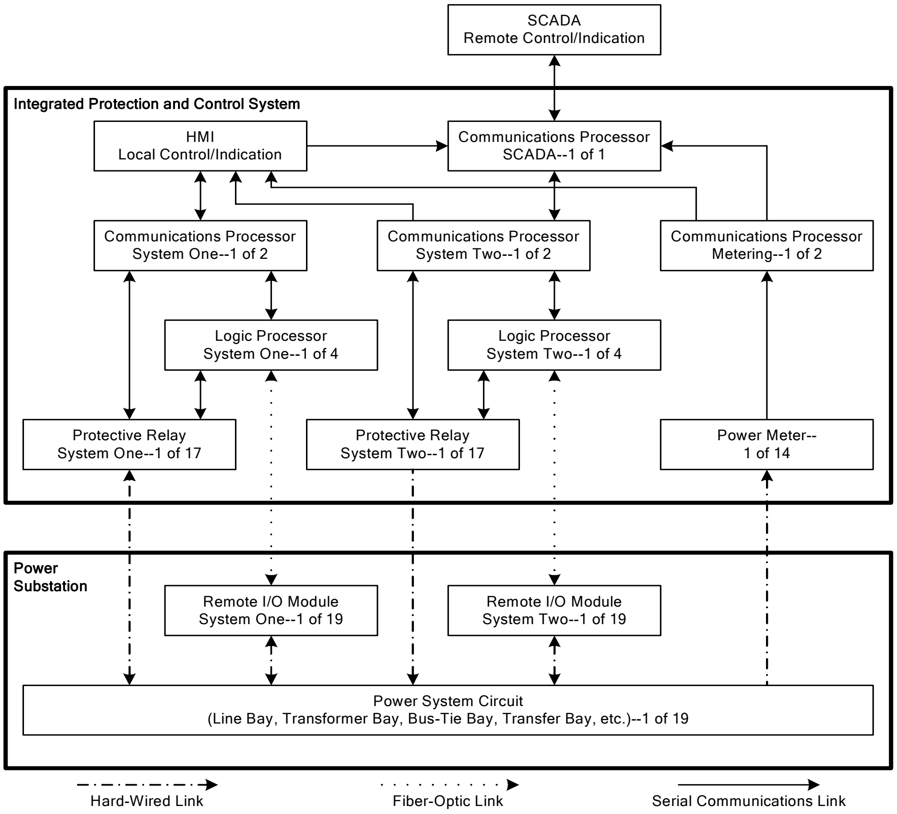


Fig. 6. Simplified System Architecture

A. Switch Status Validation

This substation has a complex bus arrangement that provides a great deal of operational flexibility. This flexibility comes at the price of protection and control system complexity. The 230 kV bus is a double bus with transfer bus arrangement. Every line and transformer circuit can be connected to one of two main buses. Each circuit can also be connected to the transfer breaker via a transfer bus. Similarly, the 115 kV bus is a single bus with transfer bus arrangement.

The status of the switching topology is extremely important in the functioning of the protection and control system. It affects several functions:

- Circuit Tripping Logic (Trip main or transfer breaker?)
- Circuit Breaker Synchronism Check (Which bus potential should be used?)
- Breaker Failure Tripping Logic (Which circuits are connected to the same bus?)
- Circuit Lockout (Which breakers are connected to a circuit that is locked out?)
- Switching Operation Interlocking (Is it safe to open or close a disconnect?)

The current transformers (CTs) and voltage transformers (VTs) are on the line side of the bus switching so the protective relay sensing (except synchronism check sensing) is not affected by the switching arrangement. However, accurate status information is very important to the proper functioning of the protection and control system. A traditional design would include separate auxiliary switches and auxiliary relays for each circuit, requiring switch status interlocking. If any individual contact is in the incorrect state, it would not be readily apparent. The hazard is that the system may have a hidden problem that may result in incorrect operation.

This is where using a fully integrated, dual-system design is a significant advantage. Each status point is brought into System 1 and System 2 once each. This status is shared through the logic processors with every circuit and interlock that needs it. The status of each point is validated by continuously monitoring the two systems for congruence in the HMI computer.

There are several advantages to using a single, validated status point throughout each system:

1. All individual systems operate consistently.
2. If one of the systems has a status indication problem, it is alarmed immediately so that the problem can be corrected before it results in an incorrect operation.
3. Because the validated status signals are used in both protective logic and for status indication to SCADA or the HMI, problems are readily apparent and easy to troubleshoot.
4. Reducing the number of problem-prone auxiliary switches also enhances the reliability of the system.

Early in the design, CFE determined that full redundancy would not be used for control of the 230 kV motor-operated disconnect switches (MODs). This posed a challenge for applying continuous status validation to these important status points. To work around this, these status points were handled differently. For these points, it was assumed that if an incorrect status failure were to occur, it would be when the status is changing. Thus, the control logic for the 230 kV MODs includes an operate fail alarm. If the operator commands an open or close and the status does not change within 5 seconds, the logic sets an operate failure alarm. The user interface is designed to prevent the operator from going to any other screen until the alarm is acknowledged. At that point, the operator could determine if the open or close operation had failed or if only the status indication had failed. Because this same status is used throughout all of the protection and control logic, the problem is known immediately and can be corrected quickly.

Wherever possible, the remote I/O modules for System 1 and System 2 are powered by breaker trip circuit 1 and trip circuit 2 respectively. This also eliminates a possible single point of failure problem. In applications without dual trip circuits, the system is wired to allow future upgrades to dual trip circuits.

B. Protection System Details

The 230 kV and 115 kV line zones use a System 1 relay and a System 2 relay. The System 1 relay provides protection, auto-reclosing, sync check supervision, and local HMI control. The System 2 relay provides protection, sync check supervision, and remote SCADA control. The 230 kV lines use single-pole trip and reclose logic. All other circuits use three-pole trip logic.

The transformer and reactor zones use differential protection for System 1 protection. The 115 kV and 230 kV main breakers each have a System 1 relay and a System 2 relay for local HMI control and remote SCADA control respectively. Each relay provides independent synchronism check supervision for its control path to eliminate any single point of failure. The sudden-pressure relays are part of the System 2 relaying to backup the sensitive differential protection. They trip through the 230 kV System 2 overcurrent relay. An overcurrent relay on the 13.8 kV tertiary bus provides System 2 back up for faults on the tertiary bus and the reactor.

On the 230 kV and 115 kV circuits, both systems provide breaker failure protection functionality—tripping through their respective system. Each system operates from a separate dc distribution cabinet through a separate trip circuit to eliminate single point of failure problems. While the 115 kV breakers do not include dual trip circuits, the circuits are wired to accommodate future upgrades to dual trip circuits.

Because each circuit's current and voltage transformers are located beyond the bus switches, the transfer breakers do not have CTs. Thus, breaker failure for each transfer breaker is provided by the individual circuit relays. The station connectivity logic determines if the transfer breaker is in the circuit, and targets breaker failure for the transfer breaker appropriately.

The only systems in the substation that are not fully redundant are the breaker failure and synchronism check functions on the 230 kV bus tie breaker and the breaker failure protection on the reactor breaker. Because breaker failure is a backup system, this does not pose a single point of failure problem in our contingency analysis.

Multifunction relays provide many tripping outputs with powerful programmable logic driving them. We improved reliability and performance by using this feature in the design. When each relay can direct trip its respective breakers for a fault in its zone of protection, potential points of failure are eliminated. Additionally, the breaker trip circuit schematics become very simple, making them easy to commission correctly. Both protection system trip and close signals and control system trip and close signals are routed through the same output contacts so that each time a breaker is manually operated, the protection path is proven—and vice versa. For example, the multifunction transformer differential relay trips the high- and low-side breakers directly. It only trips the transformer lockout relay for the purpose of locking out the breakers. The interlocking to determine whether the main breaker or the transfer breaker is to be tripped is done entirely in programmable logic, where it is under the continuous self-testing within the multifunction relay.

C. Logic Processors Handle All Interlocking

Because the substation includes a complex bus arrangement where each circuit can be connected to multiple buses through multiple breakers, tripping logic can be quite complex. The logic processors handle the substation connectivity logic. All of the remote I/O modules communicate system status and alarms from the substation yard equipment to the logic processors. Eight logic processors are arranged into four teams—System 1 and System 2 for the 230 kV and System 1 and System 2 for the 115 kV side of the station. The logic processors determine which breaker each circuit is connected to and which bus each circuit is connected to. It communicates this status to each relay via a continuously monitored serial communications link.

The design includes six physical lockout relays. However, these lockout relays have only a single deck (two NO and two NC contacts). The lockout relays do not directly trip anything. They only serve the purpose of a physical latch and indication of lockout tripped status. The status of each lockout relay is brought into each logic processor for the purpose of interlocking.

D. Continuous Self-Testing Features

In addition to using independent dual systems and continuous monitoring of status congruence between the two systems, other self-test features are built in. The goal is to monitor and alarm for problems anywhere in the system.

- Relays with extensive continuous self-test are used throughout the system.
- Relay circuits are also monitored by the relay alarm contact.
- Every breaker and lockout relay circuit includes trip circuit monitoring that alarms for loss of dc to the circuit or an open trip coil.

- Every communications link is monitored for communications failure.
- As much control logic as possible is implemented in programmable logic where it can be continuously monitored by the continuous self-test features of the device.
- Protection trip and close circuits are common with manual trip and close circuits so that these contacts and paths are verified every time the circuit is operated.

VI. CONTROL SYSTEM DESIGN DETAILS

The control system uses as a foundation all the protection and metering equipment. As previously mentioned, the KLV substation system is based on a dual protection scheme. All the information comes from IEDs into communications processors that act as servers for different clients or data consumers. Refer to Fig. 6 for details on the system architecture.

The designed control system provides two different paths to control and supervise the KLV substation.

The first path is the local HMI installed inside the drop-in control house, which allows the operator to supervise all the information available on the PCM equipment, through all seven communications processors, to control breakers and MODs, as well as enable such protective functions as 79, clear 86T, clear 86BF, and apply tags, etc.

The second path is the remote SCADA system. Through a set of communications processors, the SCADA operator supervises the most important information from the KLV substation. CFE supervises only a subset of the information available in their substations, in order to optimize the communication and data gathering. Through the SCADA system it is possible to supervise the KLV system operational status, as well as operate breakers and MODs.

For the design of the control systems, several mandatory requirements for the system were met:

- Provide optimal cost, features, flexibility, and reliability, and the ability to migrate to future technologies, if needed.
- Increase reliability by reducing the device count, and use highly reliable devices and self-diagnostics to quickly detect and correct substation alarms.
- Develop a completely graphical and intuitive interface.
- Fully integrate the system for protection, automation, and control.
- Manage event reports, and relay and meter settings.
- Fully exploit multifunction devices via communications to take full advantage of and to reduce duplication of functions within the substation.
- Develop security schemes based on functional groups, to allow/disallow certain functions.
- Satisfy the multiple consumers of substation data, such as the local HMI, the remote SCADA system, and remote engineering access.

A. *Communications Processors*

As shown in Fig. 6, the KLV substation system uses seven highly reliable communications processors. They have several functions assigned:

- Two communications processors gather data from System 1 protective relays; all of the operational status, metering, breaker maintenance and operations, and post-fault events come from this set of equipment. These communications processors send their information to the local HMI.
- Two communications processors gather data from System 2 protective relays; they have the same functions as the System 1 communications processors. These communications processors send their information to the SCADA system.
- Two communications processors gather data from the power meter, data concentrator, and data reporting. These communications processors send their information to both the local HMI and SCADA systems.
- One communications processor is used for special functions like automatic post-fault event retrieval and relay and meter settings management.

B. *Local HMI Functionality*

The HMI performs the following SCADA-like functions:

- Circuit breaker control
- Relay target reset
- Reclosing on/off
- Reset lockout (86 type device)
- Hot-line, hold, and information tag
- System 1 and System 2 data consistency checking, because of the dual equipment. In this case, there are some automation functions that display any discrepancy in the information from System 1 and System 2. For example, if System 1 is reporting OPEN for breaker 1 and System 2 is reporting CLOSE for breaker 1, the HMI will display a label that shows the UNDETERMINANT condition.
- Permanent communications links supervision that alerts the operator in case of any abnormal status in the communications links. Because this report is generated as soon as something abnormal occurs, the operator is able to verify the system and reestablish operation immediately after the failure(s).

C. *Data Acquisition*

The following information is provided to the local HMI and SCADA systems, and takes advantage of the information available from the IEDs:

- Three-phase currents and phase-neutral voltages
- Real and reactive power, and power factor
- Reclosing status
- Local/remote status

- Breaker failure, spring energy, trip coil status, and lockout indication
- Status for all communications links
- Relay targets and front-panel information for each relay
- Breaker (52A) and disconnectors status

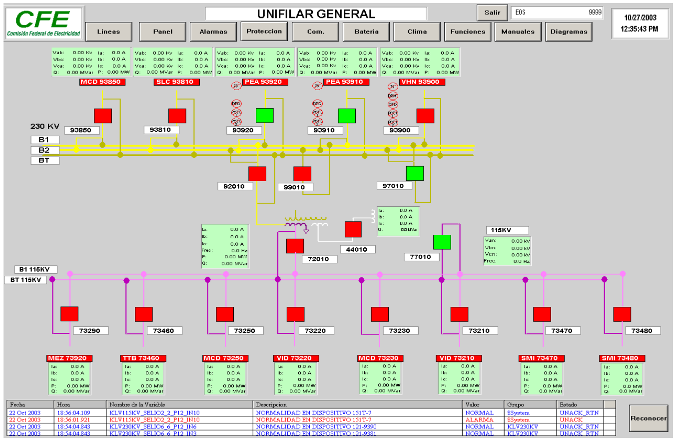


Fig. 7. KLV Substation HMI Overview

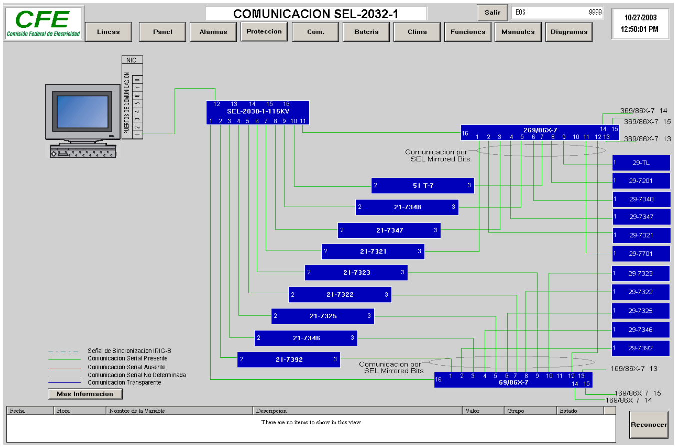


Fig. 8. Communications Links Continuously Supervised

D. HMI Screens

The following is a listing of the screens provided with the KLV HMI:

- Header (menu) bar
- One-line diagram
- Relay targets screen
- Protection overview screen
- System communications screens
- Alarm summary/history screens
- Weather status screen
- Circuit breaker control screen (see Fig. 9)

By using all these screens, the operator knows the real-time operational status of the KLV substation.

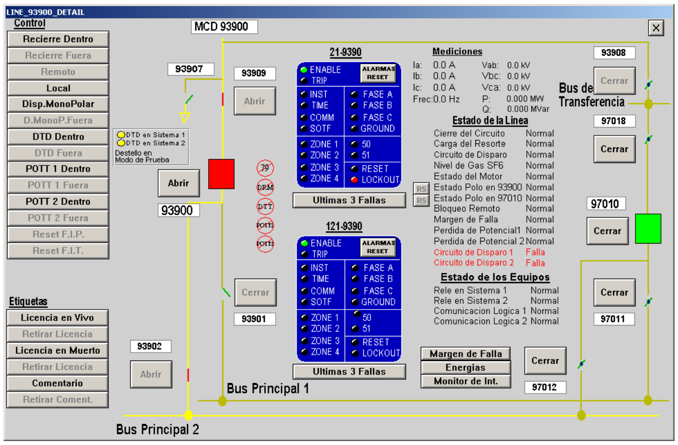


Fig. 9. Circuit Breaker Control Screen

E. KLV System Reports Nonconventional Data

The KLV integrated system provides a set of features and information not commonly exploited on traditional integrated systems. This information is available in almost every microprocessor-based relay, and it provides a set of tools to help better understand and manage the electric system. There is also a group of HMI tools that allow operational personnel to have access to some nonconventional HMI features.

Some of the nonconventional data and functions that CFE is using at full potential are:

- **Last three faults data.** Provides the operator with the most relevant data about the last three operations.
- **Breaker maintenance information.** Allows the operator to view the wear percentage per breaker pole, the number of internal and external operations, and the accumulated interrupted current.
- **Breaker failure margin operation.** Allows the operator to detect how fast or slow the breaker is operating.
- **Substation weather information.** Provides the operator with weather information to use for statistical purposes.
- **Event reports.** Reports are automatically downloaded to HMI, and archived on a database.
- **Online access to all instruction manuals.** Provides convenient, instant access to the instruction manual for any IED.
- **Online access to all AutoCAD documentation.** Provides a smart way to keep all the system design information in the substation. If any change occurs, files are updated with modifications.
- **Operating Instructions.** Provides the operator with instructions to follow in case of disturbances. CFE's engineers are responsible for providing the Acrobat format files (PDF). These files show all the operating instructions according to CFE policies and restoration procedures, as well as general information for primary equipment and protection schemes.

All these data and functions enable CFE personnel to operate the KLV substation efficiently and reliably.

VII. DESIGN DOCUMENTATION

Traditional design documentation packages can fall short with a fully integrated design such as this. In this integrated system, most of the protection and control functionality is in programmable logic where it can be continuously monitored. Most status and control signals are passed throughout the system on serial links and not on copper circuits. Because these status and control signals never become physical inputs or outputs, traditional dc schematics cannot provide enough information for understanding, operating, and troubleshooting the system. The dc schematics for this project are extremely simple. One of the design goals was to provide a superior design documentation package that would overcome these challenges.

A. Elementary Diagrams

The elementary (schematic) diagrams used for this project are combined ac/dc elementary diagrams. The elementary diagrams include extensive cross-referencing to aid the user in navigating the complex system circuitry and logic. Each diagram shows the protected circuit with CT and VT connections to the relay and metering devices. DC connections to the circuit's relay and metering devices are also shown on the same diagram. Different techniques are used to show various types of information:

- Contact sensing inputs
- Output contact/test switch tables
- Serial communications I/O tables

Each of the many status inputs for a device is shown in schematic representation. Where a contact sensing input is in a different circuit, its purpose is noted and the elementary diagram where it can be found is cross-referenced.

The large number of output contacts available in modern multifunction relays can be a challenge to manage. Tables are used to indicate the use of each output contact. The table indicates the purpose of each output contact, and cross-references each output contact with the corresponding test switch pole, circuit, and drawing.

The large number of status signals that are interconnected between devices via serial communications links are listed in tables as well. The tables list pertinent information such as from/to for each link, baud rates, addresses, communication fail states, etc.

Finally, the elementary diagrams cross-reference which logic diagram to use to determine the purpose of each input and the logic that drives each output.

B. Logic Diagrams

Because most of the protection and control functionality in a fully integrated system is implemented in programmable logic across serial communications links, logic diagrams are critical for documenting the system.

To understand the importance of the logic diagrams, it is helpful to draw a parallel between diagrams for a traditional control circuit and an integrated control system. Logic diagrams are equivalent to dc schematic diagrams. They allow the user to easily see and understand the function of the circuit. On the other hand, logic setting equations in the relay settings file are functionally equivalent to wiring diagrams. They only allow you to see how everything is connected together; it is difficult to follow the circuit and understand its functionality. A design engineer would never consider issuing a design documentation package with wiring diagrams but without schematic diagrams.

Another advantage of drafted logic diagrams is that they can be adequately annotated. Logic can be grouped into easily-digestible functional groups. Many logic variable names within a device can be quite cryptic. Variables such as intermediate logic variables or general-purpose timer variables may have no inherent meaning at all. A brief name or description can be associated on the diagram with the logic variable, making it much easier to understand.

The logic diagrams show only user-programmable logic that is part of the integrated system design. Logic settings that are circuit specific, for example, are not included in the diagrams. This helps keep the number of logic diagrams manageable. For example, logic settings such as trip and reclose initiate are left off so they can vary as required from circuit to circuit without requiring a separate logic diagram for each circuit. Also, fixed internal logic that is described in the device's instruction manual is shown as "black boxes" on the logic diagrams. Inputs and outputs of a specific protection or control function are shown because they are customer programmable. The user can consult the manual to determine how the function processes the inputs into outputs. This serves to simplify the logic diagrams and to eliminate problems associated with incorrectly interpreting the manufacturer's design.

C. Communications Diagrams

There are well over 150 serial communications links in this system. Communications links are used for two main purposes: 1) exchange of status, alarm, metering information, and control commands between devices and user interfaces, and 2) exchange of I/O signals between devices at protection speeds. Additional communications links are used for such things as distribution of IRIG-B time synch signals.

Many links are used for sending status, alarm, and metering values from the individual circuit devices to the local HMI and/or the remote SCADA systems. These same links send control commands from the user interface systems to the individual circuit devices. These links may use industry-standard protocols such as Modbus® or DNP3, or proprietary protocols.

Other links are used for exchanging status, alarm, and tripping signals between the logic processors and the individual circuit devices. This same type of link also exchanges status, alarm, and control signals between the logic processors and the remote I/O modules.

Detailed communications diagrams provide documentation of the routing of the many communications links. The diagrams indicate each link and the protocol running on the link.

VIII. IMPLEMENTATION

A successful project involves not only good design, but also good implementation. This project involved a large number of people working in different locations in Mexico and the U.S. Adding to the challenge was the fact that members of the team did not speak the same language. To facilitate communication between the design and fabrication teams in the U.S. and the end user and commissioning teams in Mexico, a liaison was designated to translate and funnel information between the two groups.

One of the initial difficulties that had to be overcome was a lack of documentation on the existing substation. The project specification provided a general description of the requirements of the system. A number of site visits filled in much of the details. Numerous email and telephone conversations filled in the gaps to start the preliminary design.

A. Preliminary Design and Review

Because this project involved such a cutting edge design, it was important that all participants had understanding and buy-in early in the design process. Furthermore, the lack of detailed information left a great number of details to be determined by assumptions that had to be confirmed to keep the project on track. To get the project off to a good start, a meeting was scheduled early in the project. The preliminary design review meeting had a number of purposes:

- Review the preliminary design.
- Get answers to detailed questions and check assumptions.
- Obtain understanding of operating scenarios and practices.
- Develop a working relationship between the principal contributors to the project.

B. Detailed Design and Fabrication and Testing

Once agreement and understanding was obtained on the requirements and the preliminary design to meet those requirements, a detailed design was completed. The elementary diagrams were sent to the factory, where detailed wiring diagrams were created. In parallel with that effort, the logic diagrams were created and finalized.

With approval of the panel elevations, bill of materials, and wiring diagrams, the control house was fabricated. The remote I/O cabinets were completed and shipped in advance so the field installation team could install them at the same time that the other site preparation work was being completed.

Once the control house was completed, a team consisting of automation and protection engineers began the factory acceptance testing (FAT). One of the fundamental aspects of this project is that it was completely factory tested prior to arrival on site. FAT involves completely proving all aspects of the design and fabrication. The following items were verified during the FAT:

- Protection and control wiring
- Auxiliary systems wiring
- Operation of auxiliary systems (HVAC, lighting, etc.)
- Communications links
- Logic programming
- Communications processor programming
- HMI database
- HMI screens (control, status, alarms, etc.)
- SCADA link database

A number of logic processors were programmed to simulate the substation yard and all of the RIO modules bringing status into the system. It was a simple matter to control logic points inside the logic processors to assert substation status points. Hard-wired connections, such as breaker trip and close, were wired to status inputs on the logic processors so they could toggle the breaker simulators in the logic processors, which in turn fed back into the system through a remote I/O link. It was verified that the appropriate action or status was seen correctly in each of the devices and on the proper screens in the local HMI system.

Early in the design process, the protection engineers designing the elementary and logic diagrams generated a complete list of all analog, status, alarm, and control points for each circuit of the substation. This list was developed in tables to help the automation engineers understand what device each data point needed to come from and what they were to do with it in the HMI system. This series of tables then became the checklist for verifying the HMI system. The elementary diagrams and logic diagrams were used to verify the wiring and logic functions.

During the final week of FAT, the end users visited the factory to witness a full functional test of the system. At this point, the users had an opportunity to make final adjustments in the design and correct any incorrect assumptions that were made during the detailed design phase. The fully integrated nature of the substation meant that adjustments such as these did not require rework of the wiring—only revision to computer screens or device settings files.

C. Field Preparation, Installation, and Commissioning

The KLV control house system is the first all-integrated system of this kind among CFE substations. Because the KLV control house system uses a new technology for CFE, we formed a multidisciplinary group to oversee system commissioning. This group included CFE and SEL personnel, including:

- Protection engineers
- Automation engineers
- Metering engineers
- Administration personnel

One of the greatest paradigms to be broken was the specialties border that existed between CFE organizations. With this new technology and system, the boundary between protection and automation is not clear, because multifunctional IEDs have both functions.

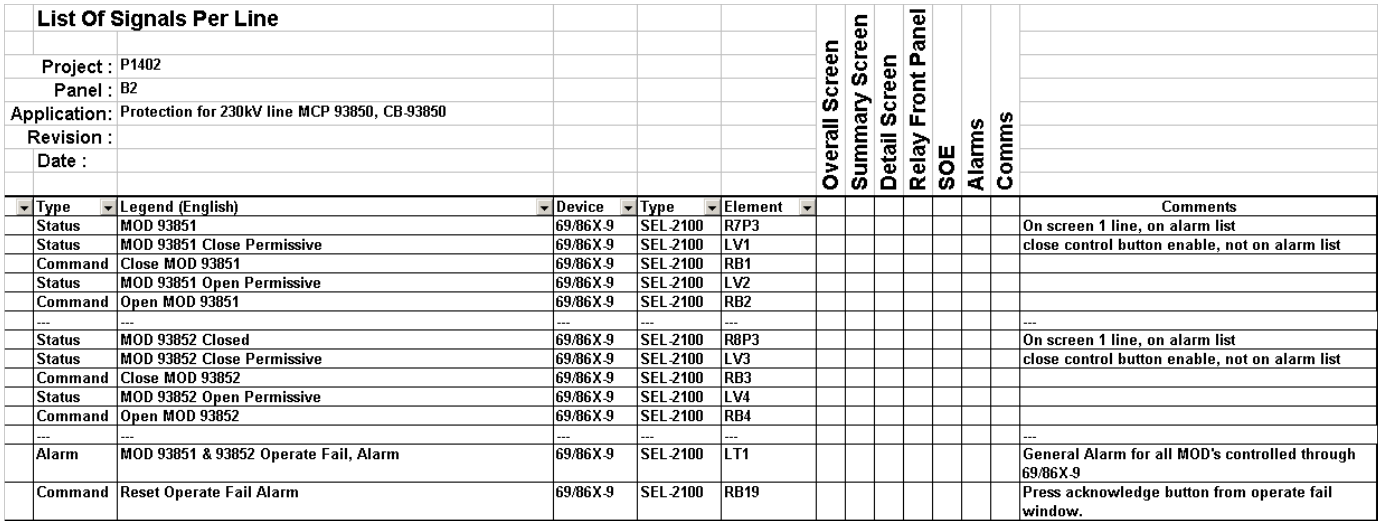
As part of the commissioning, several activities had to be completed. These are some of the most important functions:

- Battery bank installation and operation verification.
- Foundation and erection of drop-in control house.
- Foundation and erection of remote input/output cabinets on the substation yard.
- Copper control cable wiring, from primary equipment to remote I/O cabinets.
- Pipeline installation for fiber-optic installation, fiber-optic connectors, and fiber-optic links test.
- Substation equipment staging via logic simulators; this was known as the first stage, and CFE used this stage to gain confidence in the operation of the new system, and to test every possible substation operational scenario. Some of the different scenarios included just System 1 operating, just System 2 operating, or both systems working in parallel.
- As the second stage, CFE and SEL tested the KLV substation operation with real interaction to primary equipment, for one 230 kV transmission line. In this case, CFE wanted to verify all the wiring as well as all the communications links involved.
- As part of both stages, communication with local HMI and SCADA systems was conducted, using the local HMI and DNP3 test set equipment to simulate SCADA operation. A spreadsheet was designed to archive all the results for these tests, and it was used as a checklist during the tests. Fig. 10 shows an example of the checklist.

CFE had high expectations for this project, so in order to gain confidence with this new technology and assure the system would operate correctly, we conducted an exhaustive effort for 20 days to fulfill every scenario CFE wanted to test.

At the first stage (15 working days), we tested the system performance and functionality using the logic simulators, to verify control and interlocking/permissive logic operation according to CFE operational rules for the electric grid. All the protection functions were tested during those days for each 230 kV line, 115 kV line, 230/115/13.8 kV transformer, and 13.8 kV reactor.

For those tests, we used test equipment to supply voltage and current signals for the relays and meters, then a set of protection routines were run in order to test the protection functions and HMI and SCADA features in Table 1.



List Of Signals Per Line

Project : P1402
Panel : B2
Application: Protection for 230kV line MCP 93850, CB-93850
Revision :
Date :

Type	Legend (English)	Device	Type	Element	Overall Screen	Summary Screen	Detail Screen	Relay Front Panel	SOE	Alarms	Comms	Comments
Status	MOD 93851	69/86X-9	SEL-2100	R7P3								On screen 1 line, on alarm list
Status	MOD 93851 Close Permissive	69/86X-9	SEL-2100	LV1								close control button enable, not on alarm list
Command	Close MOD 93851	69/86X-9	SEL-2100	RB1								
Status	MOD 93851 Open Permissive	69/86X-9	SEL-2100	LV2								
Command	Open MOD 93851	69/86X-9	SEL-2100	RB2								
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Status	MOD 93852 Closed	69/86X-9	SEL-2100	R8P3								On screen 1 line, on alarm list
Status	MOD 93852 Close Permissive	69/86X-9	SEL-2100	LV3								close control button enable, not on alarm list
Command	Close MOD 93852	69/86X-9	SEL-2100	RB3								
Status	MOD 93852 Open Permissive	69/86X-9	SEL-2100	LV4								
Command	Open MOD 93852	69/86X-9	SEL-2100	RB4								
---	---	---	---	---								---
Alarm	MOD 93851 & 93852 Operate Fail, Alarm	69/86X-9	SEL-2100	LT1								General Alarm for all MOD's controlled through 69/86X-9
Command	Reset Operate Fail Alarm	69/86X-9	SEL-2100	RB19								Press acknowledge button from operate fail window.

Fig. 10. Commissioning HMI and SCADA Checklist

Table 1 Protection Functions and Operational Data

Protection Scheme	230 kV Lines	230 kV Busbar Tie Breaker	115 kV Lines	Transformer/Reactor
Functions	21single-pole 21 three-pole 67N three-pole 79 single-pole 50BF 86BF-1 86BF-2 25 25/27	50BF 86BF-1 86BF-2 25	21 three-pole 67N three-pole 79 three-pole 50BF 86BF-1 25 25/27	87T 51P/51N (Reactor) 67N High Voltage 67N Low Voltage 50BF 86T 86BF-1 86BF-2
	Metering Breaker Status Disconnector Status Breaker Alarms HMI and SCADA Controls SER Events	Metering Breaker Status Disconnector Status Breaker Alarms HMI and SCADA Controls SER Events	Metering Breaker Status Disconnector Status Breaker Alarms HMI and SCADA Controls SER Events	Metering Breaker Status Disconnector Status Breaker Alarms Transformer Alarms HMI and SCADA Controls SER Events

For the second stage, CFE cleared a 230 kV line to repeat all the operational tests. In this case, we tested the system in the real world, sending control operations to the breaker coils in opening/closing the breaker and MODs. We also validated all the interlocking/permissive logic against the design and CFE operational rules.

After completing these tests, CFE personnel were confident in the system and were very satisfied, because their expectations were exceeded.

These two commissioning stages not only validated and performed acceptance tests for the system, but also provided training for CFE. At the end of commissioning, a two-week training was conducted to reinforce and share the knowledge that CFE personnel had gained during testing and field commissioning.

IX. Conclusions

Taking advantage of the attributes of powerful programmable relays in creating a fully integrated substation protection and control system can have impact upon the cost, quality, and reliability of the project. A compact design using multifunction numerical devices and computerized local HMI control enables the system to be completely factory fabricated and tested prior to arrival on site. Use of remote I/O modules with fiber-optic links considerably reduces the space requirements for cabling.

Properly designed, a fully integrated protection and control system can extend the concept of continuous self test from the multifunction relays to the entire system. Important features of the design are as follows:

- Dual systems to eliminate single points of failure.
- Remote I/O modules with fiber-optic links to reduce wiring, bring many circuits inside continuous monitoring, and eliminate problems associated with induction, interference, and ground potential rise.
- Continuously monitoring the status between dual systems and alarming for incongruence between the status of each system.
- Bringing each yard status point into each system just once, validating that status, and using the validated status points throughout each circuit that requires it to eliminate hidden problems.

Good planning and implementation can lead to the success of a large project such as this.

Development of a preliminary design and then getting buy-in from all parties early in the project can lead to many benefits: the project can proceed on a tight schedule, misunderstandings and redesign are kept to a minimum, and the design can be fine-tuned to meet customer expectations and requirements from the beginning.

Factory testing can lead to significant savings by reducing expensive field commissioning time and cost.

A complex, fully integrated design can be successfully installed and operated if the design documentation package is adequate to completely describe the functionality of the system.

The lessons learned from this project are being used in planning for modernizing other substations. The design concepts and the implementation processes that were developed here can lead to significant savings in the project costs and future operating and maintenance costs for many years to come.

X. BIOGRAPHIES

Michael J. Thompson received his BS, Magna Cum Laude from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. He has broad experience in the field of power system operations and protection. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN) where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories in 2001, he was involved in the development of a number of numerical protective relays. He is a member of the IEEE and has authored and presented several papers on power system protection topics.

Manglio Alejandro López-Aguilar is an Industrial Electrical Engineer educated at Tuxtla Gutiérrez Technological Institute. He worked six years in Protection in Área de Transmisión y Transformación Sureste (ATTSE) and División de Distribución Sureste (DDSE) of CFE. His activities were supervision; preventive and corrective maintenance; design and installation of panels; and commissioning of power substation protection relays and measuring and control systems. He has experience in analysis of electrical faults, short circuits, coordination and research of protection settings, and engine protection. From 1998 to 2000, he worked in INELAP-PQE as a technical support engineer. Since 2000 he has worked for Schweitzer Engineering Laboratories S.A. de C.V. From 2000 to 2002 he worked at the South-East Technical Support Center in Coatzacoalcos, Veracruz. He has given training courses on different protection relays to CFE and private companies. During 2003 he worked as a protection engineer and has given training courses on protection relays and commissioning of power substation protection relays. Since January 2004 he has been working as manufacturing engineer, where he is responsible for control and protection panels testing and integrated systems testing.

David González Barrios received his Bachelor of Science degree in Electronic Systems Engineering from Instituto Tecnólogico y de Estudios Superiores de Monterrey in 1993. After graduation, he worked for Video y Computación Nacional as a SCADA software development and commissioning engineer. In 1998 he joined INELAP-PQE as an integration engineer, responsible for technical support and integration and automation market development. In 2000 he became the Integration and Automation Department Manager at SEL SA de CV to manage, engineer, and commission integration projects for electric utilities and industrial customers. He currently works as automation engineer and has been project leader of many innovative systems.

Joaquín Ayala Aguilera received his Bachelor of Science degree in Electric and Industrial Engineering from the Instituto Tecnologico de Durango in 1974. He started working for CFE in 1975 as zone superintendent for the Southeast Generation System Protection Department. In 1983 he was promoted to Regional Supervisor for the Southeast Transmission Region Protection Department. Since 1984 he has been the Southeast Protection and Metering Regional Manager in the Southeast Transmission Region. He was one of the pioneers in applying microprocessor-based protection relays for the transmission electric system in the Comisión Federal de Electricidad. He has been proactively involved in the design, management, and modernization of several substations in the CFE's Southeast Region.

Nicolás Erasmo Juárez Tobias received his Bachelor of Science degree in Electric and Industrial Engineering from the Instituto Tecnológico de Saltillo in 1982. From 1983 to 1984 he was working as a protection engineer in the Electric Department from the Ingenio Azucarero Tambaca, a sugar cane refinery. In 1985 he joined CFE. From 1986 to 1992 he managed the Protection Office in the Peñitas hydroelectric power plant. Since 1992 he has been managing the Electric Grid Analysis Department in the Southeast Transmission Region. He has been proactively involved on the modernization of several substations in the CFE's Southeast Region.

Gerardo Pérez Díaz received his Bachelor of Science degree in Electric and Industrial Engineering from Instituto Tecnológico de la Laguna in Torreon Coahuila in 1983. Since 1984 he has been working for the Comisión Federal de Electricidad, in the Area de Transmisión Sureste, for the Protection and Metering office. He is in charge of maintenance, operation, and commissioning of protection, control and metering equipment, in the Tabasco state Electrical Substations. He has been proactively involved in the modernization of several substations in the CFE's Subarea de Transmisión Villahermosa. He has been a recurrent lecturer in the Universidad Autonoma de Tabasco. He also works part-time as a technical counselor for private companies that work for the state-owned oil company PEMEX.

Juan Benjamín Villaverde Jiménez received his Bachelor of Science degree in Electric Control (Automation) from Instituto Tecnológico Regional de Ciudad Madero Tamaulipas in February 1980. Since August 1980 he has been working for the Comisión Federal de Electricidad in the Protection Department. He has been proactively involved in several projects, including Chicoasen hydro-electric power plant commissioning in 1981, SICTRE in 1982 (real-time SCADA system), and commissioning of 115 kV power lines for the electric substation La Angostura. In 1984 he was promoted to supervisor for the protection and metering department in the Subarea Transmisión y Transformación Villahermosa. Presently he's in manages the Protection and Metering Department in Villahermosa Tabasco.

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