Integration of Standard IEDs in TEPCO's 66 kV Protection Scheme Philosophy

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Integration of Standard IEDs in TEPCO's 66 kV Protection Scheme Philosophy

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***Abstract*—The Tokyo Electric Power Company (TEPCO) considered departing from their traditional operating practices in 2005 when they began to develop a pilot project to reduce costs in the electric utility's protective relaying schemes by changing existing, customized hardware to world-standard intelligent electronic devices (IEDs). For the pilot project, which includes stepped distance protective relays to protect transmission lines in a high-impedance-grounded 66 kV network, TEPCO developed a detailed comparison of company standards and specifications against IED functions and specifications. They then identified IEDs with flexible logic to satisfy company requirements for relay element performance, relay logic, and panel integration. TEPCO integrated the IEDs into a panel and conducted functional and performance tests.**

The pilot scheme has been in service for two years, during which time the scheme has operated correctly for internal faults, including one that resulted in an islanded network. The installation has also operated securely for more than 60 external faults and transient faults that the adjacent Petersen coil-grounded networks deionized.

I. Introduction

The Tokyo Electric Power Company (TEPCO) is one of ten electric utilities in Japan. Their service area includes Tokyo, the Japanese political and economic center. TEPCO has 27 million customers, with the peak demand recorded in 2001 at 64.3 GW. The generation capacity is 75.3 GW, and 40 percent of energy is supplied by nuclear power. Fig. 1 shows the service areas of TEPCO and other Japanese electric utilities.

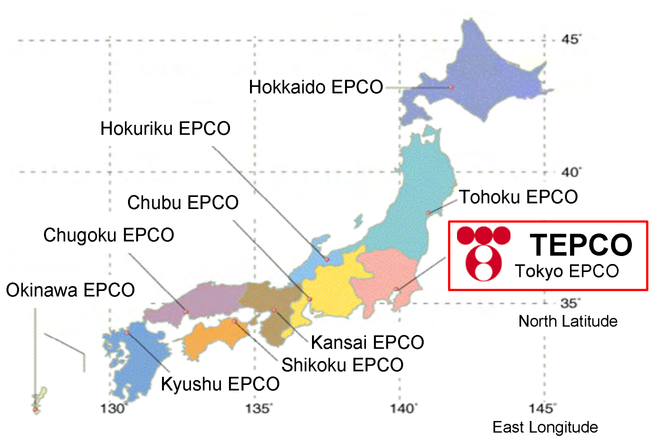


Fig. 1. Service areas of TEPCO and other Japanese electric utilities

TEPCO is in charge of the generation, transmission, distribution, and retail of electric power in the Kanto area, including Tokyo. TEPCO transmission and distribution networks can be summarized as follows:

- A 500 kV meshed backbone to which major power plants are connected around the load center.
- Transmission and subtransmission networks at 275 kV, 154 kV, and 66 kV, connected and receiving power from the 500 kV backbone. The design of these networks is a meshed configuration, but they are operated as radial systems to limit fault currents and enable simpler power system operations.
- Automated self-healing schemes. System integration protection schemes and reliable unit protection from microprocessor-based current differential relays have been operating on a dedicated, company-owned communications network for more than 20 years.
- A distribution automation system that has been applied to most of the distribution networks.

During the last few years, TEPCO has achieved world-class network safety and reliability indicators. The TEPCO calculated System Average Interruption Duration Index (SAIDI) is less than 5 minutes. This is a reliability indicator of the number of minutes an average customer would be without electricity. The SAIDI index is defined as:

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}} \tag{1}$$

Typical numbers observed in North American utilities are in the order of several tens of minutes.

The TEPCO System Average Interruption Frequency Index (SAIFI) is about 0.1 for the whole service area. This index is an indicator of the number of interruptions that a customer would expect in a year. The SAIFI index is defined as:

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} \tag{2}$$

Typical SAIFI indexes observed for North American utilities are greater than 1.

The TEPCO performance indexes are due to the hard work and dedication of their employees and to conservative engineering practices and processes based on many years of experience in power system operation. An important component of power system operation and the high reliability of the services provided is the protective relaying system and the engineering philosophies behind it. The purpose of the pilot project described in this paper is to maintain the high reliability and successful engineering practices using standard, high-reliability protective devices.

The power system protection and control schemes at TEPCO have the following features and characteristics:

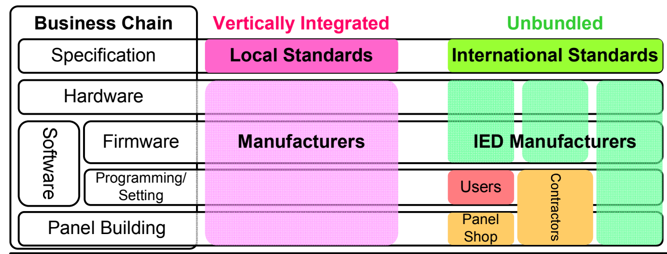
- The detailed specifications have been developed between TEPCO and Japanese manufacturers. The specifications are combined to achieve specific functional requirements. This means that the final solutions solve TEPCO requirements but are different from standard solutions used by utilities worldwide.
- Since the 1980s, more than 95 percent of solid-state and/or electromechanical relays have been replaced with microprocessor-based relays.
- Due to the TEPCO microwave and fiber-optic network, current differential protection is widely applied. Some unique relaying schemes are used (e.g., selective-pole tripping is used in the 275 kV and 500 kV bulk power systems).
- The customized design and rapid evolution of microprocessor technology have created problems for TEPCO in terms of spare parts and training of the work force.

In 1989, TEPCO introduced a new digital protection and control system using the IEEE 802.4 token ring technology as the protocol for the substation LAN (local-area network) [1]. The protection and control equipment was placed close to the primary equipment, reducing wiring, EMC (electromagnetic compatibility) requirements, and cost. For dedicated bus protection, TEPCO designed a process bus based on an optical LAN. This design was applied to a few of their new transmission substations. Unfortunately, obsolescence in some of the electronic components caused maintenance headaches and challenges. To redesign a similar project with newer components would require starting a new project with the vendors and internal processes within TEPCO.

On the other hand, in the worldwide market, IED (intelligent electronic device) diffusion, evolution of computer-aided design tools, and standards like IEC 61850 (substation automation) and IEEE 37.118 (wide-area measurement and synchrophasor technology) have provided more opportunities for utility innovation in engineering protection and control schemes. Manufacturers are able to cope in a more flexible way with component obsolescence, offering alternate or equivalent IEDs manufactured with newer components. The utility engineer does not even notice the transition.

Based on the above discussion, TEPCO decided to perform some studies on subjects related to protection and control systems. These studies focused on the present practice in TEPCO and other practices found in utilities worldwide. The research included peer-reviewed papers, as well as reviews of literature from other utilities and product manufacturers. Moreover, TEPCO engineers started participating in IEEE and CIGRE working groups to share and learn from the experiences of other utilities. Several visits to pioneering utilities throughout the world were also conducted to compare practices, share experiences, and learn of problems in order to improve TEPCO protection and control projects.

This research approach, the engineering activities, and official information exchanges with other utilities allowed TEPCO to perform a benchmark study comparing their practices to others. Fig. 2 illustrates their comparison of two business models in the protection and control industry. TEPCO practices a vertically integrated model.



Roles	Major Roles by Manufacturers, Less Burden on Utilities	Various Ways, Utility Can Have More Choices
Costs	Expensive, Propietary	Inexpensive, Competitive
Features	Closed, Dependable	Open, Modular, More Choice, Self-Responsible

Fig. 2. Comparison of protection and control business practices

In a vertically integrated practice, specifications are developed in compliance with local industry and company standards. The hardware design, manufacturing, software programming, logic setting, firmware management, and panel building are comprehensively done by manufacturers. For TEPCO, this enabled highly reliable protection and control systems, resulting in a world-class network and safety and reliability indexes. However, the high dependency on local manufacturers and proprietary technologies is a reason for high premiums in the cost of their protection and control system.

On the other hand, most of the foreign utilities visited follow the "unbundled" business model, as shown in Fig. 2. These visits revealed approaches and activities for protection and control different from that of TEPCO. For example, some utilities perform their own relay logic programming. Some design their own panels and outsource the panel building to reliable panel shops. Some utilities elect to ask manufacturers for turnkey projects. These visits also indicated that approaches were based on utility policies.

The information illustrated in Fig. 2 is the basis for the TEPCO desire to investigate additional options in protection and control projects.

TEPCO is considering a departure from their traditional protection and control practices so as to contribute to the company management goal of pursuing cost reduction while keeping world-class system reliability.

Changing the company business practice to the unbundled model may be a solution for the reduction of life-cycle costs. It is possible to procure less-expensive, off-the-shelf products from bigger markets. Relaying system integration and panel building can be outsourced to a qualified integrator instead of the original equipment manufacturers.

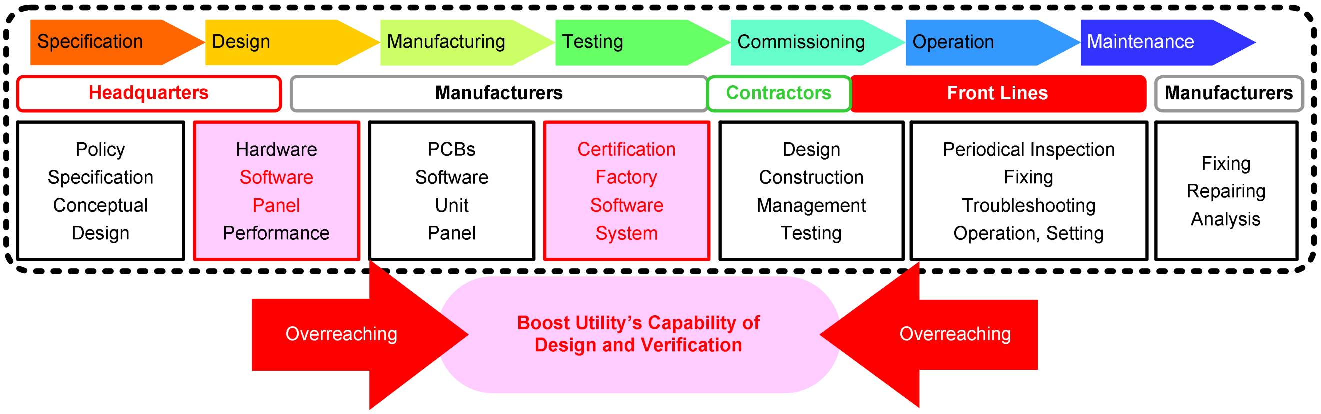


Fig. 3. Modified business model

Fig. 3 illustrates the TEPCO understanding of the changes required in the company and the location of the activity. It describes the details of the protection-related business chain composed of specification development, design, manufacturing, testing, commissioning, and O&M (operations and maintenance) and how to move the TEPCO protection and control business roles toward the company goals. The software integration, panel building, and detailed tests that have previously been conducted by a single manufacturer will be done by TEPCO. Because of the present structure in the utility, this requires boosting their engineering and facility capabilities. TEPCO expects to confirm the cost reduction of using worldwide standard products and technologies during this pilot project.

TEPCO is carefully approaching the change related to protection and control project development. The goal is to migrate from the vertically integrated model toward the unbundled model, using off-the-shelf, flexible devices that can accommodate the protection requirements and, at the same time, keep the reliability indexes as high as they are presently.

II. Examples of Protection and Control Innovations

Several documented projects served as examples of protection and control innovations. Written from the utility perspective, they contained lessons to be learned by TEPCO.

A modular protection, automation, and control (MPAC) concept was introduced by PG&E (Pacific Gas and Electric Company) [2]. This concept involves replacing device panels instead of individual numerical devices for 230 kV and lower-voltage networks. As part of the decision-making process, PG&E considered the benefit of cost reduction when upgrading aging control rooms.

To gain additional benefits, PG&E decided to deploy an integrated system using enterprise IT (information technology) architecture rather than replacing only the protective relays. The key concept emphasizes replacement of the entire control building and the development of a long-term plan with multiyear funding and standardization.

For the vision to come true, the MPAC core team was formed. This team included a cross section of expertise within the company and interfaced with various impacted departments. PG&E formed alliances with some protective relay and automation equipment suppliers. A "proof of concept" lab facility was established at the engineering headquarters to refine the objectives, develop the details for the architecture, troubleshoot the concepts, evaluate overall performance, and identify requirements and challenges.

The lessons learned from this experience that are beneficial to the TEPCO plan can be summarized as follows:

- Strong utility engineering leadership that sets a vision determined from company-wide viewpoints and long-term plans is essential for the success of the project and the expected improvements.
- Pursuing core-team cooperation with the line departments and lab facilities is important to obtaining cost reduction and, at the same time, securing safety and reliability. This activity also enhances in-house engineering and related skills.
- Replacing a whole control building may bring more benefits than replacing equipment on a per-panel basis. (TEPCO has had similar experiences with this approach. They involved the replacement of protection and control schemes for 154/6.6 kV and 66/6.6 kV distribution substations and new transmission substation projects.)

TEPCO compared benchmark studies and made technical visits to pioneering companies. Some of the projects that were observed to conduct similar approaches included the following: the Tennessee Valley Authority Bradley projects of multivendor IEC 61850 implementation [3], the American Electric Power standardized protection and control solutions [4], and the Southern California Edison centralized remedial action scheme (RAS) project [5].

III. TEPCO IED Pilot Project

In 2005, TEPCO proposed to launch an IED pilot project to find solutions to reduce the costs of their protection and control projects. They decided that it would benefit the company to investigate the performance of flexible devices in the marketplace. The project proposal included the following goals:

- Determine whether an overall cost reduction can be achieved with in-house engineering and off-the-shelf IEDs.
- Achieve protection and control requirements and standards with native or programmable logic in the IEDs.
- Obtain a comparison to the first generation IEDs in their system on a panel functionality basis.
- Maintain their world-class reliability indexes.

The next sections describe some interesting and unique aspects of the pilot project.

A. Customers-as-Innovators Approach

Reference [6] introduces the customers-as-innovators approach to developing customized products. Fig. 4 describes the changing supplier and customer roles. This idea proposes that the customer can reduce product development costs and avoid the traditionally lengthy interaction with the supplier. Well-designed, customer-friendly tool kits have allowed customers to develop products based on their needs and requirements. Although the participation of the customer in the design, prototype, and testing of the protection scheme may not be new to engineers in other utilities, this approach is new for TEPCO and one that the company may follow.

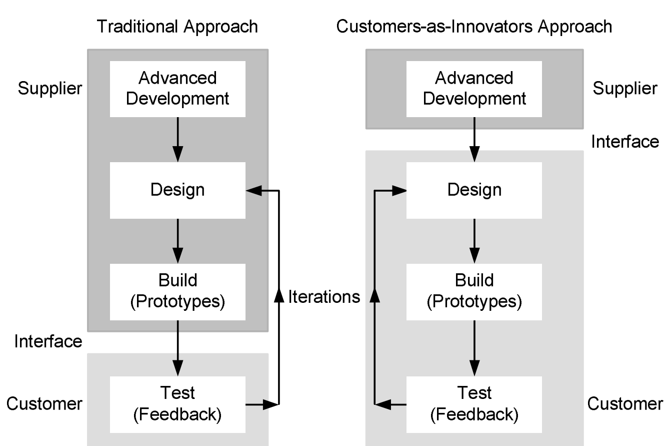


Fig. 4. Traditional approach and customers-as-innovators approach [6]

This idea can be applied for designing and integrating protection and control systems as well, because powerful tools for programming protection and control functionality in the IEDs are available. This is expected to bring innovation and cost reduction to TEPCO.

B. Compliance of Off-the-Shelf IEDs With TEPCO Standards

To design and integrate protection and control systems in compliance with TEPCO standards, TEPCO engineers needed to understand and clarify the specifications of the off-the-shelf products. TEPCO philosophies are responsible in large part for the high level of performance that their reliability indexes demonstrate. These operating and design philosophies must be maintained for that purpose, with training of the operations personnel kept to a minimum. It is easier to train personnel on a new device if it behaves similarly to the old device.

First, TEPCO compared the required protection and control functions and performances in their standards to the specifications described in the instruction manuals of the off-the-shelf products. Fig. 5 describes the concept. Common functions and performances are confirmed by conducting certification tests and checking the related documentation.

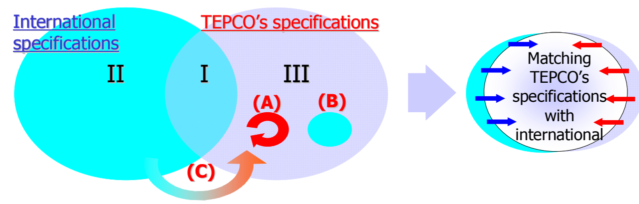


Fig. 5. Concept of comparing IED specifications with TEPCO requirements and matching international standards

The pilot project included the following important steps during the planning and execution phases:

- TEPCO studied the impact to their unique functions and high performance should they decide to use the programming capabilities of off-the-shelf products. This activity is shown as (A) in Fig. 5. The programmability of these IEDs is an important functionality for achieving project compliance with TEPCO requirements.
- As needed, TEPCO reviewed the necessity of the unique specifications, which is shown as (B). There may be functions or requirements to which these devices do not comply. TEPCO evaluated the options when this happened and found a solution with additional hardware or programmable logic.
- The functions and performances of off-the-shelf products that were not covered by TEPCO standards and that exceeded their standards were accepted as new functions or alternatives, shown as (C). The new features in modern IEDs can be considered for new functionalities. For example, new IEDs are capable of synchronized phasor measurement by default, which may be used for wide-area monitoring in the future.

These comparison studies helped TEPCO to accept the pilot project because the studies showed that TEPCO would still be able to match their specifications to internationally accepted standards and maintain their best practices using worldwide suppliers. These studies were also good opportunities to refresh accumulated knowledge concerning protection and control technology. They also showed that it is possible to develop well-balanced protection and control requirements by identifying key quality and cost factors.

C. Protective Relaying System for Subtransmission Line

TEPCO decided that the first step of the pilot project would be the integration and trial application of a stepped distance protection scheme for a 66 kV subtransmission line in the field. Choosing this network meant less risk of unwanted interruptions and less disruption to the operation of the power network should the pilot scheme misoperate.

The TEPCO subtransmission network, which includes operating voltages at 154 kV and 66 kV, is illustrated in Fig. 6 and summarized as follows:

- The subtransmission system is operated in a radial configuration. There are connecting paths to make the network meshed, but for simplicity and operational considerations, the subtransmission network is operated in a radial configuration.
- Most lines are composed of double circuits running parallel on single transmission towers. The origin and destination for both circuits are the same. In some distribution substations that step down to 66 kV or 22 kV and high-voltage (HV) customers, the loads are tapped with no intended looping.
- The networks are high-resistance grounded, where the phase-to-ground fault current ranges from several hundred to a few thousand amperes. Ground fault relaying is therefore different from solidly grounded networks, traditional in other parts of the world.

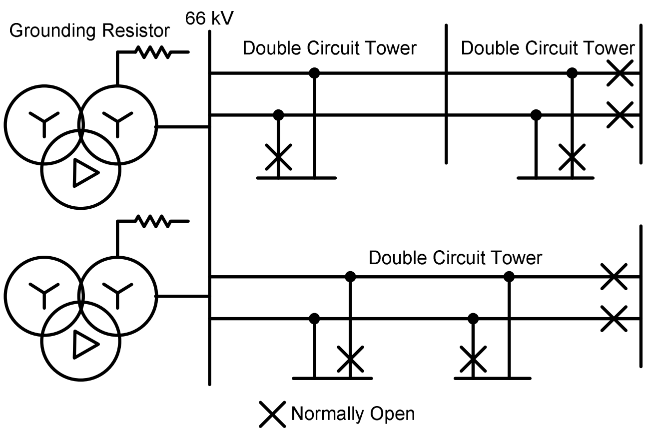


Fig. 6. Typical configurations of TEPCO subtransmission networks

D. Hardware

It was important to understand the behavior of the off-the-shelf IEDs and how their protection functions could be adapted to the TEPCO network. For example, most of the reviewed IEDs are designed for solidly grounded networks; the TEPCO system at 66 kV is high-resistance grounded. Ground fault detection, therefore, should be adapted.

Protective relays that allow users to design and program their own protection logic and customized relaying units are available in the market. This powerful programmability allowed the design of a subtransmission protection panel that meets TEPCO philosophies and redundancy standards. Fig. 7 shows the panel already installed in the pilot project site. The programmable inputs and outputs of the devices, the programmable logic, and the communications facilities provided the functionality required, similar to the custom-designed projects that TEPCO uses in their substations.

Fig. 7. Pilot project panel

The panel is composed of multifunctional distance and multifunctional directional overcurrent relays. The combination of these two devices meets supervision and redundancy requirements. The TEPCO philosophy is to supervise the operation of the main protection scheme (distance relay) with fault detectors programmed in a different hardware structure (overcurrent relay).

Some highlights of the installation are described in the next sections.

E. Main and Fail-Safe Design Philosophy

According to the TEPCO protection design standard, two individual relaying units are used for two-out-of-two voting for security in case of a single hardware malfunction. In Japan, this is called a main and fail-safe design philosophy.

Fig. 8 shows an example of this design philosophy when applied to subtransmission line protection. In this example, phase faults are protected by stepped phase distance (21P) elements, and single-line-to-ground faults are protected by a wattmetric element (67G) or zero-sequence overvoltage element (64B). These protective elements are regarded as main protection, programmed inside IED-1. On the other hand, inside IED-2, overcurrent (50P) and current deviation (50D) elements are programmed as supervision for faults to improve protection security. This is called fail-safe or fault detection (FD). Another zero-sequence overvoltage element (64) is also programmed for the same purpose for single-line-to-ground faults. Output contacts from IED-1 and IED-2 are connected in series for two-out-of-two voting.

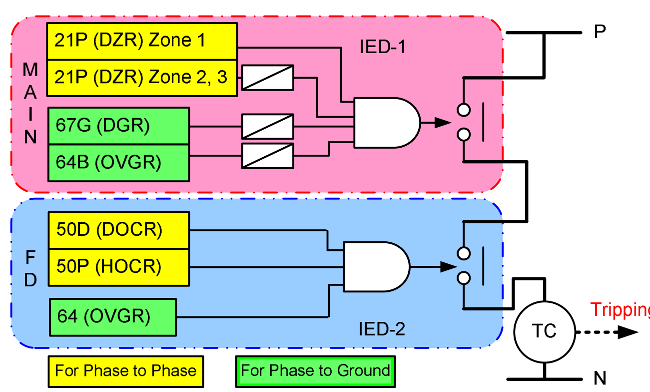


Fig. 8. Main and fail-safe design philosophy

F. Design of a Current Deviation Fault Detector

The TEPCO philosophy is to supervise tripping with a disturbance detector (current deviation unit). This unit is essentially a verification that a sudden change (fault) has happened in the power system. The phase currents are monitored, looking for the current change ΔI.

The current deviation element (50D) was created by using the programmable logic capabilities of the IED. This type of relaying element is not generally available but can be readily programmed in IEDs capable of accessing the current measurements. The programming of this element also allowed TEPCO engineers to creatively take advantage of the IED capabilities. The IED exposes a 10-cycle average of the measured current. The disturbance detector can be implemented by comparing this average to the instantaneous measurement, as shown in Fig. 9. In programmable logic, this relaying element is a threshold comparison to the measured change ΔI:

$$\begin{aligned}\Delta I &= \left(I_{10\text{-cycle average}}\right) - \left(I_{\text{Instantaneous}}\right) \\ 50D &= \left(\Delta I \geq 50D_{\text{setting}}\right)\end{aligned} \tag{3}$$

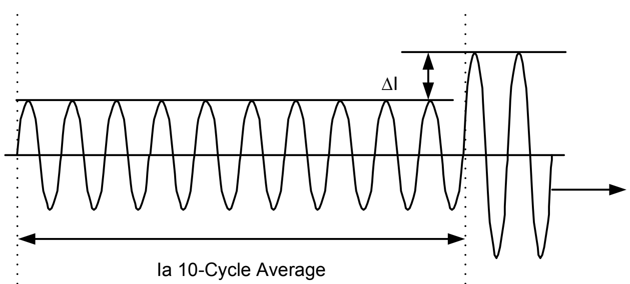


Fig. 9. Stepped distance protection for a phase-to-phase fault

Several simulations and fault analyses indicated that this is a reliable disturbance detector.

G. Stepped Distance Protection and Coordination

As a standard, TEPCO requires stepped phase distance protection for subtransmission lines, which are operated in a radial manner. The fact that the lines are radial simplifies the coordination of distance zones. Distance elements provide a definite reach. This reach does not depend on the value of the source impedance in the system.

Fig. 10 illustrates the required distance element characteristics at TEPCO. These nonstandard characteristics can be implemented by combining mho and reactance distance elements found in line distance IEDs. Zone 1 and Zone 2 are realized by the combination of the reactance and mho elements. Zone 3 only uses the mho element. Fig. 10 shows the zones covered by the stepped distance protection, the relaying logic, and the relaying characteristics.

The particular IED used in the pilot project does not have a reactance phase distance element. However, the programmable logic in the IED allows for the implementation of a custom reactance line programmed by TEPCO engineers. The mho elements, however, are part of the IED.

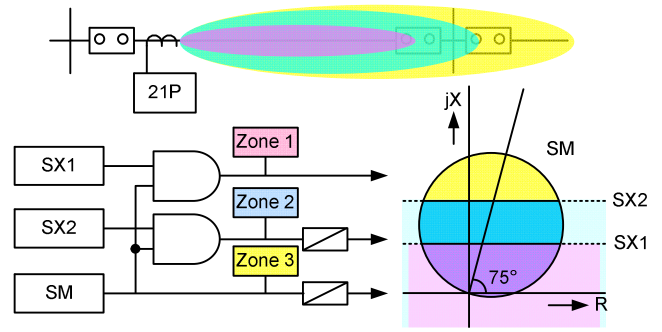


Fig. 10. Stepped distance protection for a phase-to-phase fault

TEPCO engineers validated the phase distance behavior and programming. A team conducted several static tests and performance validation. Historical events captured and recorded were played back using test equipment. All of the coordination concerns were clarified.

For example, Fig. 11 illustrates a typical coordination concern that may result in a security problem if not identified when a fault occurs outside the protected zone and is cleared successfully. If the line is long and carries heavy load flow, the apparent impedance seen by the distance relay at Terminal A is measured around F1. This load-impedance point on the plane is outside Zone 1 but inside the reactance element of SX1. If a phase-to-phase fault occurs in the next section from Relay A, the apparent impedance can jump to F2. This is also outside Zone 1 but inside the mho element SM. After the fault is cleared, the apparent impedance jumps back to the original load-impedance point F1.

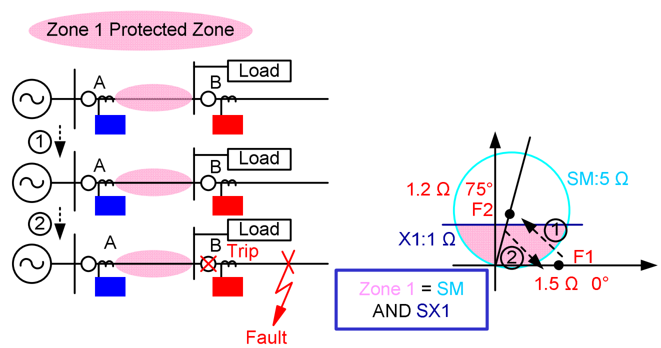


Fig. 11. Coordination concerns in the case of outside fault and clearing

During the series of system changes, the line protection at Terminal A must not initiate tripping. However, if the coordination of pickup and reset between impedance and mho elements is not appropriate, unwanted tripping may happen. Besides some coordination timing for heavily loaded lines, line protection IEDs have internal checks and load-encroachment functions that are useful for preventing these occurrences.

A team of engineers dynamically tested the IED. The dynamic testing of the relay is a very important activity that finds security and/or dependability issues and their solutions. The testing team performed EMTP (Electromagnetic Transients Program) simulations, testing currents and voltages derived from circuit models representing different states of the power system, depending on the breaker positions.

Dynamic testing with no feedback from the power system to the relay (open-loop testing) may be enough to validate the operation of the scheme. Closed-loop testing, where the relay voltages and currents represent the actual power system behavior during switching conditions, can provide additional information. The cost and the benefit of each test approach should be evaluated.

H. Wattmetric Ground Directional Element

The TEPCO 66 kV network is a resistance grounded system. The fault currents are within a range and controlled by sizing the substation transformer neutral resistor properly. On the zero-sequence network, this has the effect of shifting the relationship of V0 and I0 for ground faults.

IEDs designed for solidly grounded networks expect that the I0 and V0 relationship is inductive. Fault angles in the range of 90 and 270 degrees are expected, and the ground directional and ground distance relays are designed under these assumptions. The effect of using a large resistor in the power transformer neutral shifts the angle relationship between I0 and V0. Therefore, off-the-shelf IEDs have a hard time detecting ground faults in the TEPCO 66 kV network.

TEPCO engineers programmed flexible logic that allows the comparison of measured angles, making it possible to implement a wattmetric directional element. The wattmetric directional element assumes fault angles in the vicinity of 0 and 180 degrees. The possibility of comparing two measured angles, I0 and V0, proved to be extremely useful in the design of a complete protection scheme. Ground faults are detected by this programmable wattmetric element with a time delay.

Although TEPCO operates the 66 kV system as radial lines, in high-resistance-grounded networks, the unfaulted feeders contribute capacitive current to the fault. Therefore, a simple current check is not appropriate. The wattmetric implementation in the pilot project has proven to be effective and similar to the present TEPCO standards.

I. Trip Circuit Continuity Monitoring and Automatic Testing for Auxiliary Contacts

Continuous monitoring of the trip circuit continuity and automatic testing of the auxiliary contacts are required by TEPCO standards. These functions are obtained by using the IED optoisolated inputs and output contacts, as illustrated in Fig. 12. The main output contact comes from the main protection IED, and the FD contact comes from the FD protection IED. The logical NOT implemented in the 11X output contact will disable the trip circuit during automatic testing, which is programmed in the FD IED.

For monitoring purposes, optoisolated inputs are connected in parallel with the relay output contacts, as shown in Fig. 12. The logic diagram to detect trip circuit failures is programmed using the IED programmable logic capability.

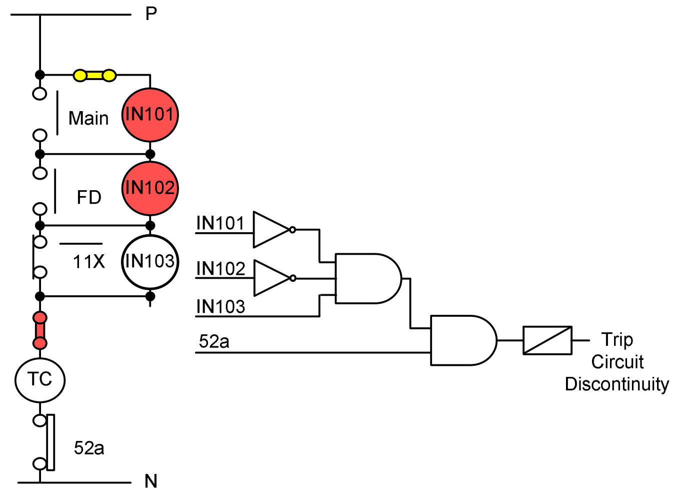


Fig. 12. Relaying logic for trip circuit continuity monitoring

When both main and FD output contacts are off under normal conditions of an in-service circuit breaker, and there are no relay operations, a small current flows through inputs IN101, IN102, and 11X. This results in IN101 and IN102 set to logical 1 and IN103 to logical 0. This condition does not assert trip circuit failure.

In the case of a break in the trip circuit at any point between the trip coil and the IEDs, all inputs drop out, which results in asserting trip coil circuit failure after a timer. This logic can also be used to identify misoperation of either the main or the FD IED. For example, if the main IED operates, IN101 and IN103 do not pick up, and IN102 does pick up. This results in asserting a trip circuit failure and denotes a misoperation in this case.

TEPCO also requires the automatic testing of output contacts. This function can be programmed using the same inputs in parallel to the trip contacts, as shown in Fig. 12. The closing of a trip contact is sensed by the parallel binary input. The sequential operation of this automatic testing must be designed to avoid unwanted tripping. The normally closed 11X contact is set to logical 1 (open) to disable the trip circuit. While 11X is open, the operations of the main IED contact and FD IED contact are checked by operating the associated contacts sequentially.

Per TEPCO standards, the procedure of automatic testing of auxiliary contacts has to be interrupted, resuming normal operation after no more than 200 milliseconds. Tripping is effectively disabled while testing the contacts.

J. Phase Selection Issues

The TEPCO 66 kV network is grounded through a resistor (for example, a 333-ohm resistor) located at the power transformer neutral. In this example, this resistance effectively represents a 1,000-ohm, zero-sequence grounding impedance, which contrasts with the traditional solidly grounded practice for transmission and subtransmission lines. The protective relaying logic is designed under the assumption that high-performance protective relaying systems are designed for solidly grounded networks. It is therefore to be expected that some internal IED logic would not be compatible with TEPCO requirements, and this logic should be modified, adapted, or disabled via programmable logic or relay settings.

TEPCO uncovered one of these logic issues when simulating faults with a network simulation program. The simulated network is shown in Fig. 13. For a solidly grounded network, line protection IEDs are often applied in single-pole trip (SPT) schemes. Phase selection algorithms are required to properly select the faulted phase and open the proper pole. This particular IED selected the faulted phase by comparing the phase angles, I2 and I0. For example, if A-phase negative-sequence current IA2 were in phase with I0, A-phase would be selected. There is more than this simple logic in the IED phase selection logic, because a BCG fault would have a similar signature for I2A and I2.

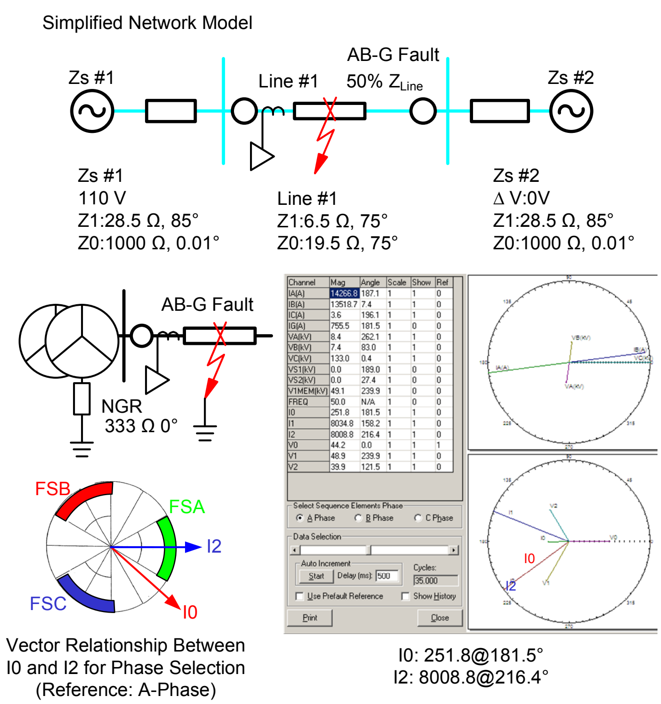


Fig. 13. Simulated fault and phase selection problem

Because TEPCO is not implementing SPT at this voltage level and not using the ground fault algorithm programmed in the IED (leaving the default ground fault detection disabled in the IED), it was necessary to disable the phase selection logic. The phase selection logic in the IED can be disabled by increasing the minimum ground current required to allow the algorithm to operate. This is illustrated in Fig. 14.

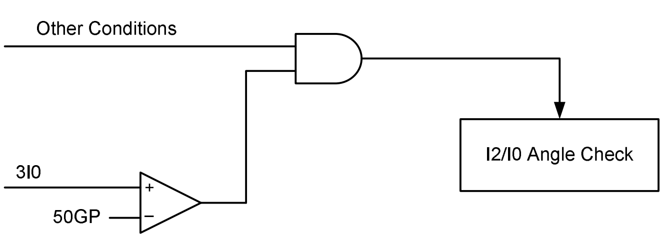


Fig. 14. Phase selection enable logic

The internal logic in the IED is such that phase distance elements do not need a phase selection signal to operate. By raising the 50GP setting, the phase selection logic is basically disabled.

This section has illustrated how TEPCO creatively used internal IED logic programming to meet the protection requirements of the company. It is only with careful study of the IED and appropriate support from the manufacturer that these issues can be overcome.

IV. Field Test Results

A. Commissioning

TEPCO engineers integrated and tested the distance relay protection for a 66 kV subtransmission line. The relay was then installed in a TEPCO substation in February 2007.

As illustrated in Fig. 15, the pilot relaying scheme is connected to a real line. Actual voltage and current signals are introduced to the relaying system and are connected to the relaying system. Instead of connecting the trip circuits to the line breaker, these are connected to the trip circuits of a nonoperational test breaker. This very conservative approach will be used until TEPCO is fully confident of the prototype performance.

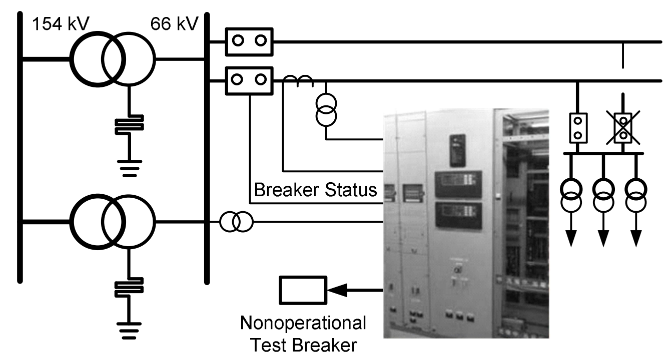


Fig. 15. Field test installation of 66 kV subtransmission line protection

B. Example Cases for Faults Caused by Lightning

The substation where the tested relaying scheme is installed was selected from a few locations in an area that experiences frequent lightning strikes. Since the system was commissioned, five protective relaying operations have been required. All faults were caused by lightning strikes. These five operations were promptly analyzed and demonstrated successful performance. The analysis of the events is important for TEPCO to verify the scheme and gain knowledge on the behavior of the new technology. Two cases from these five are described here.

1) *Case I*

Fig. 16 shows the corresponding oscillographic record of phase voltages, line currents, zero-sequence current, zero-sequence voltage, and relay operation for a single-phase-to-ground fault evolving to a double-phase-to-ground fault. The protection scheme operated correctly for the fault sequence. The sequence of operation was the following:

- The ground directional element picked up the A-phase-to-ground fault. The event was a simultaneous fault in the 66 kV and 154 kV networks.
- Approximately four cycles later, the fault cleared, indicating the effect of the Petersen coil scheme. The ground directional element reset.
- Nine cycles after the first fault, a C-to-A-phase-to-ground fault occurred.
- The CA element for Zone 1 picked up the fault and issued the trip.

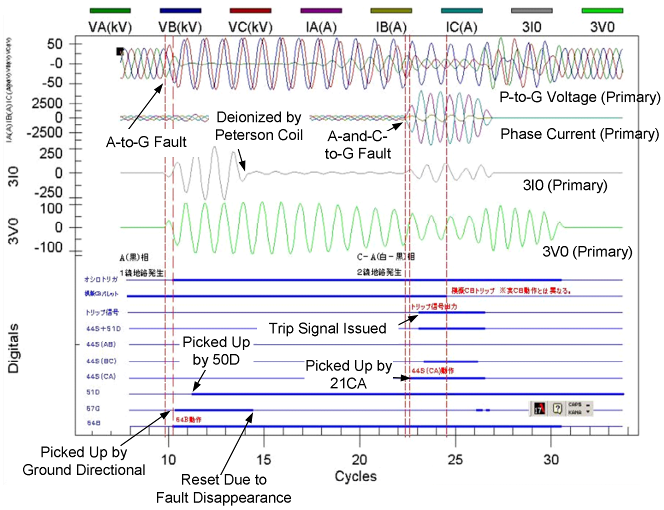


Fig. 16. Single-phase-to-ground fault following double-phase-to-ground fault

2) *Case II*

The second example was caused by a complicated cross-country fault. The substation where the pilot relay scheme is installed is supplied from a 154 kV double-circuit transmission line.

Fig. 17 shows the network configuration. The 66 kV lines, including the one protected by the pilot relaying scheme, and the two 154 kV lines share a common tower structure for a significant length, illustrated in Fig. 17.

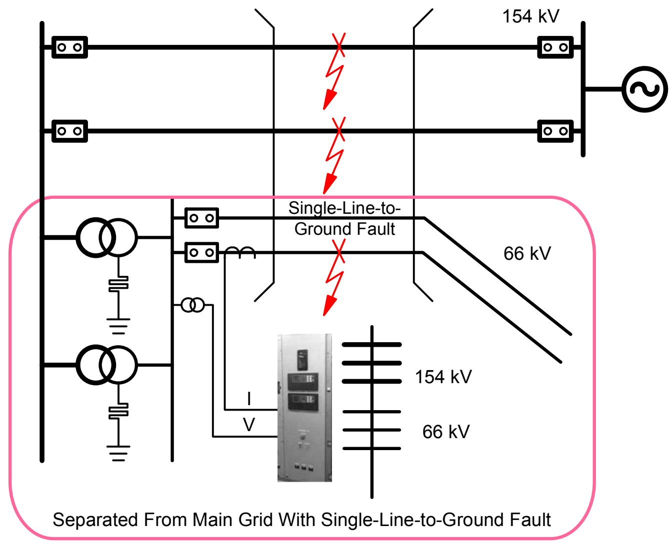


Fig. 17. Configuration of the network including the substation where the tested relay is installed

A lightning strike caused simultaneous faults on both the 154 kV circuits and the 66 kV line protected by the pilot relaying scheme. On the protected 66 kV line, the resulting fault was a single-line-to-ground fault. The operation sequence included the following steps:

- The ground directional element of the tested relay picked up for the single-phase-to-ground fault on the 66 kV line.
- The 66 kV network lost the source from the 154 kV network approximately 15 cycles after the fault. The two 154 kV lines tripped because of internal faults. Effectively, the 66 kV network was separated from the main grid.
- The 66 kV network included small amounts of power from hydroelectric power stations. That is the reason the 66 kV network could support a single-line-to-ground fault.
- The fault was cleared by the protective relaying scheme after the programmed 600-millisecond delay.

Even with the very fast frequency decay experienced, the ground directional and zero-sequence overvoltage elements operated properly to trip the nonoperational test breaker successfully. The frequency tracking algorithms in the protective relays allow large frequency deviations and proper protective relaying response. Fig. 18 illustrates the oscillographic event captured for the fault sequence described.

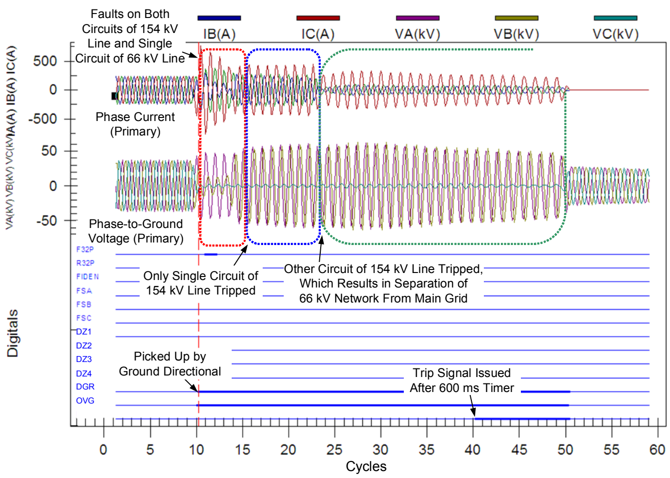


Fig. 18. Single-phase-to-ground fault with frequency decay because of system separation from main grid

The security performance of the pilot scheme has also been confirmed. A recorded number of 20 external faults of different types yielded no unwanted operations. These faults were detected in the 66 kV network and in the adjacent 154 kV network, which is Petersen coil grounded. Some 66 kV faults were transient and cleared by the Petersen coil mechanism.

C. Cost Reductions

Although it is too early to discuss details of cost reduction for TEPCO protection and control schemes based on the pilot project, a rough comparison with the present custom-developed relaying system is possible.

1) Savings

During the implementation of this pilot project, TEPCO has identified the following savings that can benefit the company:

- *Material costs, such as IEDs, wires, and terminals.* The selection of IEDs accepted widely in the worldwide market and the competition between manufacturers provide utilities with more economical IED choices. Compared to TEPCO custom-designed schemes, much less wiring will be required between IEDs. This is due to the compact design of the IEDs that include all the necessary components in one box.
- *Less iteration with suppliers*. TEPCO engineers were able to choose IEDs manufactured by suppliers who provided instruction manuals covering all the information required for the selection and well-designed computer-aided design (CAD) tools, thus reducing design iterations with suppliers compared to the custom-developed numerical relays. Formerly, TEPCO had to ask suppliers to implement any changes of relaying logic and allocations of input/output interfaces because programmable logic and design tool kits were only available for designers, developers, and manufacturers—not the utility engineers.
- *Open and competitive environment*. TEPCO expects to take advantage of the competiveness of the world market for IEDs.

2) Expenses

The pilot project allowed TEPCO to gain experience and information about the following expenses:

- *In-house labor.* TEPCO is planning on new costs for programming, configuration, and testing. The panel integrator will assume the product and firmware management, support for field engineers, and interact with the IED manufacturers.
- *Training and education*. Because this is new technology for TEPCO, there will be expenses for in-house engineers and technicians.
- *Testing and lab facilities*. TEPCO acknowledges expenses for testing and lab facilities as well as test outsourcing.

V. Conclusions and Future Plans

The pilot project conducted by TEPCO aims at reducing costs. The technical and motivational issues to pursue the project were described.

TEPCO has researched several options to implement this pilot project, as well as studied projects performed by other leading utilities. A search for standard IEDs was also conducted to find IEDs that would properly satisfy TEPCO requirements. Once the IEDs were selected, protection logic and some of the missing relaying algorithms were programmed into the IEDs, implementing TEPCO philosophies. TEPCO engineers tested and verified the programming.

IED diffusion, evolution of CAD tools, and standardizations such as IEC 61850 and synchrophasor technology are allowing the electricity industry to provide more innovative opportunities in the protection and control engineering field. The TEPCO panel-based replacement approach, following the customer-as-innovator approach, is a good start. Moreover, having TEPCO design protection and control schemes based on the company philosophies and practices will allow them to maintain their world-class performance indexes.

Through this pilot project, TEPCO found that the cost structure of protective relaying systems could be improved. This knowledge will be beneficial to achieve future cost-reduction goals.

Based on the experience gained during this pilot project, the TEPCO project team is now trying to integrate a current differential protection system for a 154 kV transmission line with off-the-shelf IEDs and communications devices. Because IEDs from different manufacturers will be combined, IEC 61850 GOOSE messages will be used for data exchanges. The field testing began in the spring of 2009.

So far, TEPCO is analyzing panel-based replacement as the first option. However, entire substation control house replacement, including the protection and control systems, will be further studied as a second option.

TEPCO also wants the enhancement of in-house engineering knowledge to bridge any engineering gaps between protection and control and IT. This will allow TEPCO to introduce an open and competitive environment, creating benefits to the company in many different ways.

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VII. Biographies

Shinichi Imai joined Tokyo Electric Power Company, Inc. (TEPCO) after he earned his Master's degree from the Osaka University in 1989. After 14 years of experience with power system operation and protection, he is currently the group manager of worldwide benchmarking and manager of the IED pilot project for the TEPCO power network division. His special fields of interest include power system protection, power system stability, and special protection systems. He has been actively involved in IEEE PSRC, PSDP, and CIGRE working groups. He is a member of IEEE and IEEJ (Institute of Electrical Engineers of Japan). He is a registered professional engineer in the state of California.

Tomoo Ohmori joined Tokyo Electric Power Company, Inc. (TEPCO) in 1997 after completing graduate school. He has experience in the maintenance and operation of substations for six years and of a nuclear plant for three years. Tomoo is a team member of the TEPCO IED pilot project and responsible for system design, integration, setting, testing, and training.

Hiroaki Kitajima joined Tokyo Electric Power Company, Inc. (TEPCO) in 2001 after he earned his Master's degree from the University of Tokyo. After six years of experience in substation operation and maintenance, he is a team member of the TEPCO IED pilot project and responsible for system design, communications integration, and IEC 61850 GOOSE configurations. He is a member of IEEJ (Institute of Electrical Engineers of Japan).

Hiroshi Okamura joined Tokyo Electric Power Company, Inc. (TEPCO) in 1994. After 11 years of experience in power system operation and protection, he is a team member of the TEPCO IED pilot project and responsible for system design, system analysis, setting, and testing.

Fernando Calero received his BSEE in 1986 from the University of Kansas, his MSEE in 1987 from the University of Illinois (Urbana-Champaign), and his MSEPE in 1989 from the Rensselaer Polytechnic Institute. From 1990 to 1996, he worked in Coral Springs, Florida, for the ABB relay division in the support, training, testing, and design of protective relays. Between 1997 and 2000, he worked for Itec Engineering, Florida Power and Light, and Siemens. Since 2000, Fernando has been an application engineer in international sales and marketing for Schweitzer Engineering Laboratories, Inc., providing training and technical assistance.

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