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Servando Sánchez, Alfredo Dionicio, Martín Monjarás, Manuel Guel,
Guillermo González, and Octavio Vázquez
Comisión Federal de Electricidad

José L. Estrada
Altos Hornos de México, S.A. de C.V. (AHMSA)

Héctor J. Altuve, Ignacio Muñoz, Iván Yánez, and Pedro Loza
Schweitzer Engineering Laboratories, Inc.

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Héctor J. Altuve, Ignacio Muñoz, Iván Yánez, and Pedro Loza, *Schweitzer Engineering Laboratories, Inc.*

Abstract—**In this paper, we first review the need for communications-assisted protection of subtransmission lines, describe the communications channels available, and compare applicable protection schemes. We show the advantages of directional comparison protection over digital point-to-point radio channels for this application. Later we present a summary of the applications of directional comparison protection over radio channels in Mexico. We also provide statistical data on the field performance of protection schemes and radio channels installed in Mexico. We then present and discuss several cases of protection scheme operation for actual faults. Finally, we provide guidelines for applying directional comparison protection over radio channels to subtransmission lines.**

I. INTRODUCTION

In the Mexican power system, many subtransmission lines are short, looped lines, and some of them are multiterminal or multitapped lines. Overcurrent and distance protection schemes are not a good solution for these line configurations. Low-cost communications-based protection schemes are now available for subtransmission lines using digital point-to-point radio channels.

Comisión Federal de Electricidad (CFE), the largest Mexican electric utility, has 13 directional comparison schemes with digital radio channels in operation on 115 kV subtransmission lines. The first scheme was implemented in 2000. Some of the lines terminate at a substation owned by an industrial customer. Altos Hornos de México (AHMSA) has four directional comparison schemes with digital radio channels operating in an industrial 34.5 kV network. Standard NRF-041-CFE [1] includes directional comparison protection over a digital radio channel as an accepted primary protection scheme for lines up to 10 km long, with nominal voltages between 69 and 161 kV.

This paper presents the experience of CFE and an industrial customer in the design and operation of directional comparison schemes with digital radio channels. The paper provides real statistical data on the performance of protection schemes and radio channels and discusses several cases of protection scheme operation for actual faults. Finally, the paper provides guidelines for applying directional comparison protection over radio channels to subtransmission lines.

II. SUBTRANSMISSION LINES REQUIRE COMMUNICATIONS-BASED PROTECTION SCHEMES

A. Line Configurations

Overcurrent and distance protection schemes are the traditional solution for radial subtransmission lines. However, many subtransmission lines are short, looped lines, and some of them are multiterminal or multitapped lines. Overcurrent and distance protection is difficult to apply for these line configurations. In addition, protection coordination requires high operating times.

B. High-Speed Fault Clearing

Fast fault clearing preserves system stability, reduces equipment damage, and improves power quality. In the past, high-speed tripping was considered necessary only for transmission systems.

Modern distribution and subtransmission systems also require high-speed protection. Loads are becoming more sensitive to voltage sags caused by faults because of the use of electronic equipment and computer-controlled processes. The Information Technology Industry Council (ITIC) created the ITIC Curve (an updated version of the CBEMA Curve) to represent the voltage tolerance of computer equipment (see Fig. 1). A voltage variation is tolerable if the point defined by the measured percent deviation from nominal and time duration is between both curves shown. For example, a fault causing the voltage to sag to 70 percent of nominal should not last more than 0.5 s.

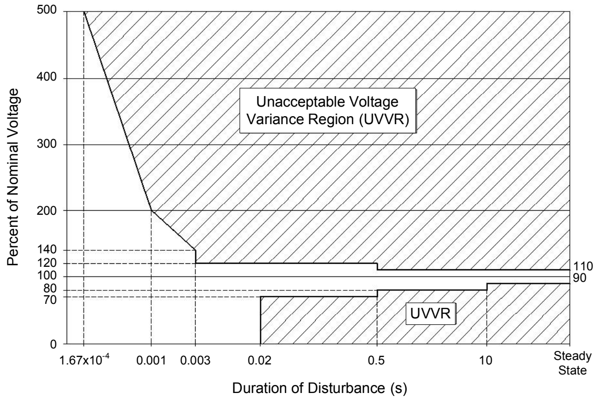

Fig. 1. ITIC Voltage Tolerance Curve Defines Transient and Steady State Voltage Tolerance Limits for a Given Load

Delayed fault clearing may cause voltage stability problems. For example, in areas with a large amount of air conditioning load, the voltage sag caused by a fault can initiate a voltage collapse [2]. Distribution or subtransmission systems with distributed generation also require high-speed tripping to preserve transient stability.

Typical clearing times of overcurrent and distance protection schemes are above 0.5 s for many faults, which is unacceptable for modern subtransmission lines.

III. COMMUNICATIONS-BASED PROTECTION SCHEMES

A. Directional Comparison Protection

Directional comparison schemes use a communications channel for the relays to exchange information on the status of their directional elements. For this reason, directional comparison does not require a high bandwidth channel.

Fig. 2 shows the basic elements of a directional comparison scheme. At each line terminal, forward- and reverse-looking instantaneous directional overcurrent or distance elements provide information for the scheme logic. The forward-looking elements at each terminal are set to overreach the remote terminal with sufficient margin to detect all in-section faults. For an internal fault, both forward-looking elements operate. For an external fault, one forward-looking and one reverse-looking element operate. The scheme uses this information at each line terminal to provide fast tripping for internal faults. Underreaching elements (not shown in the figure) at each terminal provide instantaneous protection, which is independent of the communications-assisted tripping logic.

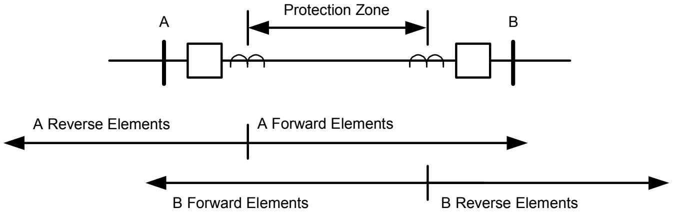

Fig. 2. Directional Comparison Schemes Use Forward- and Reverse-Looking Directional Overcurrent or Distance Elements

Directional comparison schemes for subtransmission lines in Mexico use Permissive Overreaching Transfer Trip (POTT) logic. A pilot trip (TRIP) occurs for an internal fault if any local forward-looking element operates and a permissive trip (PTRX) is received from the remote terminal (see Fig. 3). At either end, the forward-looking element pickup keys the transmitter (KEY). For faults close to one of the line terminals, the breaker of that line terminal trips instantaneously via pickup of the underreaching distance or directional overcurrent element. The remote breaker trips in pilot time. An external fault is a reverse fault as seen from one line terminal. The forward-looking element of this line terminal does not operate. Therefore, no local tripping signal is issued, and no permissive trip signal is sent to the other terminal. The scheme does not operate for this out-of-section fault.

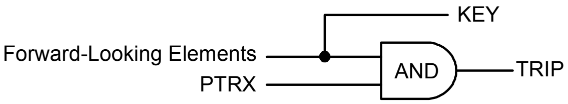

Fig. 3. Basic Permissive Overreaching Transfer Trip Logic

This POTT scheme uses the reverse-looking elements in the logic required to prevent misoperation for current reversals in parallel or looped lines and to ensure tripping when one line terminal is open or has a weak source. This logic is not shown in Fig. 3 for simplicity.

Table I, adapted from [3], summarizes the main characteristics of POTT schemes. A communications channel failure causes the POTT scheme to fail to operate for internal faults. For channels that could fail as a result of the internal fault, one solution is a Directional Comparison Unblocking (DCUB) scheme. DCUB has the same basic logic as the POTT scheme, but it opens a time window that allows a trip without receipt of the trip signal when the channel fails. A radio channel is suited for POTT logic because it is completely independent from the protected line.

Using a logic processor, we can apply the POTT scheme to lines having up to 15 terminals. The logic processor receives and processes logic information from all line terminals to make a tripping decision and sends the tripping signal to all line terminals. A POTT scheme can be implemented over a channel with a bandwidth of 9.6 kbps or higher.

B. Line Current Differential Protection

In a digital line current differential scheme, the relays exchange current data over the communications channel. Using current information from all line terminals, each relay executes a differential protection algorithm.

Current data may consist of digitized current samples or phasor values. Some systems combine the three phase currents into a single signal to reduce the amount of data to transmit. Modern channels support phase-segregated systems, which communicate information on all three phase currents separately.

Table I summarizes the main characteristics of line current differential schemes. A combination of phase and sequence differential elements in the same relay provides very fast operation for phase faults and very high fault resistance coverage for ground faults. Continuous channel monitoring is important to deal with channel loss problems. Making the differential comparison only when the channel is healthy improves differential scheme security [4]. Line current differential protection requires a digital channel with a bandwidth of 56 kbps or higher.

TABLE I
PROTECTION SCHEME COMPARISON

	Permissive Overreaching Transfer Trip (POTT)	**Current Differential**
Operating Speed	1.5–2 cycles	1–1.5 cycles
Fault Resistance Coverage	Lower	Higher
Maximum Number of Line Terminals	15	3
Bandwidth Requirement	9.6–38.4 kbps	56–115 kbps
Loss-of-Signal Consequence	Failure to Trip	Failure to Trip
Loss-of-Signal Mitigation	Add Trip Window (DCUB)	Continuous Channel Monitoring
Upgrading Existing Protection Requires Major Panel Changes	No	Yes

IV. COMMUNICATIONS CHANNELS

Two communications channels are currently used in Mexico for subtransmission line protection: spread-spectrum radio and fiber-optic cable.

A. Spread-Spectrum Radio

Spread-spectrum radio is a good solution for subtransmission line protection. If a tower for elevating the antenna is not required, the cost of a spread-spectrum radio system is approximately $4,000 (U.S.) per line terminal (including installation). Once the system is installed, there are no additional recurring costs, such as license fees. The radio channel is physically independent from the protected line, and all of the radio equipment except the antenna can be installed in a protected enclosure.

Spread-spectrum radios use multiple frequencies in the 900 MHz and 2.4 GHz license-free ISM band to provide a point-to-point connection. Another radio using the same frequency at the same time may interfere with the signal; however, the spread-spectrum system spends a very short time at each frequency within the band. Frequency interferences typically cause very short periods of channel unavailability.

Table II, adapted from [3], summarizes the main characteristics of spread-spectrum radio channels.

B. Direct-Connected Optical Fiber

A direct fiber connection has significant operational advantages over spread-spectrum radio (see Table II). For subtransmission line applications, the main limitation is cost. The typical cost of an optical ground wire (OPGW) or an all-dielectric self-supporting (ADSS) direct fiber channel is in the order of $3 per foot, equivalent to $10,000 (U.S.) per kilometer (including installation). Because of data transmission capability, point-to-point fiber-optic cable is suited for current differential relaying.

TABLE II
COMMUNICATIONS CHANNEL COMPARISON

	Spread-Spectrum Radio	**Direct Fiber-Optic Cable**
Channel Unavailability (Typical)	0.0003	Very Low
Longest Failure (Typical)	1 s	Very Short
Cost (10 km, Two Terminals)	$8,000 (U.S.)	$150,000 (U.S)
Communications Delay	4 ms	0.1 ms
Data Rate	115.2 kbps	4 Gbps

V. DIRECTIONAL COMPARISON SCHEMES IN OPERATION

The Appendix provides data on the subtransmission lines in Mexico that have directional comparison protection schemes over radio channels. Line length ranges from 0.8 to 12.07 km, with 4.95 km as the average length. All lines are two-terminal lines with no load taps. Some of the lines are part of a looped system with generation at several buses.

TABLE III
PERFORMANCE OF DIRECTIONAL COMPARISON PROTECTION SCHEMES OVER RADIO CHANNELS IN SUBTRANSMISSION LINES IN MEXICO

No.	Line	Number of Years in Operation	Internal Faults				External Faults	
			Total	Correct Trips	Average Scheme Operating Time (Cycles)	Maximum Scheme Operating Time (Cycles)	Total	Correct No Trips
1	73160	2	0	0			1	1
2	73370	2	1	1	1.125	1.125	0	0
3	73040	2	1	1	4.75*	4.75*	0	0
4	73360	2	0	0			1	1
5	73200	2	1	1	2.25	2.25	0	0
6	73350	2	0	0			1	1
7	73180	2	0	0			1	1
8	73590	0.75	1	1	2.25	2.25	3	3
9	73110	7	2	2	1.59	1.68	5	5
10	73090	4	2	2	1.5	2.0	3	3
11	HBB435 – HAM402	4	0	0			1	1
12	HAM403 – HPG435	4	1	1	2.0	2.0	0	0
13	HBA432 – MPC412	0.6	0	0			0	0
14	HBA412 – MPC413	0.6	0	0			0	0
15	73260	3	1	1	1.875	1.875	3	3
16	73440	5	1	1	1.5	1.5	4	4
17	73390	4	1	1	1.44	1.44	4	4

* This fault started as external and evolved to an internal fault; the current-reversal logic delay caused the 4.75 cycles operating time.

VI. FIELD OPERATION EXPERIENCE

A. Protection Operation Data

Table III summarizes the performance of directional comparison protection schemes over radio channels currently in operation in Mexico. All schemes have POTT logic, with some schemes in operation since 2000. The total time of operation is 46.95 years. The average time of operation is 2.76 years.

These schemes have properly cleared all 12 internal faults and have remained secure for all 27 external faults. The average scheme operating time is 1.73 cycles (measured from fault inception to the emission of the breaker tripping signal). The longest operating time has been 2.25 cycles. In this analysis, we do not consider the 4.75-cycle operating time for the 73040 line fault. Since this fault evolved from external to internal, the current-reversal logic introduced an additional time delay, as discussed in Section VII.

B. Radio Channel Data

Some digital relays have the capability of continuously monitoring the performance of the radio channel. The relay report provides historic data on the number of channel failures, the longest recorded failure, and the resulting channel unavailability. This information is important to evaluate the impact of channel failures on the protection scheme reliability and to take corrective actions.

Table IV provides data on radio channel performance for some of the schemes in operation in Mexico. These data show that radio channels have performed very reliably, with unavailabilities between 0.00001 and 0.000585. The longest unscheduled channel outage has been 4.184 s. Channel failures have not coincided with faults. No relay has been disabled because of a channel failure.

TABLE IV
RADIO CHANNEL PERFORMANCE DATA

Line	Time Period	Total Failures*	Relay Disabled	Longest Failure (s)	Unavailability
73370	07/26/07 07/27/07	256	0	0.108	0.000103
73040	07/18/07 07/27/07	256	0	4.184	0.000098
73590	05/16/07 05/25/07	256	0	1.626	0.000156
73110	05/16/07 05/25/07	256	0	0.8	0.000049
73090	05/16/07 05/25/07	256	0	0.038	0.000585
HBB435 – HAM402	07/04/03 08/21/03	256	0	0.896	0.000010
73260	04/14/07 06/29/07	256	0	515.73 **	0.000089

* 256 failures is the maximum buffer length in the relay's report.

** This time does not correspond to a failure, but to a programmed disconnection.

VII. EXAMPLES OF SCHEME OPERATION FOR ACTUAL FAULTS

A. Internal Fault Case

The 73370 line connects substations Azteca and Gemini in the 115 kV subtransmission ring of the Ciudad Juárez Distribution Zone, CFE North Distribution Division, which serves important industrial customers and includes a generating station (see Fig. 4).

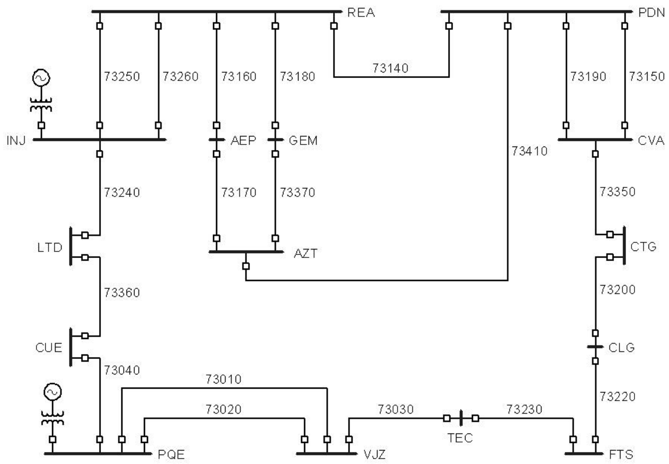

Fig. 4. Subtransmission 115 kV Looped System Serving the City of Ciudad Juárez, Chih., Mexico

The 73370 line has a directional comparison protection scheme with direct relay-to-relay communications over a spread-spectrum radio channel. This scheme was implemented using existing digital directional overcurrent relays. The POTT logic uses phase (67P2), negative-sequence (67Q2), and ground (67G2) directional elements as the overreaching forward-looking elements required for tripping and keying the transmitter. The logic also uses reverse-looking 67P3, 67Q3, and 67G3 elements for current-reversal and weak infeed logic.

A single-phase-to-ground fault occurred on this line on October 31, 2006. The fault current contributions were 4988 A from the Azteca terminal and 4265 A from the Gemini terminal. From the oscillogram recorded at the Azteca substation (Fig. 5), we conclude the following:

- The fault starts on cycle 4.1.
- The phase (67P2), negative-sequence (67Q2), and ground (67G2) overreaching directional elements operate on cycle 4.5. The internal bit KEY of the POTT logic asserts, and a transfer trip signal is transmitted via relay-to-relay communications using the internal bit TMB1A.
- RMB1A bit asserts on cycle 5.35, indicating reception of the transfer trip signal from the remote end, and bit PTRX asserts to complete the tripping logic (see Fig. 3). Bit TRIP asserts to initiate local breaker tripping 1.25 cycles after fault inception.
- The scheme operating time is 1.25 cycles.
- The local breaker clears the fault on cycle 9.5.
- The total fault clearing time is 5.4 cycles.

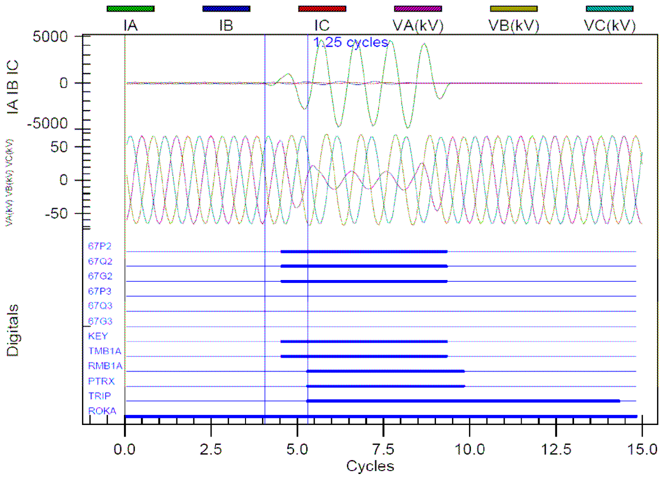

Fig. 5. Oscillogram Recorded at the Azteca Terminal of the 73370 Line

Since the relays are not time synchronized, the fault starts on cycle 5.1 in the Gemini substation oscillogram (Fig. 6). Protection operation is exactly the same as that of the Azteca terminal. Bit TRIP asserts to initiate local breaker tripping 1.25 cycles after fault inception. Total fault clearing time is 4.9 cycles.

The POTT protection scheme operated correctly to clear this internal fault in 5.4 cycles.

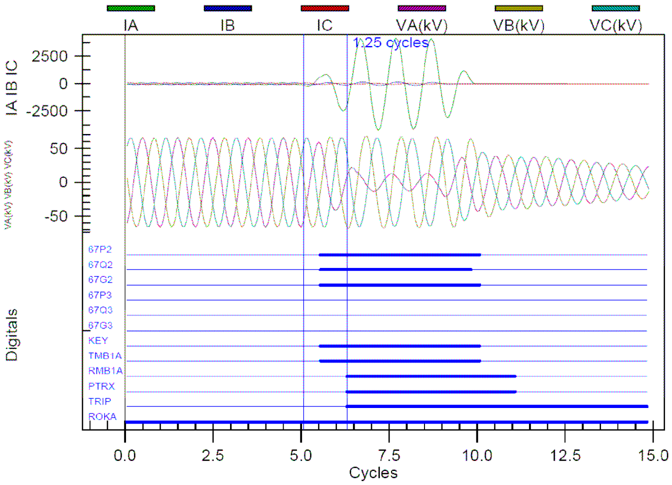

Fig. 6. Oscillogram Recorded at the Gemini Terminal of the 73370 Line

The fault records also serve to evaluate the communications channel performance. The ROK bit remains asserted during the fault, indicating good reception of the channel signal. We can measure the transmission time as the time difference between the remote TMB1A bit assertion and the local RMB1A bit assertion. This time is 0.8 cycles for both line terminals.

B. External Fault Case

Fig. 7 shows part of the 115 kV subtransmission loop of the city of Querétaro. Several lines of this looped system have directional comparison protection schemes with direct relay-to-relay communications over a spread-spectrum radio channel. The POTT logic uses overreaching forward-looking 67P2, 67Q2, and 67G2 directional elements, and also reverse-looking 67P3, 67Q3, and 67G3 directional elements.

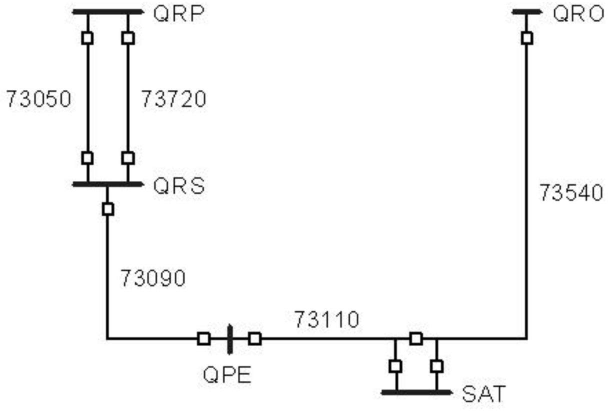

Fig. 7. Part of the Subtransmission 115 kV Looped System Serving the City of Querétaro, Qro., Mexico

A single-phase-to-ground fault occurred on February 2, 2002 on the 73540 line connecting Satélite (SAT) and Querétaro (QRO) substations. The directional comparison protection scheme of the adjacent 73110 line correctly did not operate for this external fault. This line connects substations Querétaro Poniente (QPE) and Satélite (SAT).

From the oscillogram recorded at the QPE substation (Fig. 8), we conclude the following:

- The fault starts on cycle 3.5.
- The phase (67P2), negative-sequence (67Q2), and ground (67G2) overreaching directional elements operate on cycle 4.25. The internal bit KEY of the POTT logic asserts, and a transfer trip signal is transmitted via relay-to-relay communications using the internal bit TMB1A.
- A transfer trip signal is not received from the remote end, bit RMB1A does not assert, and there is no local tripping for this external fault.
- Operation of the faulted line primary protection clears the fault on cycle 8.8.

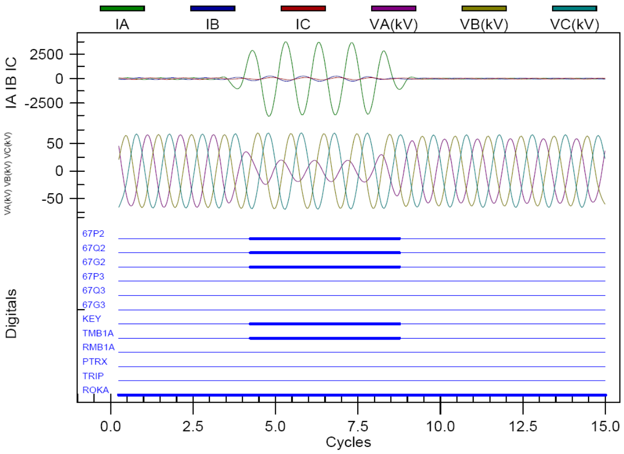

Fig. 8. Oscillogram Recorded at the QPE Terminal of the 73110 Line

The oscillogram recorded at the SAT substation (Fig. 9) shows that:

- The fault starts on cycle 3.4.
- The reverse-looking negative-sequence (67Q3) and ground (67G3) directional elements operate on

cycle 4.0. Phase directional element 67P3 operates 0.25 cycles later. The logic blocks transmission of the transfer trip bit TMB1A (no forward-looking elements asserted).

- RMB1A bit asserts on cycle 5.0, indicating reception of the transfer trip signal from the remote end. However, bit TRIP does not assert for the external fault because forward-looking elements are not asserted.
- Operation of the faulted line primary protection clears the fault on cycle 9.3.

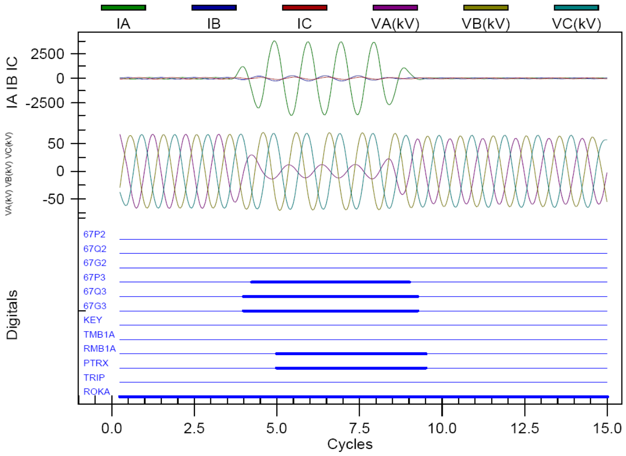

Fig. 9. Oscillogram Recorded at the SAT Terminal of the 73110 Line

C. Evolving Fault Case

The 73040 line connects substations La Cuesta (CUE) and Parque (PQE) in the 115 kV Ciudad Juárez subtransmission looped system (see Fig. 4). On July 11, 2005, a lightning storm caused several faults on this system. Fig. 10 shows the oscillogram recorded at La Cuesta substation for a fault that evolved from external to internal. This is the worst-case scenario for protection operation speed because the POTT current-reversal logic delays operation for the internal fault. The sequence of events is as follows:

- The reverse-looking negative-sequence directional element 67Q3 remains operated during the initial phase-to-phase external fault. The fault current is below the 67P3 element pickup.
- The 67Q3 element resets on cycle 4.3, indicating clearance of the external fault. This reset activates the POTT current-reversal logic (not shown in Fig. 3), which blocks local tripping and prevents transmission of the transfer trip signal for a preset time.
- An internal fault starts on cycle 4.5.
- The forward-looking negative-sequence element 67Q2 operates on cycle 5.2. The fault current is below the 67P2 element pickup.
- RMB1A and PTRX bits assert on cycle 5.7, indicating reception of the transfer trip signal from the remote end; however, the current-reversal logic blocks local tripping.
- The current-reversal logic timer expires on cycle 9.25. Bits KEY and TMB1A assert to send a transfer trip signal. Bit TRIP also asserts to initiate breaker tripping 4.75 cycles after fault inception.
- The scheme operating time is 4.75 cycles because of the current-reversal logic delay.
- The breaker clears the fault on cycle 13.0. Total fault clearing time is 8.5 cycles.

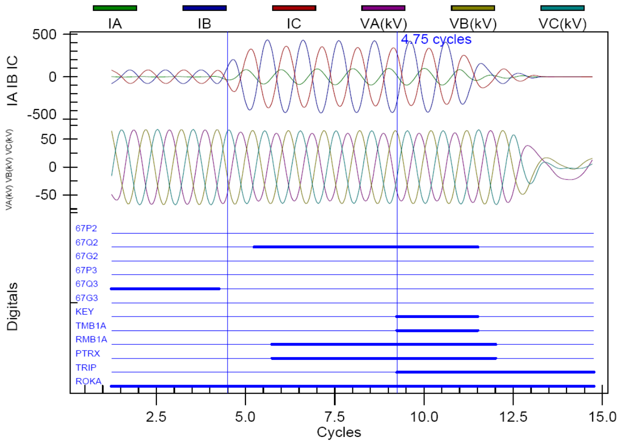

Fig. 10. Oscillogram Recorded at the La Cuesta Terminal of the 73040 Line

VIII. APPLICATION GUIDELINES FOR DIRECTIONAL COMPARISON SCHEMES OVER RADIO CHANNELS

A. General Application Considerations

Use directional comparison over radio channels to provide fast fault clearing in new or existing subtransmission and distribution lines at very low cost. POTT logic is a good choice for radio channels.

Add the radio channel for approximately $4,000 per line terminal to upgrade existing schemes when relays are suited for the application.

The relays should have these features:

- Phase and ground directional overcurrent and/or distance elements. When available, use negative-sequence directional elements to provide good fault resistance coverage for unbalanced faults.
- Programmable functions to transmit and receive relay internal bits over a direct relay-to-relay communications channel.

Listed below are some general guidelines to select and set directional overcurrent/distance elements for POTT logic.

- Use forward-looking directional Level 1 or distance Zone 1 elements to directly trip the breaker.
  - Set to underreach the remote line terminal.
  - For short lines, it may be necessary to block these elements.
- Use forward-looking directional Level 2 or distance Zone 2 elements to enable local breaker tripping and to initiate transfer trip transmission.
  - Set to overreach the remote line terminal.
- Use reverse-looking directional Level 3 or distance Zone 3 elements for the current reversal and weak infeed logic when required.
  - Set to overreach the Level 2 or Zone 2 elements of the remote terminal.

- Use forward-looking directional Level 4 or distance Zone 4 elements to provide time-delayed remote backup protection.
  - Set to overreach the longest adjacent line to the remote terminal.
- Evaluate the need to add a 0.25 to 0.5 cycle security time delay to negative-sequence elements to avoid temporary false channel keying because of unequal breaker pole opening or closing.

B. Multiterminal Line Applications

Use a logic processor to apply directional comparison protection to multiterminal lines. The logic processor must have programmable logic to receive, process, and transmit relay internal bits over a communications channel.

Fig. 11 shows the directional comparison scheme for a three terminal line. This scheme is applicable to lines having more than three terminals. The logic processor, installed at Terminal 3 in this example, communicates with relays at Terminal 1 and Terminal 2 via digital radio or fiber-optic channels. The processor also communicates locally with the Terminal 3 relay via fiber or copper wires.

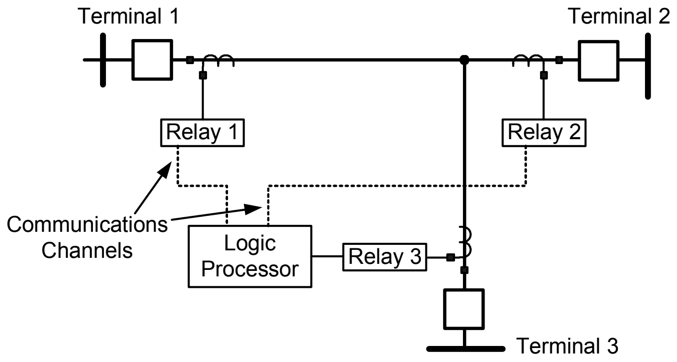

Fig. 11. Directional Comparison Protection for a Multiterminal Line Using a Logic Processor

Fig. 12 shows the processor logic for the Terminal 3 scheme. The same logic applies for the other line terminals. When transfer trip signals PTRX1 and PTRX2 are received for the remote terminals, bit KEY12 asserts to send a transfer trip signal to the Terminal 3 relay. This operation converts the multiterminal line into a two-terminal line as seen from Terminal 3. Bit PTRX12 asserts in Relay 3, indicating reception of the transfer trip signal from the logic processor. The POTT scheme of the Terminal 3 relay operates according to the logic diagram shown in Fig. 3, with PTRX12 replacing PTRX.

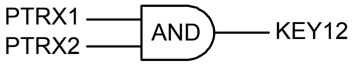

Fig. 12. Processor Logic for Terminal 3 Directional Comparison Scheme in a Three-Terminal Line

A directional comparison scheme using this logic is under commissioning on the 73750 line, which is part of the San Juan del Río 115 kV looped system, in the state of Querétaro, Mexico [5]. The 73750 line connects substations San Juan Potencia, San Juan del Río, and IND-4 (an industrial customer with cogeneration). This scheme uses direct fiber-optic communications.

IX. CONCLUSIONS

- Modern subtransmission lines require fast fault clearing to preserve transient and voltage stability and to meet load voltage tolerance requirements. Overcurrent and distance protection do not provide high-speed tripping for all internal faults.
- Directional comparison protection using point-to-point digital radio channels provides fast fault clearing at low cost for subtransmission and distribution lines.
- In Mexico, the first subtransmission line directional comparison scheme over radio channels was commissioned in 2000. There are 17 schemes in operation today.
- The schemes in service in the Mexican power system have correctly cleared all 12 internal faults, with an average operating time of 1.73 cycles. The longest operating time has been 2.25 cycles. The schemes have remained secure for all 27 external faults.
- Channel monitoring data show a very reliable performance of the radio channels. Unavailability has been no higher than 0.000585. The longest channel outage has been 4.184 s. Channel failures have not coincided with faults. No relay has been disabled because of a channel failure.
- Using a logic processor, we may apply directional comparison protection to lines having more than two terminals. The logic sends a transfer trip signal to each line terminal when it receives tripping signals from all the other terminals.

X. APPENDIX

TABLE V
SUBTRANSMISSION LINES WITH RADIO CHANNELS IN MEXICO

No.	User	Location	Line	Voltage (kV)	Length (km)
1	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73160	115	6.05
2	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73370	115	3.34
3	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73040	115	3.45
4	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73360	115	4.78
5	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73200	115	4.68
6	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73350	115	2.08
7	Juárez Zone, North Distribution Division, CFE	Cd. Juárez, Chih.	73180	115	8.8
8	Querétaro Zone, Bajío Distribution Division, CFE	Querétaro, Qro.	73590	115	5.2
9	Querétaro Zone, Bajío Distribution Division, CFE	Querétaro, Qro.	73110	115	3.1
10	Querétaro Zone, Bajío Distribution Division, CFE	Querétaro, Qro.	73090	115	6.3
11	AHMSA	Monclova, Coah.	HBB-435 – HAM-402	34.5	4.0
12	AHMSA	Monclova, Coah.	HAM-403 – HPG-435	34.5	0.8
13	AHMSA	Monclova, Coah.	HBA432 – MPC412	34.5	1.87
14	AHMSA	Monclova, Coah.	HBA412 – MPA413	34.5	1.40
15	Tlaxcala Zone, Centro Oriente Distribution Division, CFE	Tlaxcala, Tlax.	73260	115	6.6
16	Uruapan Zone, Centro Occidente Distribution Division, CFE	Uruapan, Mich.	73440	115	12.07
17	Uruapan Zone, Centro Occidente Distribution Division, CFE	Uruapan, Mich.	73390	115	9.58

XI. REFERENCES

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XII. BIOGRAPHIES

Servando Sánchez received his BSEE degree in Electrical Engineering and his M. Sc. degree in Power Electronics from the Technological Institute of Morelia, in Morelia, Mich., Mexico. He has worked for the Mexican electric utility Comisión Federal de Electricidad (CFE) since 1984. From 1991 to 1996 he was head of the Substation Protection Department of the Morelia Distribution Zone, Centro-Occidente Distribution Division (CODD). From 1996 to 2001 he was head of the CODD Substation Protection Department. Mr. Sánchez has been the head of the Substations Department, CODD since 2001. He has also conducted research work at CFE and has authored and coauthored technical papers related to line protection. His main research interests are in power system protection and power transformer monitoring.

Alfredo Dionicio Barrón received his BSEE degree in Industrial and Electrical Engineering from the Querétaro Regional Technological Institute in 1991. He completed a set of graduate courses on power systems at the Guanajuato University in 1994. He has worked for Comisión Federal de Electricidad (CFE) since 1991. From 1991 to 1992 he was a Rural Electrification Supervisor at the Bajío Distribution Division (BDD). From 1992 to 1994 he was head of the Distribution Section at the Celaya Distribution Zone, BDD. Mr. Dionicio has been the head of the Protection Office of the Querétaro Distribution Zone, BDD since 1994.

Martín R. Monjarás M. received his BSEE degree in Electrical Engineering from the University of Guanajuato in 1990. He has worked for Comisión Federal de Electricidad (CFE) since 1991. From 1991 to 1994 he was head of the Distribution Section at the San Juan del Río Distribution Zone, Bajío Distribution Division (BDD). From 1994 to 1997 he was head of the Substations, Lines and Protection Office at the San Juan del Río Distribution Zone. Mr. Monjarás has been the head of the BDD Substation Protection Department since 1997.

Manuel Guel received his BSEE degree in Electrical Engineering from the Autonomous University of San Luis Potosí, Mexico. Since 1984 he has worked for Comisión Federal de Electricidad (CFE). From 1991 to 2004 he was head of the Substation Protection Department of the Golfo Centro Distribution Division (GCDD) in Tampico, Tam. Mr. Guel has been the head of the Communications and Control Department, GCDD since 2004.

Guillermo González Cavazos received his BSEE degree in Electronic Engineering from the Technological Institute of La Laguna, in Torreon, Coahuila, Mexico. Since 2002 he has worked for Comisión Federal de Electricidad (CFE). From 2002 to 2004 he served as a field engineer of the Protection and Measurement Department of the Juarez Transmission and Transformation Sub-Area. Since 2004 Mr. Gonzalez has been the head of the Communications and Control Office of the Juarez Distribution Zone, North Distribution Division (NDD). He has worked on the expansion and installation of radio frequency and fiber-optic channels for protection, voice, and data communications.

Octavio Vázquez Gamboa received his BSEE degree in Industrial and Electrical Engineering in 1981 from the Technological Institute of Puebla, in Puebla, Pue., Mexico. From 1980 to 1982 he was the head of the Electrical Maintenance Office at Industrias Polifil, S.A. de C.V. During 1983 he was the head of the Electrical Maintenance Department at Aceros Tlaxcala. He has worked for Comisión Federal de Electricidad (CFE) since 1984. From 1984 to 1989 he was the head of a Protection Office of the Southeastern Distribution Division (SDD). From 1990 to 1993 he was the head of a Substations and Lines Office of the SDD. From 1994 to 2000 Mr. Vázquez was the head of the SDD Substation Protection Department. In 2001 Mr. Vázquez was made the head of the Substation Protection Department of the Central-Eastern Distribution Division in Puebla, Pue. He is a member of the CFE Protection Panel Committee and has served as an instructor in distribution system protection courses at CFE Celaya and Campeche Training Centers. Mr. Vázquez has authored and coauthored technical papers on distribution system protection and is currently developing power quality monitoring systems for CFE.

José L. Estrada received his BSEE degree in Electrical Engineering in 1977 from the National Polytechnic Institute, Mexico City, Mexico. Since 1980 he has worked for Altos Hornos de México, S.A. de C.V. (AHMSA) the largest steel mill in Mexico, as a high voltage project manager. Mr. Estrada is also an Adjunct Professor at the Mechanical and Electrical Engineering School of the Coahuila University, in Monclova, Coahuila, Mexico.

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

Juan Ignacio Muñoz González received his BSEE degree in Electrical Engineering from the University of Guanajuato in 1978. From 1981 to 1997 he worked for Comisión Federal de Electricidad (CFE) as a protection engineer in the distribution and transmission areas. From 1988 to 1997 he was also an Adjunct Professor of the Engineering Sciences Department at the Iberoamerican University, León Campus. From 1997 to 2000 he was a technical support engineer for INELAP-PQE. Since 2000 Mr. Muñoz has worked for Schweitzer Engineering Laboratories, Inc., where he is currently the project administration manager of its Mexico subsidiary. Mr. Muñoz is an IEEE Member and also a Member of the College of Mechanical and Electrical Engineers of the State of Guanajuato.

Iván Yánez received his BSEE degree in Electrical Engineering in 1994 from the Technological Institute of Hermosillo, Hermosillo, Son., Mexico. From 1995 to 1998 he worked for Comisión Federal de Electricidad (CFE) as a protection engineer in the Transmission and Transformation Northwestern Area. He worked on the single-pole tripping and reclosing project for the 230 kV CFE Northwestern System. In 1999 he joined Schweitzer Engineering Laboratories, Inc., where he is currently a field application engineer in the Monterrey, Mexico office.

Pedro Loza received his BSEE degree in 1998 from the National Autonomous University of México (UNAM). He completed the courses for an M.Sc. Degree in Power Systems at UNAM and is currently working on his thesis. From 1998 to 1999, Mr. Loza worked in the Electric Research Institute in Cuernavaca, Mor., Mexico where he conducted research on small signal stability. In September 2000, he joined Schweitzer Engineering Laboratories, Inc., where he worked as a design engineer, and is currently a field application engineer in the Mexico City office.

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