Updated Transmission Line Protection Communications

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***Abstract*—The telecommunications revolution has increased the options and capabilities available for communications-based protection of transmission lines. To improve tripping speeds on long and short lines, protection engineers can select from a host of media, protocols, and logic schemes. The question to address is what communications scheme is best for which circumstances.**

This paper begins by establishing performance baselines of protection scheme operating times measured in event reports for a variety of in-service lines. It includes various successful systems and takes into account all of the elements that must be addressed when engineering a protection scheme, such as relay pickup time, communications interface and latency, coordinating time delays, and sequential tripping times.

These in-service schemes are compared with laboratory tests of new systems, using radio and fiber-optic communications with serial and Ethernet protocols. Methods of optimizing different systems are tested and evaluated; the final results are tabulated and compared.

No single scheme is best for all circumstances. With comparison data, the protection engineer can select the best options to improve the overall power system performance. Recognizing the strengths and weaknesses of different schemes assists the engineer in addressing new situations. Comparing laboratory tests and in-service performance provides a tool for evaluating a transition to new technologies.

I. Introduction

Communications-based transmission line protection schemes have been in service for well over half a century [1]. Early communications systems used copper conductors and included privately owned pilot wire channels, dedicated telephone circuits, and power line carrier channels. In the early 1970s, utility-owned microwave links began to replace copper wires in transmission systems, and licensed radio transceivers extended supervisory control and data acquisition (SCADA) reach into medium-voltage distribution circuits. Protection schemes were designed to accommodate the weaknesses and strengths of the communications medium in order to reduce overall tripping times and improve system security.

Optical fiber and radio are two relatively new communications systems available today. When selecting a protection scheme, compare different types of these systems. The scheme selection must address the reliability of transmitting a signal to the remote end during a fault and preventing a false transmission during a fault.

Selecting a protection scheme and communications type has been further complicated by the use of advanced protocols to send fault information between the line terminals. In addition to contact closures, serial and Ethernet protocol options are now available for data transmission. The impact of protocol overhead, error detection and correction, addressability, and other factors must be included in the process of selecting a communications-based protection scheme.

This paper only addresses two-terminal lines. Many of the principles discussed here apply to multiterminal lines but should be addressed in a separate paper due to the added complexity. While many of the elements of Fig. 1 are not included in every scheme, it will be used as a general case throughout this paper.

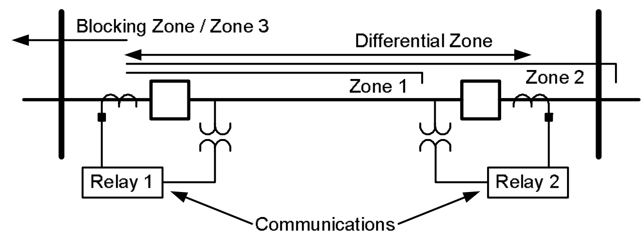

Fig. 1. General transmission line protection with communications

The details of the protection elements are not part of the discussion in this paper. The only requirements are that Zone 1 elements (only shown for Relay 1 in Fig. 1) do not overreach the end of the line, Zone 2 elements reliably reach beyond the line end, and reverse-looking Zone 3 elements reach beyond Zone 2 elements from the remote end.

II. Protection Schemes

Pilot protection, or teleprotection, exchanges information between the transmission line terminals over a communications channel to provide high-speed fault clearing for 100 percent of the protected line. Pilot protection includes directional comparison and current-only schemes.

A. Directional Comparison Schemes

In a directional comparison scheme, forward- and reverse-looking instantaneous directional overcurrent or distance elements provide information for the scheme logic at each line terminal. The forward-looking elements are set to overreach the remote terminal with enough 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 at each terminal provide instantaneous protection, which is independent of the communications-assisted tripping logic. Directional comparison does not require a high-bandwidth channel because the relays only exchange information on the status of their directional elements.

There are many variations and combinations of permissive tripping, blocking, underreaching, and overreaching schemes. Because many of these scheme variations are a result of communications limitations, we will try to examine a few of the most common concerns in each scheme.

B. Permissive Tripping Schemes

As indicated by the name, a permissive tripping scheme must receive “permission” at one end of the line from the other in order for a trip to take place. Fig. 2 shows a simple logic diagram of this concept.

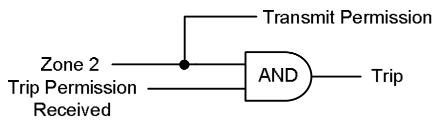

Fig. 2. Simplified permissive tripping logic

This simplified logic only shows the basic principle of the scheme operation. Operating experience has led to an expansion of the logic to include features such as weak-infeed echo repeat, current-reversal coordinating logic, and logic to detect evolving faults. Fig. 3 shows a more complete logic of a permissive overreaching transfer trip (POTT) scheme, only to indicate the growth in complexity that accompanies the solutions to operational issues.

The logic of how the permission signal is keyed and how it is used in the relay does not fully enter into the scope of this paper, other than how the scheme logic deals with possible incorrect keying or the effect of a lost signal.

Concerning communication, it is critical to the scheme operation that permission to trip be received in a timely manner and channel noise not cause an incorrect trip.

C. Blocking Schemes

Unlike permissive tripping schemes, which send a tripping signal when they detect a fault in the forward direction, blocking schemes (as seen in Fig. 4) send a signal to prevent tripping when they detect a fault in the reverse direction.

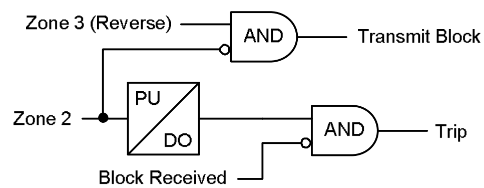

Fig. 4. Simplified blocking scheme logic

If the local reverse-looking Zone 3 element detects a reverse fault, it sends a trip-blocking signal to the remote end. At the remote end, the overreaching Zone 2 elements trip after a short coordinating time delay if they are not blocked by the blocking signal. In many applications, a nondirectional element sends the blocking signal. In these cases, the blocking signal quickly shuts off if the fault is in the forward direction.

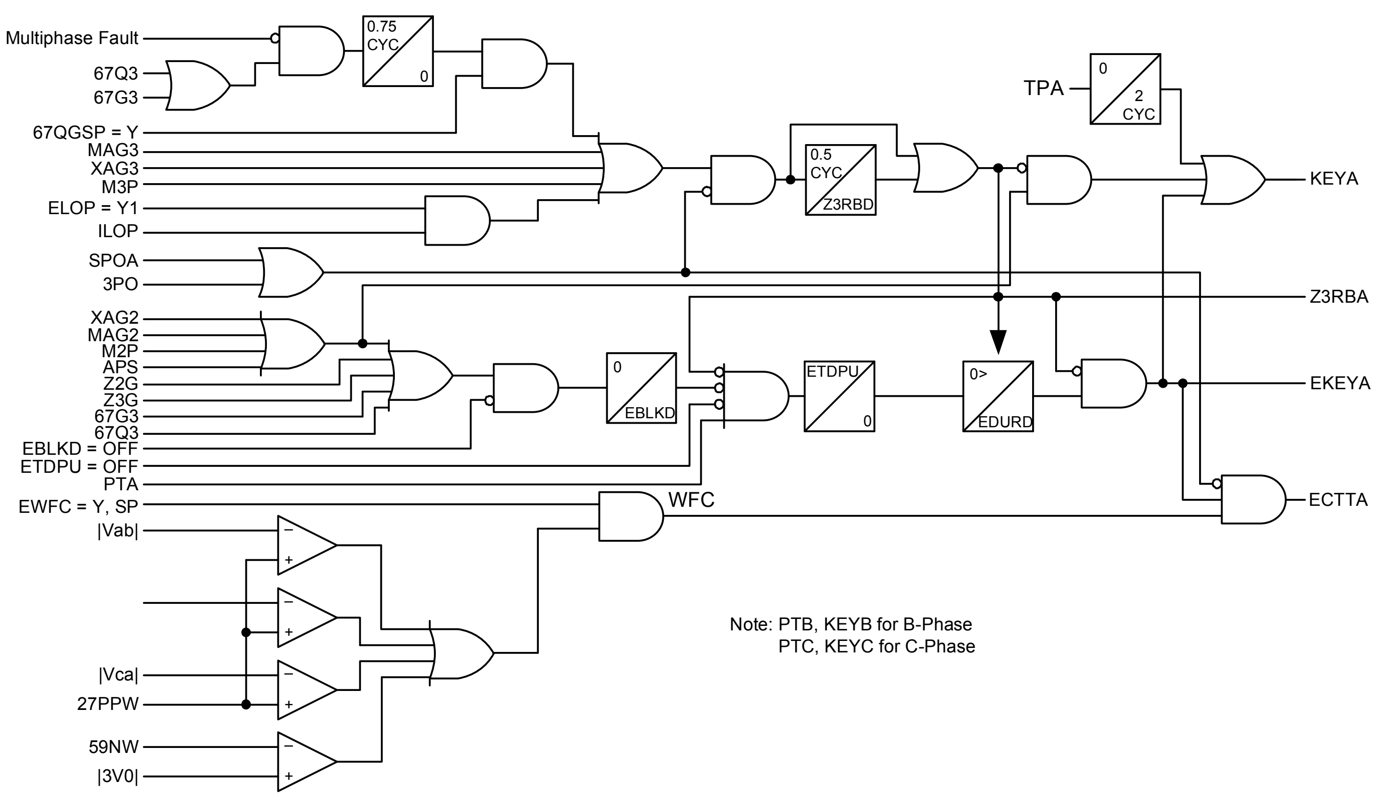

Fig. 3. POTT scheme logic with echo and weak infeed [2]

D. Current Differential Schemes

In a digital line current differential scheme, the relays exchange current data over the communications channel. This scheme typically requires a digital channel with a bandwidth of 56 Kbps or higher, and it is the most sensitive to communications channel propagation delay variations and asymmetry. Line current differential schemes may solve the propagation delay variations and asymmetry problems by transmitting a locally generated time stamp or using an external clock source, such as GPS, to synchronize the two relays.

Previously, engineers used phase comparison schemes to reduce the required communications bandwidth below ten kilobits per second. However, these schemes are less sensitive than line current differential schemes.

III. Communications Systems and Operational Experience With Examples

A. Power Line Carrier

Using the power line to transmit a signal from one end of the line to the other has the advantage of the channel being under the utility's control but the disadvantage of possibly trying to transmit a signal through a fault.

In order to trip as quickly as possible, even when the signal does not get through, it is common to use blocking schemes. In these situations, it is critical to measure the signal time to ensure proper coordination and avoid false trips.

Fig. 5 shows the test results of a directional comparison line protection scheme using power line carrier communications. In this event, the relay correctly blocked tripping, with the blocking signal (IN3) arriving just in time to prevent 67N2 from operating the trip.

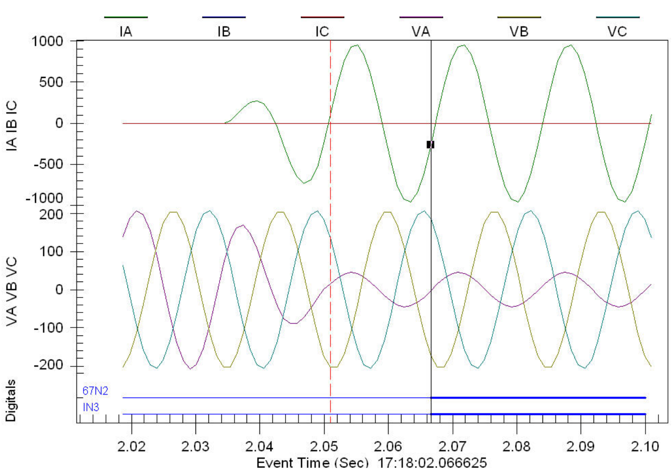

Fig. 5. Test result of a directional comparison scheme over a power line carrier: correct blocking for an external fault

Fig. 6 shows another test of the same system. In this case, the blocking signal arrives two milliseconds too late to prevent the tripping (shown at the top of the figure as the difference between the two lines).

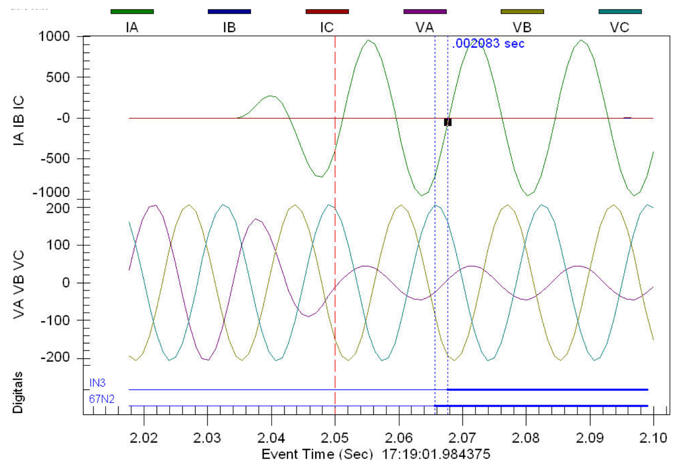

Fig. 6. Test result of a directional comparison scheme over a power line carrier: the scheme misoperates for the external fault

These test results suggest three recommendations regarding the system:

1. Temporarily increase the coordinating delay to ensure that the blocking signal will arrive before tripping for external faults.
2. Determine what is causing the delay in the power line carrier signal arrival. There should have been sufficient coordinating time, but there was not. Improper tuning, faulty line traps, improper interface contacts, or other mysterious signal attenuation can cause delays.
3. Install high-accuracy clocks to exactly measure signal timing.

B. Optical Fiber

Because of its bandwidth, security, and immunity to electromagnetic interference, fiber-optic communication is applicable for any type of protection scheme. Point-to-point fiber-optic connections are ideal for protection but can be considered wasteful of bandwidth when only one or two bits of data are sent on a path that can readily carry gigabits. For this reason, it is becoming more common to apply multiplexed communication, where protection takes only a small portion of the total available bandwidth.

Synchronous optical networks (SONETs) supply fast, reliable, and secure communication for all types of protection schemes. A SONET ring topology, shown in Fig. 7, provides for the loss of any path segment.

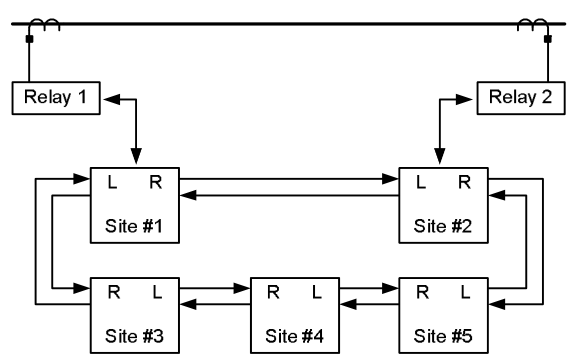

Fig. 7. SONET ring topology

This diagram also illustrates a complication of using a SONET for protection. If the signal travels around the ring from one end to the other using a different path than the return communication, channel asymmetry will result. In other words, the communication from one end may be faster than the other. Tacoma Power installed a line current differential system that operated properly despite channel-switching operations, causing intermittent channel asymmetry [3].

When sending a permissive signal, it is possible to either transmit a digital relay-to-relay message or use a contact closure to initiate a signal being sent over the network. These two methods differ in where and how the permissive signal message is converted from an internal logic assertion in the relay to the data stream transmitted over the network.

In the event reports shown in Fig. 8 and Fig. 9, a contact output from the line relay is connected to a direct transfer trip (DTT) card; then, a multiplexer is connected to optical ground wire (OPGW) fiber. The communications time from transmission to reception in both directions is 1.5 cycles. Because no synchronized clocks were available at the stations involved, this is an estimate, but it is certainly the average of the two directions.

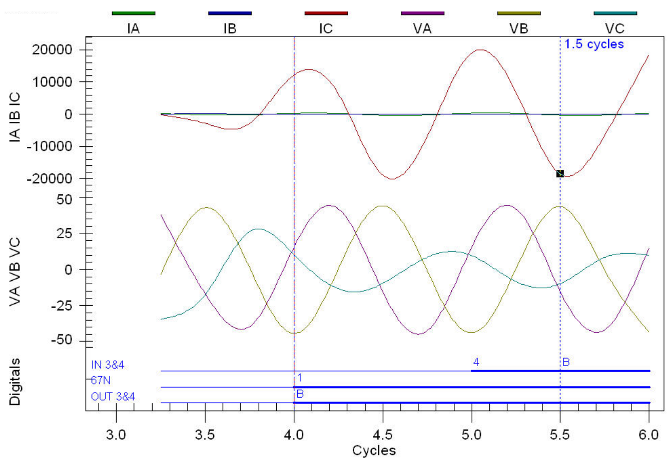

Fig. 8. Line fault (End 1) with contact output keying DTT card in multiplexer

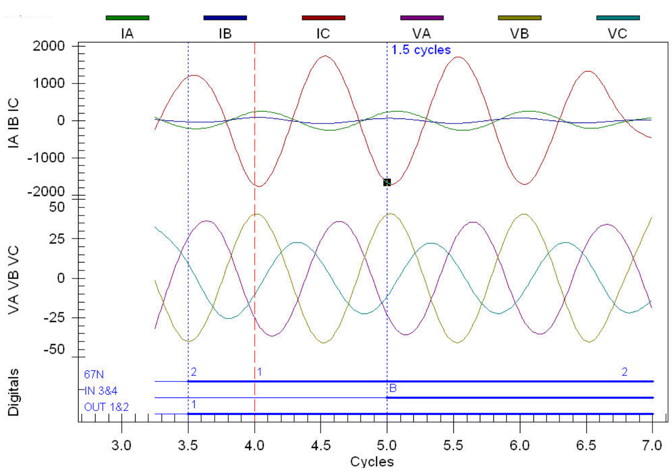

Fig. 9. Line fault (End 2) with contact output keying DTT card in multiplexer

Notice the improvement in communications time in the event reports shown in Fig. 10 and Fig. 11 for a scheme using relay-to-relay digital communications. In this case, one line end (top of Fig. 10) tripped in Zone 1 with permissive keying 0.375 cycles after the fault was initiated. The other end received the signal after 0.75 cycles, indicating a transmission time of 0.375 cycles. This is on the same optic system as Fig. 8, indicating that the only difference in the total time is direct data input versus contact keying. This example shows the advantage of data over contact transmission. A small, efficient data stream provides error checking and communications logging, and avoids the need for output contacts, which introduce a 0.25-cycle delay.

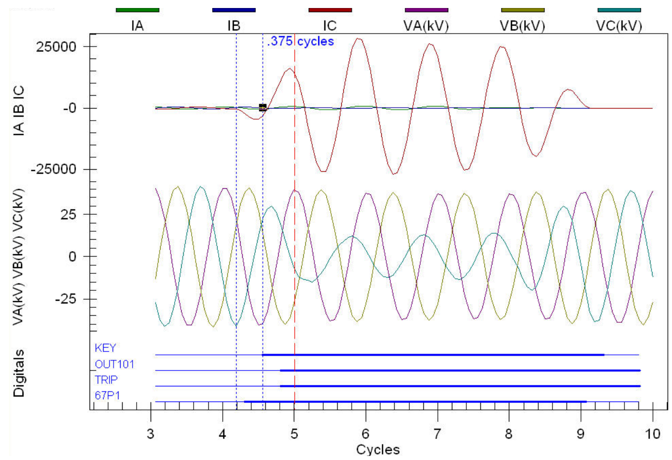

Fig. 10. Line fault (End 1) with relay-to-relay serial keying a low-speed data card in multiplexer

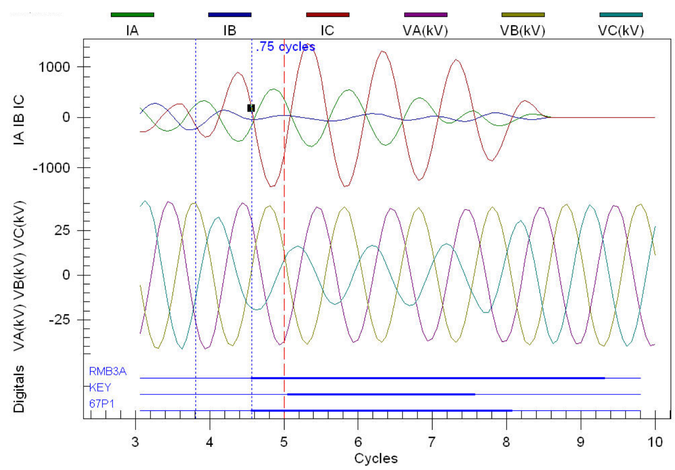

Fig. 11. Line fault (End 2) with relay-to-relay serial keying a low-speed data card in multiplexer

C. Radio

It is somewhat inaccurate to differentiate between a microwave system and other radios; however, in common communications usage, a microwave system is a high-bandwidth data system backbone. In this case, the radios are low-power, point-to-point systems. We are considering two basic types of radios, spread spectrum and licensed.

1) Spread Spectrum

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, but 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.

The advantages of spread-spectrum radio communication include communications security, interference immunity, low probability of detection, low jamming, and low cost.

Spread-spectrum radio systems were first used for secure government communication. Commercial uses have grown since the United States Federal Communications Commission permitted license-free operation under certain conditions. For power system protection, the advantages of spread-spectrum radio channels include freedom from licensing requirements.

Assuming a line of sight between line ends and a range of less than 25 miles, spread-spectrum radio communication has the speed necessary for high-speed line protection. The performance of a complete scheme was well illustrated by several years of operational experience on 17 subtransmission lines in Mexico, using POTT schemes for protection. Table I summarizes the performance of these systems [4].

There are several items of interest in Table I. First, the scheme operation was always correct for both internal and external faults. Second, the average operating time for the schemes, operation of relays at both line ends, is a respectable 1.73 cycles. This is very impressive, considering the relays used for this application have a nominal operating time of 1.25 to 1.5 cycles, which indicates the total permissive signal time was typically less than 0.5 cycles. In these stations, as in others considered in this paper, high-accuracy clocks would have been useful for exact measurement of transmission times.

In these protection schemes, a digital signal was used instead of sending a simple change of state of a contact, as done in typical power line carrier schemes. An advantage of a digital relay-to-relay signal is that continuous monitoring of the signal status is available. Table II shows the radio channel performance data reported in [4]. The data show that the reliability is very good for sending a permissive signal, especially considering that radio signal loss did not occur during faults.

TABLE I
PERFORMANCE OF DIRECTIONAL COMPARISON PROTECTION SCHEMES OVER RADIO CHANNELS IN SUBTRANSMISSION LINES IN MEXICO [4]

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-cycle operating time.

TABLE II
RADIO CHANNEL PERFORMANCE DATA [4]

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.

Contrast the performance of the serial relay-to-relay communication reported for the Mexico system with test results from a similar radio sending Ethernet protocol messages. In the case of Ethernet signals, the tested speed of round trip signal transmission is listed in Table III [5].

TABLE III
TESTED SPEED FOR ROUND TRIP SIGNAL TRANSMISSION [5]

Round Trip Time	Number of Messages	Percentage
< 20 ms	232	0.78%
20–30 ms	29.303	98.76%
30–40 ms	127	0.43%
40–80 ms	10	0.03%

Table III shows that the typical speed is 20 to 30 milliseconds (1.25 to 2 cycles) under laboratory conditions. The latency of the Ethernet protocol, as well as the larger IEC 61850 message, led to a significantly longer time than in the serial scheme. This measured time is an improvement to the 50-millisecond buffering time identified as typical in an IEEE report on Ethernet in spread-spectrum radio [6].

The transmission times listed in Table III can also be compared to the event reports from the power line carrier scheme, shown in Fig. 5 and Fig. 6. In that case, the blocking coordination time was set to 1 cycle, which resulted in borderline security performance with a recommendation to add one cycle to the coordination time. In the case of Ethernet radio sending a Generic Object-Oriented Substation Event (GOOSE) message [5], a coordination time of 2 cycles would still result in a "late" blocking signal in 0.46 percent of the cases, resulting in false trips. Avoiding these false trips would require a coordinating time of 2.5 cycles, practically eliminating the improvement in tripping speed offered by communications.

This performance contrasts with other tests that transmitted a GOOSE message over a fiber-optic Ethernet system [7]. Southern California Edison reported transmission times as low as four milliseconds, depending on the supplier. This indicates that the GOOSE message size causes significant slowing of the signal when radio is used as compared to optical fiber.

2) Licensed

A radio system is clearly suitable for POTT schemes, as shown in Table II and described at length in [4]. However, we wanted to test the suitability for line current differential systems. Spread-spectrum radio may be suitable for line current differential protection. However, we strongly feel that the fact that spread-spectrum radio operates in an unlicensed, unprotected band precludes its use for line current differential protection. Licensed radios are a possible solution to the need for relatively short line communications of line current differential signals.

Because we wanted to test the system in real-world conditions, the decision was made to connect the radio system between two locations that were several miles apart with a reasonable line of sight. The test was not perfect since a large battery system, which would be found in a substation, was not available to provide power to the radio. We did lose signal occasionally because of loss of power and inadvertently unplugging the power to the radio. Fig. 12 shows the communications event log.

```
Summary for 87L Channel X

Channel Status Alarms
  ROKX = 1  DBADX = 0  RBADX = 0  AVAX = 0

For 6/30/2008 05:53:27.447 to 7/28/2008 07:48:46.001

COMMUNICATION LOG SUMMARY  COMMUNICATION STATISTICS
# of Error records  4      Last error                 Data Error
Data Error          2      Longest failure            26.897 s
Dropout             2      Lost Packets, prev. 24 hrs 0
Test Mode Entered   0      One Way Delay (Ping-Pong)  22.5 ms

Error          Recovery
#  Date   Time         Date    Time         Duration Cause
1 7/22/08 21:58:07.632 7/22/08 21:58:07.638  0.006 Data Error
2 7/22/08 21:57:40.735 7/22/08 21:58:07.632 26.897 Dropout Error
3 6/30/08 05:53:46.407 6/30/08 05:53:46.411  0.004 Data Error
4 6/30/08 05:53:38.027 6/30/08 05:53:46.407  8.380 Dropout Error
```

Fig. 12. Communications event log for a line current differential scheme with licensed radio

A loss of radio signal because of rain and snow conditions was reported in [6]. Although the test was performed during the summer, we were fortunate enough to experience a heavy snowfall. There was no data loss because of snow or, on other occasions, rain.

Fig. 12 indicates that the direct measured communications time is 22.5 milliseconds. This is slower than a radio sending a simple permissive or blocking signal because of the larger packet size required for a current differential scheme and the interleaving of the transmitted signal for error detection and correction. Interleaving was considered unnecessary because the relay checks for signal integrity. The test was repeated with a reduced value for interleaving. The results are shown in Fig. 13.

```
Summary for 87L Channel X

Channel Status Alarms
  ROKX = 1  DBADX = 0  RBADX = 0  AVAX = 0

For 8/26/2008 09:50:29.437 to 8/27/2008 08:56:18.875

COMMUNICATION LOG SUMMARY  COMMUNICATION STATISTICS
# of Error records  0      Last error
Data Error          0      Longest failure            0.000 s
Dropout             0      Lost Packets, prev. 24 hrs 0
Test Mode Entered   0      One Way Delay (Ping-Pong)  2.0 ms
```

Fig. 13. Communications event log for reduced interleaving

Notice that reducing interleaving values reduced the one-way delay to only 2.0 milliseconds. Even though the test was performed on a rainy day, this is a significant improvement.

IV. Communications Channel Comparison

Table IV provides data for comparing communications channel performance.

TABLE IV
COMMUNICATIONS CHANNEL AND PROTECTION SCHEME APPLICATION COMPARISON

	Power Line Carrier	**Spread-Spectrum Radio**	**Licensed Radio**	**Optical Fiber**
Permissive Tripping (serial relay-to-relay)	–	~12 ms	–	24 ms (contact) 6 ms (digital)
Permissive Tripping (Ethernet)	16–32 ms	Not tested because of lack of continuous monitor	–	4–20 ms
Blocking (serial relay-to-relay)	16–32 ms	~12 ms (same as permissive)	–	–
Blocking (Ethernet)	–	20–40 ms	–	4–20 ms
Current Differential	–	Not recommended	2.0–22.5 ms	2–4 ms

V. Conclusions

1. Channel speed, security, and dependability are critical to the selection of a transmission line protection scheme.
2. Multiple communications options are available to provide for secure, dependable, and affordable high-speed line protection.
3. The format and type of data being transmitted between line terminals should be selected to optimize the protection system and avoid unnecessary fault-clearing delays. Digital relay-to-relay communication can provide security and continuous channel monitoring without significantly increasing communications latency.
4. Licensed radio is suitable for line current differential relaying.
5. Proper evaluation of any communications-based protection scheme requires the use of high-accuracy clocks.

VI. References

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VII. Biographies

Ken Fodero is currently a research and development manager for the time and communications product lines at Schweitzer Engineering Laboratories, Inc. (SEL) in Pullman, Washington. Before coming to SEL, he was a product manager at Pulsar Technology for four years in Coral Springs, Florida. Prior to Pulsar Technology, Ken worked at RFL Electronics for 15 years, and his last position there was director of product planning.

Roy Moxley has a BSEE from the University of Colorado. He joined Schweitzer Engineering Laboratories, Inc. (SEL), in 2000 and serves as a senior product manager. Prior to joining SEL he was with General Electric Company as a relay application engineer, transmission and distribution (T&D) field application engineer, and T&D account manager. He is a registered professional engineer in the State of Pennsylvania and has authored numerous technical papers presented at national and international relay and automation conferences.

Héctor J. Altuve received his BSEE 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 of the Graduate Doctoral Program in the Mechanical and Electrical Engineering School at the Autonomous University of Nuevo León, Monterrey, Mexico, from 1993 to 2000. In 1999 and 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. (SEL), 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.

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