Applying Digital Current Differential Systems Over Leased Digital Service

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ABSTRACT

In the early 1980s, many utilities had current differential pilot wire systems installed on lower voltage lines. These relay systems were applied over either a privately owned communications cable (pilot wire) or a dedicated leased circuit from the local telephone company.

In the mid-to-late 1980s, the digital communications boom began and telephone companies started converting their infrastructure to fiber optics. New fiber-optic technologies like SONET and ATM allowed the telephone companies to take advantage of the high bandwidth fiber optics and allowed the greater flexibility of circuit allocation and routing.

As with all new technology, this new communications architecture was promoted as great for everybody except, of course, those applications designed to operate specifically over a point-to-point dedicated circuit. Many utilities that relied on these circuits for their pilot wire relaying were advised that these circuits would be obsolete and no longer available. The existing pilot wire relays would not operate over the new circuits creating a dilemma for the utilities that had relied on them.

Faced with this challenge, some utilities converted their pilot wire systems to fiber optic, some converted the protection schemes to distance-based pilot protection, and some held on to the old system as long as possible.

In the 1990s, current differential relay systems also evolved from their analog pilot wire roots to completely digital systems with modern high-speed digital communication interfaces. Now, once again, many utilities desired to apply these systems over leased digital communication circuits.

INTRODUCTION

Many utilities have tried leasing digital circuits from the local telephone provider for their current differential relaying. Some of these trial systems studied yielded indeterminate signal stability and other problems, which ultimately led engineers to decide that these systems were not viable for the application. The emphasis of this paper is that you can use leased digital circuits for current differential protection if the relay engineer, utility communications engineer, and the field engineer for the telephone company (Telco) establish circuit performance criteria and communications circuit protection guidelines early in the project, and if the circuit performance is verified prior to relying on 87L protection.

This paper outlines successes and failures of several digital current differential relay system applications over leased digital circuits.

Examples of the areas covered in this paper include:

- Interface equipment for leased communication channel—Channel Service Unit/Data Service Unit (CSU/DSU)
- Leased communications channel Digital Data Service (DDS)
- Copper connection guidelines from the substation to the Central Office (CO)
- Circuit provider fiber-optic system performance
- Service classes available/achievable (A, B, C)

San Diego Gas & Electric (SDG&E) started to use digital differential relaying over fiber optics on a 138 kV line with mixed overhead and underground sections in 1994. During this time several faults have occurred with high-speed clearing by the differential relaying using the principle of charge comparison.

SDG&E owned the fiber-optic cable that communicates via a T1 multiplexer in a dedicated point-to-point path as shown in Figure 1.

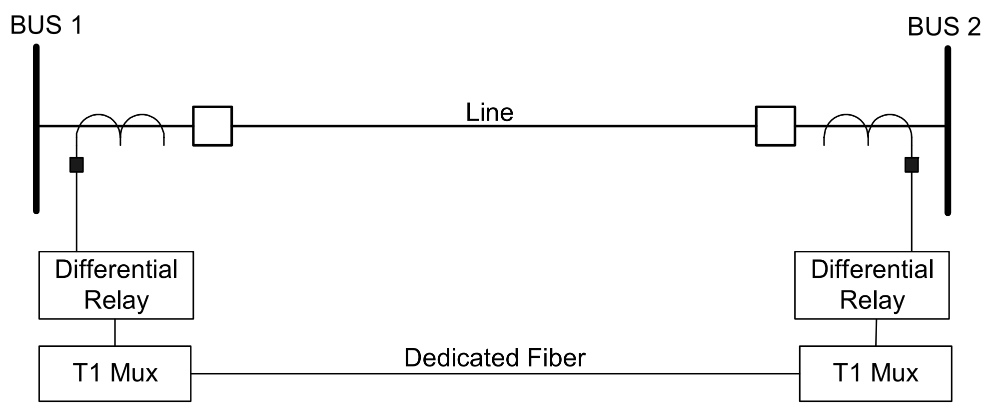

Figure 1 Dedicated Point-to-Point T1 Path

SDG&E also has numerous 69 kV lines which use electromechanical current differential relaying over copper pilot wire (PW) (see Figure 2 below). In 1998, the local telephone company notified SDG&E that a number of these communications circuits could no longer be maintained and an alternative method of protecting these lines had to be found.

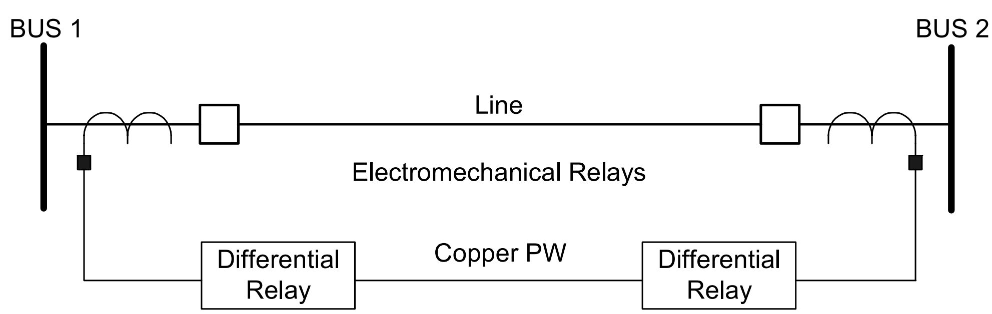

Figure 2 Electromechanical Differential Relaying

Current differential is one of the best relaying schemes developed and is preferred by SDG&E protection engineers. SDG&E could not afford to install fiber between all of the existing pilot wire relays due to the congestion of the metropolitan areas involved. Leased circuits were the most viable alternative. SDG&E had been using charge comparison differential relays over fiber optic, so the concept was to see if these relays could also be applied over dedicated 56 kb digital lines that were leased from the local telephone company.

Several meetings with the local telephone company were initiated to find out more information about the type of digital service available and the reliability of this service. We were assured that these digital circuits were very reliable and special tagging with warning notes would be placed on these circuits within their computer systems. The digital service was called Advance Digital Network (ADN) with a four-wire bipolar signal. A project was started to replace the electromechanical differential with the charge comparison differential relay.

A new device was introduced called a Channel Service Unit/Data Service Unit (CSU/DSU). This unit, required by the local telephone company, gives them isolation between their central station network and the utility system. Additionally, they could test the line from their office to the CSU/DSU by doing a loopback check. This loopback test, when activated, will momentarily disable the digital communication and takes the differential relay out of service, something that is not preferred by the utility.

Figure 3 shows a typical application of the major components for applying differential protection over a digital telephone network including the CSU/DSU.

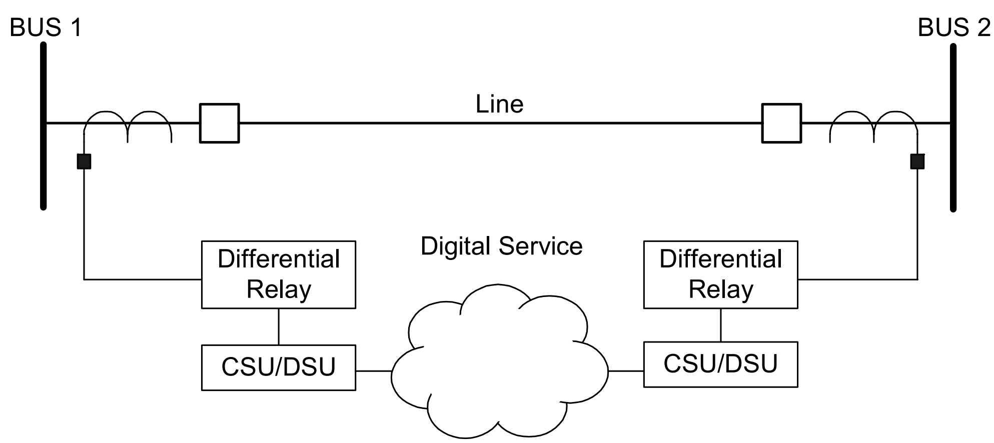

Figure 3 Typical Application of Major Components for Applying Differential Protection Over a Digital Telephone Network

From the initial installation to the present, we have had mixed experiences with the digital network. There are approximately sixteen lines protected over leased digital circuits and three lines protected over SDG&E fiber.

Some of the digital lines have experienced higher than desired noise. This degrades the continuous communication that takes place between the relays and causes momentary communication alarms. After several non-operations during internal faults, it was discovered that the communication between relays had stopped during the faults and then was re-established again. Obviously, this was an undesirable condition, and additional meetings with the Telco were scheduled to determine if these interruptions were logged into their system.

During these meetings we provided the times and events from the relay to the Telco to determine if a similar interruption was logged into their system. However, the response received was that the line was in-service during the times in question and that the Telco system did not show any records of failures.

We asked the question, "What could be done by the Telco to improve the quality and reliability of this digital service?" To our surprise, we found that three levels of services were available for digital lines called A, B, and C, whose definitions are listed below.

- Class A—Non-interruptible service performance (must function before, during, and after the power fault condition).
- Class B—Self-restoring interruptible service performance (must function before and after power fault condition).
- Class C—Interruptible service performance (can tolerate a station visit to restore service).

The above classes are also defined for audio-tone channels in the IEEE C37.93, Guide for Power Systems Protective Relay Applications Over Voice Grade Circuits. To our surprise, we found that the class of service provided to us was Class B. This type of service was not acceptable to SDG&E and we started a program to switch to Class A. All new project requests for digital telephone circuits are now issued as Class A.

What Is Class A Service?

For Class A service the Telco installed a mutual drainage reactor at the central office. This neutralized the longitudinal voltage on the cable pair so that gas tubes would not fire and communication was maintained over the digital circuit during a power system fault (see Figure 4 and Figure 5).

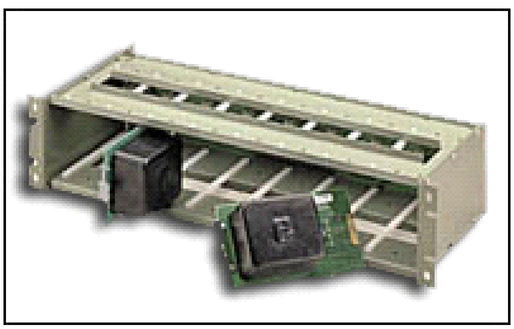

Figure 4 Drainage Reactor Assembly

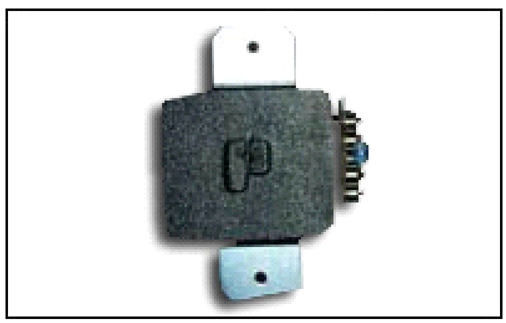

Figure 5 Drainage Reactor Unit

Starting in 2004 a new digital current differential relay using the principle of vector ratio of the remote-to-local current was tested for compatibility over a similar digital circuit. The first issue we encountered was that the CSU/DSU was designed for a V.35 communications circuit and the relay was only available with an EIA-422 interface. After an exhaustive search it was determined that there currently was no CSU/DSU device on the market that supported EIA-422 synchronous communications.

The relay manufacturer did an evaluation of the standards and determined that the electrical signal requirements between the two standards made the devices incompatible.

Figure 6 CSU/DSU

The relay vendor supplied a passive interface converter to interconnect the two devices with the opinion that it would not work. The converter adapter adapted the 36-pin Winchester connector (big rectangular plug) specified for V.35 to a DB-25 pin connector wired for EIA-530. This adapter (Figure 7) provided the cross connection required to interface the two devices without shifting the electrical signal levels (wires only). The system synchronized and started working.

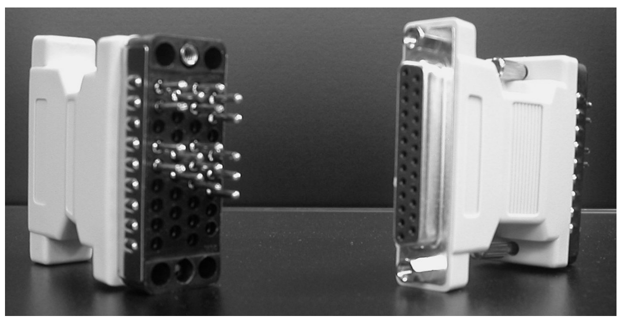

Figure 7 V.35 to EIA-530 Adapter

A test circuit between the SDG&E Engineering Lab and SDG&E's Sub Relay Shop was installed. The distance between the two locations was about two miles. This test system was monitored for several months. Only the communications were tested—no currents were applied to the relays during this test. Between November of 2003 and January of 2004, no errors were logged by the relay. This was not because the relay was not capable of detecting the errors. In fact, the test system was capable of detecting even single bit errors and recording them in a variety of SER formats.

The test system started reporting errors in February 2004. The circuit provider ran tests and concluded that the problem was not in their system. SDG&E's Telecom Department was suspicious of the CSU/DSU device.

A test was designed for the CSU/DSU. The SDG&E digital microwave system was very reliable, was monitored, and provided a circuit that was compatible with the CSU/DSU. The relays and CSU/DSUs used for the test were moved onto a guaranteed reliable circuit. If any errors were reported, data would exist to confirm the cause of the errors.

This system was monitored between March and August of 2004. The test system started to log errors within the first week. It turned out that because the test system was connected to the ac service in the microwave building, it was logging a failure every Tuesday at 9:00 p.m. when the communications emergency generator kicked in and again about thirty minutes later when it switched out.

This test demonstrated that the CSU/DSUs did operate reliably when applied over a reliable communications circuit.

During the microwave testing we were also working with the CSU/DSU manufacturer to understand why this system was working in the first place and if there was a possibility of any long-term issues. The CSU/DSU manufacturer was not concerned about the application but was willing to develop a version of the CSU/DSU with an EIA-422 interface. Prototype EIA-422 units were delivered to the relay manufacturer and to SDG&E for testing.

What Is Inside the Cloud?

Communication systems are typically shown as a cloud. This symbol is used to depict the Internet, telephone circuits, and even leased DDS circuits. A cloud is a simple way to show that there is a whole communications infrastructure out there about which we have no idea of what it is or how it works.

A test circuit was installed at the relay manufacturer's location (see Figure 8), consisting of:

- Two current differential relays with IEEE C37.94 interfaces
- Two IEEE C37.94 to EIA-42 converters
- Two CSU/DSUs
- One current test source
- Everything in between the above items

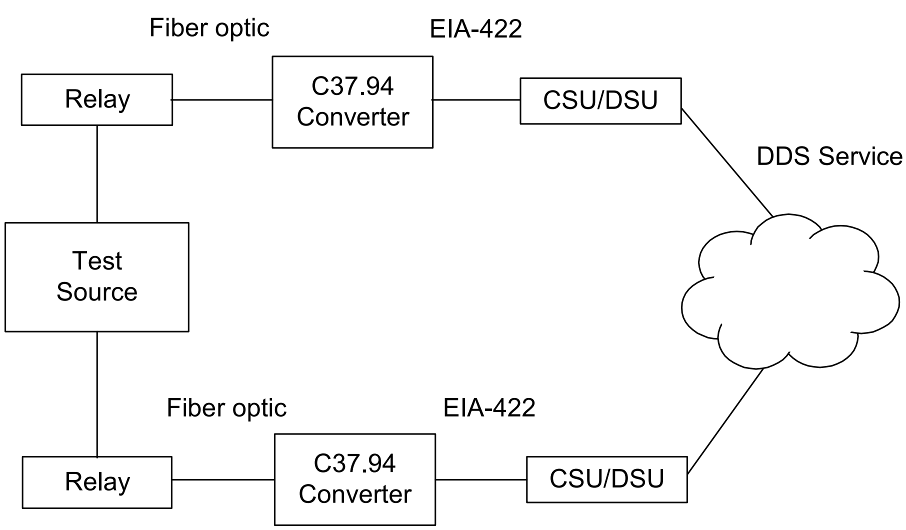

Figure 8 Test System at the Relay Manufacturer's Location

After a six-week wait, and a healthy installation cost, a pair of DDS circuits became available. Because the two test circuits were terminating at the same location (actually the same outlet), care was taken to ensure that the circuits actually left the premises.

The goals of the test were to work with the circuit provider to understand, or answer, the following questions:

- What was inside the cloud?
- What are the rules for these circuits?
- If SDG&E could get a Class A digital circuit, did this provider know what a Class A circuit is, and could they provide one?

The test system was connected to the newly installed circuits and with only three settings made on each CSU/DSU the system was in service. With communications established, the statistics available in the relays could now be used to monitor the channel.

The circuit ran error free for eight days. The one-way channel delay measured 15 ms on each relay. Because the relay uses the ping-pong method to determine one-way delay, another measurement method was required to determine if channel asymmetry was present.

Because both relays in the test system were connected to a common current source, a through-load condition could be simulated. With accurate control of the phase relationship of the through load, the measured Vector sum could be monitored to detect channel asymmetry. The initial installation metering indicated an alpha plane radius of one at an angle of 179 degrees. This indicated almost no channel asymmetry, because 180 degrees indicates perfect delay symmetry.

Nine days into the testing a storm rolled through the area and, coincidentally, from that time forward 5–6 packets were being dropped per hour. In addition to the errors, the channel delay changed to 15.2 ms and the angle changed to 159 degrees indicating a channel asymmetry of nearly 2 ms.

The CSU/DSU diagnostics were run and the test results indicated that the leased circuit was satisfactory. It was determined that if the clock edges were incorrectly set it was possible for the system to run on the edge until something changed. One of the clock edge settings on the IEEE C37.94 converter was changed, thus eliminating the errors. The errors could be turned on again by returning the edge setting to the as-installed positions. This is a common problem with EIA-422 circuits. When the clock edges are set incorrectly the system can operate normally until some minor change in the channel characteristics occurs.

The communications log was reset and the test resumed.

The clock edge settings did not seem to explain where the channel delay asymmetry was coming from, so the service provider was contacted to determine if something changed in their system.

The first order of business was to determine what the system looked like. Figure 9 depicts the circuit path between the wall sockets. This diagram was derived based on a telephone interview with the service provider's Technical Support person.

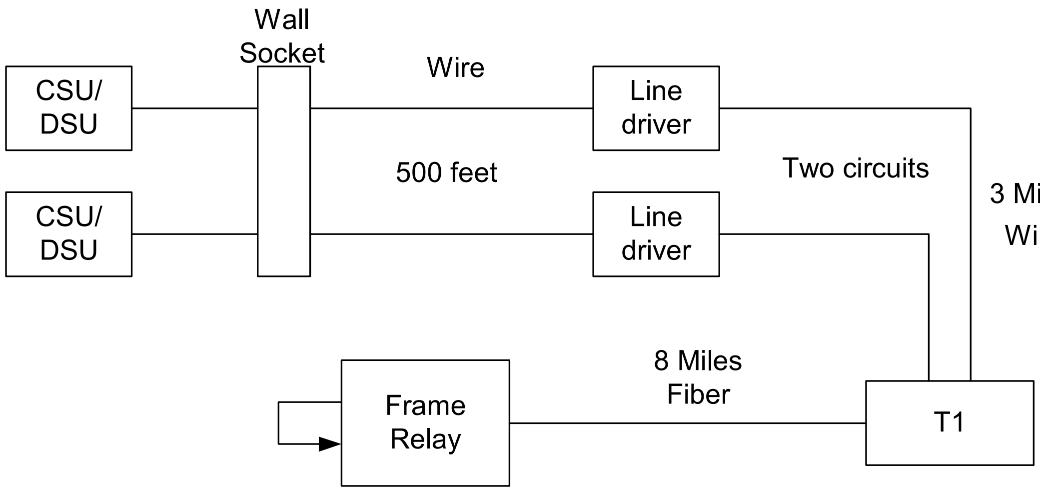

Figure 8 Telco Circuit Details

The service provider claimed there was nothing in the circuit that could introduce channel asymmetry. After sketching out the system, it appeared that only the frame relay could be a possible source. Through further telephone interviews with our technical contact, we were able to determine the make and model of all of the components except the frame relay, which was in a different office location and outside of the control of our local office. Figure 10 shows a picture of the DDS line driver. This device is line powered from the interfacing channel module in the T1 channel bank at the Telco facility.

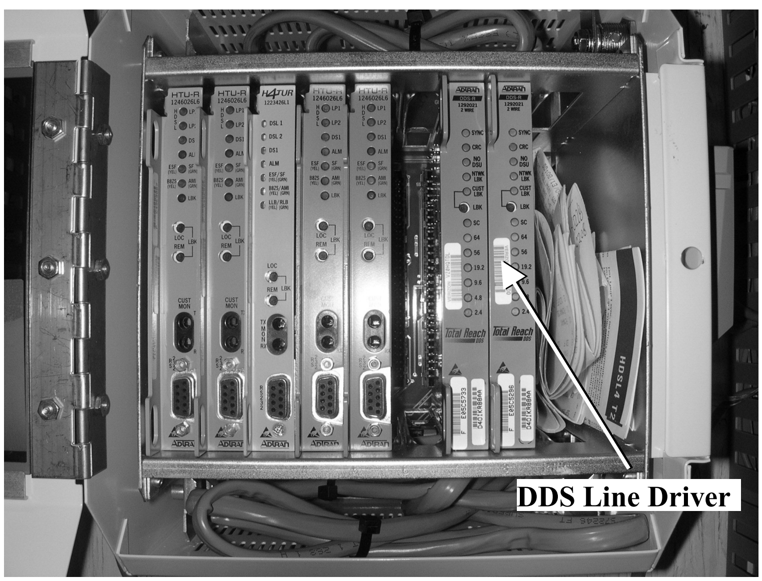

Figure 10 DDS Line Drivers Mounted in a Telco-Provided Equipment Shelf

The Digital Data Service (DDS) line driver is the interface between the CSU/DSU and the wires running through the city to the Telco T1 channel bank. We questioned if there was a standard that dictated how far the wire connection between the line driver and the central office could be. Our technical contact was not aware of a standard. When we looked up the data sheet for the line driver we found that they claimed 68,000 feet max (12 miles) under the correct wire size and power conditions, but 50,000 feet (9 miles) was specified as the normal operating conditions.

Since we had no indication that any of the devices in the system were capable of adding channel asymmetry, the decision was made to let the system run for a few days and monitor it for changes.

We noticed in the past that with current differential relay applications in other locations some multiplexer manufacturers implement separate “elastic buffers” on transmit and receive data. When these buffers are skewed in opposite directions the resultant delays appear as channel asymmetry.

After five days of monitoring, only one data error was logged, and the meter report indicated no change in the channel asymmetry. We decided that some interaction would be required to verify if data buffering was causing the asymmetry. Systematically, different components in the system were reset while monitoring for changes in the asymmetry.

The test plan was simple. Starting from the ends of the communication lines, each piece of equipment was reset until something changed starting with the relays, then the IEEE C37.94 interface converters, and then the CSU/DSUs. When the CSU/DSUs were re-initialized, a change was noted in the channel asymmetry. Entering the program mode and returning to the operating mode or simply disconnecting the RJ-45 connections to the wall caused the initialization. The asymmetry varied from 1 to 25 degrees or almost 0 to just over 1 millisecond of asymmetry.

We needed to determine if the source was the CSU/DSU or the line driver. We had a good technical contact at the CSU/DSU manufacturer, so we started there. We learned that the DSU portion connects to the relay and the CSU part connects to the leased line. While they were sure that there was no buffering in the DSU portion, they needed to sift through the CSU code to verify that this portion of the device was not capable of adding this asymmetry.

We determined that a test with the CSU/DSUs running back-to-back with only these devices in the circuit might help determine the delay source more quickly. Figure 11 shows the test connections for this test, including the null modem cable.

With the CSU/DSUs connected back-to-back we were also able to measure the total channel delay introduced by these devices. The one-way ping-pong test indicated 4.2 milliseconds. Our one-way delay in the complete circuit was 15.2 milliseconds. This means that 11 milliseconds were introduced by the leased circuit topology.

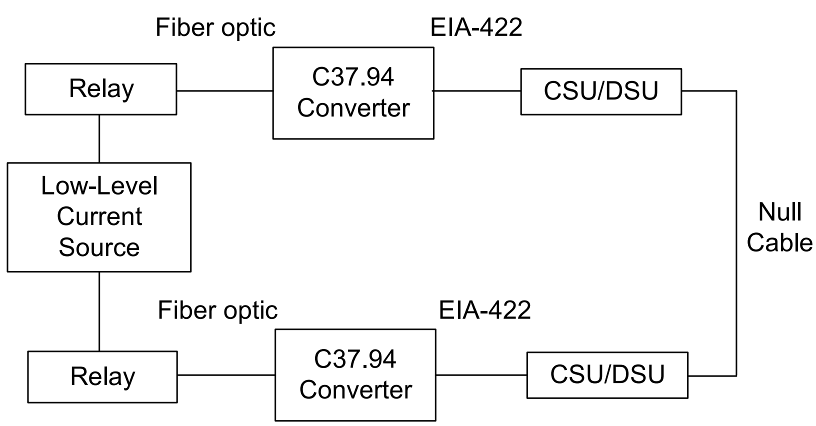

Figure 11 Looped Back Test Circuit

After several CSU/DSU initializations, we were able to change the channel asymmetry from 0.25 to 1 millisecond (6 to 23 degrees). We then cycled the power to the CSU/DSU, resulting in similar results. One disappointing test result was that we could not get the system to re-initialize without channel asymmetry, which was the original system state when the test was started.

During this testing, we observed that the system seemed to be taking a long time to come back into service during re-initialization. We ran several tests and found that the CSU/DSU would consistently take 17 seconds to recover from channel interruption. Interestingly, when the power was interrupted to the CSU/DSU (cold boot) it still recovered in 17 seconds. While not extremely long, 17 seconds is longer than the 5 seconds expected for a relay system to recover from a power interruption. We put the system back in service over the leased circuit. The re-initialization test was repeated. To our surprise, the system consistently recovered in 7 seconds. The only setting difference was when the CSU/DSUs were connected back-to-back. One of them had to be set for internal timing. When applied on the leased line, both were set for external timing mode.

We informed the CSU/DSU manufacturer of our test results for comparison to their analysis of the internal code. In addition, we expressed our concern about not being able to reset the channel asymmetry back to zero. The CSU/DSU manufacturer suggested re-initializing without active data. We powered down the CSU/DSUs, disconnected the relays, reapplied the power, and then re-connected the relays. The result still included 10 degrees of channel asymmetry. Next, we performed the same test with the addition of disconnecting the leased circuit. The start-up sequence for this test was to power the CSU/DSUs, wait until they were settled, plug in the leased circuits, and then the relays.

This sequence successfully reset the channel asymmetry to zero. Additionally, the ping-pong channel delay measurement returned to 14 milliseconds. This test also confirmed that the buffering was being introduced in the CSU portion of the device. This test ran for several days with no errors or changes in channel delays.

Now that we obtained good data on the performance of this circuit, we decided to change the size of the cloud.

For another nominal fee, our circuit provider worked out a way to add more equipment and distance to our test circuit. The circuit that was terminated in the frame relay would now be routed through the Telco’s long distance SONET system. Approximately 90 miles (as the bits fly) was added to the test circuit and then looped back. Figure 12 depicts the new channel topology.

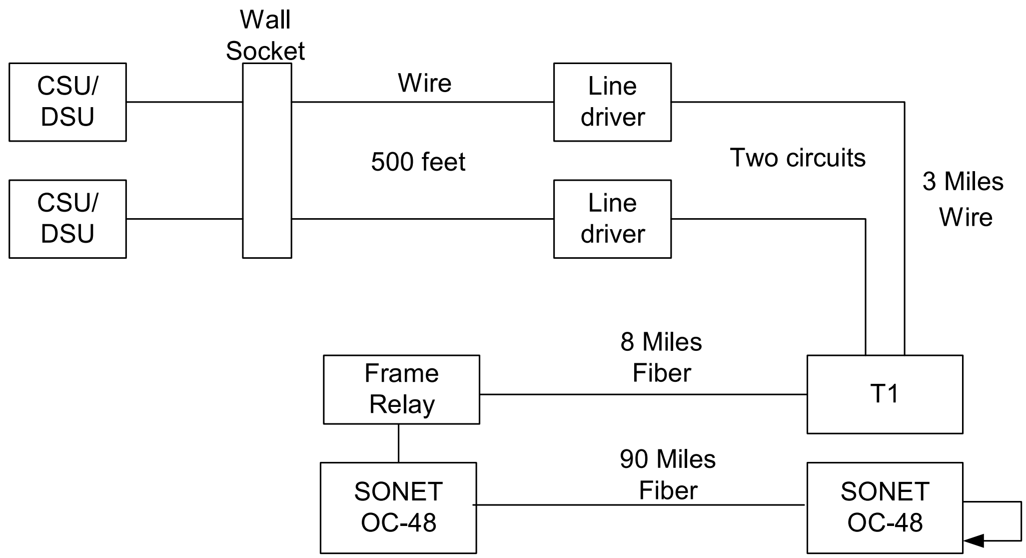

Figure 12 Revised Telco Circuit

The Telco let us choose the method to cut in the new circuit. They could disable our current circuit and re-enable it when they were done or they could just cut it in with no regard to how this effected the data. We asked for the no regard, no regret method as this would represent the worst case. To ensure the worst-case scenario all around we left load current on and disabled channel addressing in the relay. This would ensure that if the signal were looped back the relay would record it in the form of a misoperation.

The circuit cut-in took about a half hour with the relay communications mostly disabled. No misoperations occurred and the CSU/DSU provided information as to what the Telco was up to (loop-backs and testing). When the cut-in was completed the relay communication did not recover. We suspected that one of the CSU/DSUs might be hung up. The suspect CSU/DSU was reinitialized from the front panel and communications was restored. The additional 90 miles added only 1 millisecond of channel delay and no additional channel asymmetry. This circuit ran for several weeks and only recorded a single channel error within the first few hours of the conversion.

Communications Circuit Protection

The more things change, the more they stay the same. The original pilot wire systems relied on neutralizing reactors, mutual drainage reactors, and gas tube devices to protect the equipment and wires from hazardous induced voltages. Figure 13 depicts a typical pilot wire relay application.

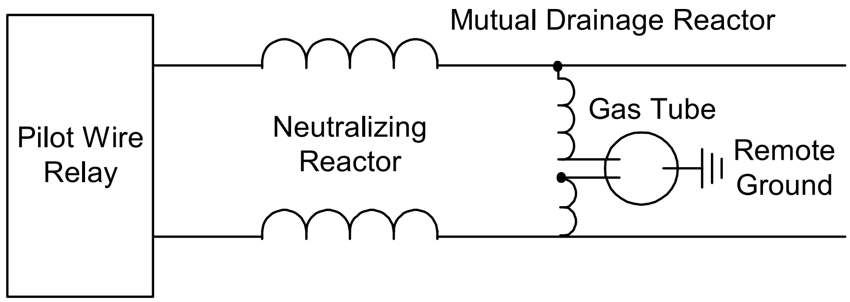

Figure 13 Typical Pilot Wire Protection

The problem of Ground Potential Rise (GPR) does not disappear for digital communications systems applied over leased facilities. This condition exists for any metallic communications circuit that continues beyond the substation ground mat. When a Class A circuit is requested you are leaving it up to the service provider to determine the type of protection equipment that will be installed. There seems to be inconsistencies across service providers as to the types of protection devices that are placed on the circuit. There are three basic types of protection: isolation, lightning, and noise reduction.

A discussion with a manufacturer of these protection devices was extremely enlightening. When the current differential application was described and the desired performance requirements were discussed, they were able to recommend the types of protection devices required. They also stated that all of these devices are approved for use by all of the service providers, and they had to be installed by the service provider. The only way to be sure that these devices would be installed was to specify them when ordering the circuit.

Figure 14 shows the portion of the leased circuit located at the substation termination point. The ISDN Isolation Device provides 65 kV peak surge isolation and 20 kV rms continuous isolation between the CSU/DSU and the line. The Induction Neutralizing Transformer (INT) treats noise problems caused by excessive induced ac voltages or currents or by switching surges on nearby power lines or lightning.

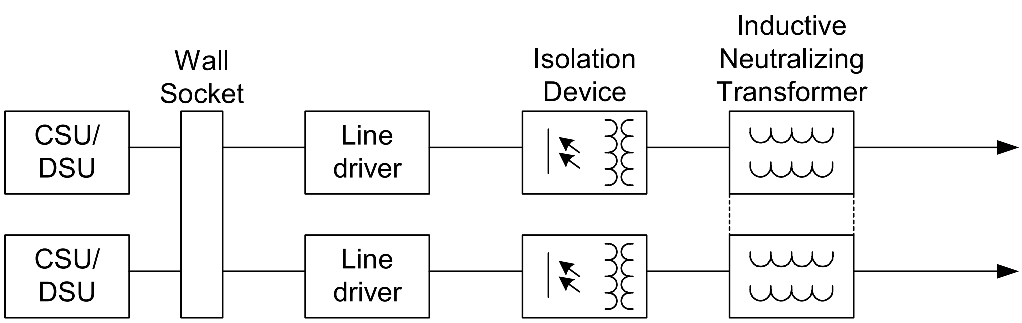

Figure 14 Protection Device Circuit Location

The one form of protection that typically does not have to be specified is lightning protection. If the circuit is in an area that has a high incidence of lightning, the service provider will include this protection. For example, in Southern California all circuits east of I-5 include lightning protection circuits. On circuits west of I-5, lightning protection will be installed only upon request.

Another approach to mitigate the effects of GPR would be to locate the line interface outside of the area of influence. This application will not always be feasible due to real estate or fiber constraints. Figure 15 depicts this topology. It should be noted that this equipment configuration is almost identical to our test system. The main difference is the distance between the IEEE C37.94 converter and the relay, a few feet versus a few kilometers. Unlike our test circuit, the Inductive Neutralizing Transformer (INT) is included. The INT is used for power system and lightning noise reduction on the circuit.

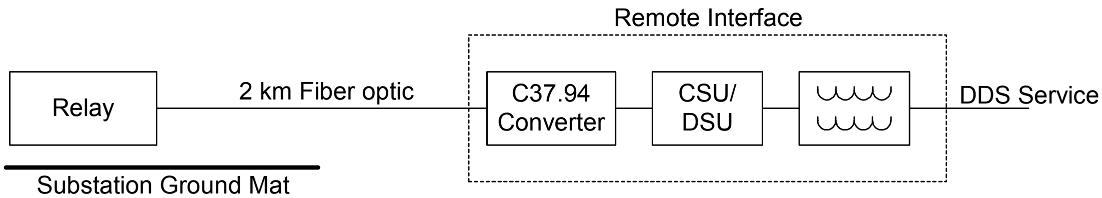

Figure 15 Using Fiber Optics to Isolate the Communications Circuit

Other issues that would need to be resolved for this implementation include mounting and powering. However, if you have a location for this remote interface the rest should be easy.

Field Testing at SDG&E

Installed using fiber optic for the primary channel, and a leased digital channel for backup communication, this new relay is also operating in parallel with the Charge Comparison Relay and has given SDG&E a way to compare the speed of operation with redundant differential protection (see Figure 16).

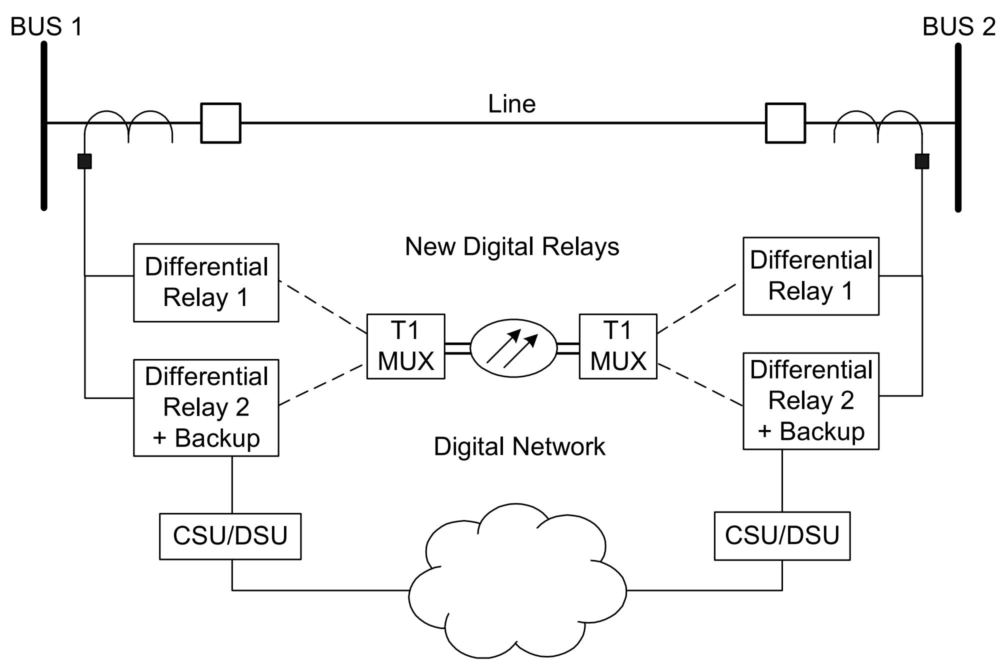

Figure 16 Field Test System

The above application with multiple communication paths will be used whenever sensitive customers are connected to one of the buses and the line faults need to be cleared quickly.

One such application is shown in Figure 17, Figure 18, and Figure 19.

Figure 17 SDG&E Differential Relay 1

Figure 18 SDG&E Differential Relay 2 Front View

Figure 19 SDG&E Differential Relay 2 Rear View

CLASS A CIRCUIT RESULTS

Unfortunately, due to Telco lead times, the Class A test circuit was not installed at the time this paper was published. Based on this experience, planning and scheduling needs to be performed in close cooperation with the Telco. For information on the future results of this testing contact the authors.

CONCLUSIONS

- Equipment exists today to implement digital current differential relaying over leased telephone services.
- When planning or designing a digital current differential relay system that will be applied over a leased circuit, involve your telecommunications department and local service provider early, and specify the type of protection devices desired.
- If you have one of these installations and are having less-than-desirable performance, consider adding the protection devices discussed in this paper. Additionally, verify that the provider has not inadvertently added load coils to the circuit.
- While the test results to date have not been as conclusive as desired, they have provided the insight required for understanding what is inside the cloud and what performance levels are achievable.

REFERENCES

[1] N. P. Albrecht, W. C. Fleck, K. J. Fodero, and R. J. Ince, "Charge Comparison Protection of Transmission Lines—Communication Concepts," Paper 92 WM 210-5 PWRD, presented at the IEEE/PES 1992 Winter Meeting, New York, New York, January 30, 1992.

[2] L. J. Ernst, W. C. Fleck, W. L. Hinman, "A New Digital Transmission Line Current Differential Relay System—Concepts and Test Results," presented at the Western Protective Relay Conference, Spokane, Washington, October 20–22, 1992.

[3] Application Guide AC Pilot Wire Relaying System SPD and SPA Relays, General Electric GET-6462A.

[4] IEEE C37.94 IEEE Std C37.94-2002, IEEE Standard for N times 64 kilobit per second Optical Fiber Interfaces between Teleprotection and Multiplexer Equipment.

[5] IEEE C37.93 IEEE Std C37.93-2004, Guide for Power System Protective Relay Applications of Audio Tones Over Voice Grade Channels.

BIOGRAPHIES

Ken Fodero is a Product Manager for the Schweitzer Engineering Laboratories, Inc., Pullman, Washington Protection Communications Engineering Division. Before coming to work at SEL he was a product manager at Pulsar Technology for four years in Coral Springs, Florida. Prior to Pulsar, Ken worked at RFL Electronics for 15 years, his last position there was Director of Product Planning. He has also worked for Westinghouse Electric, now ABB, as a Relay System Technician. Fodero is the current chairman of the Communications Subcommittee for IEEE PSRC. He graduated from RETS in New Jersey as an Electronic Technologist.

Girolamo (Gerry) Rosselli received his B.S. degree in Electrical Engineering from the University of Illinois in 1978. Upon graduation he was hired by Commonwealth Edison Company where he worked on the planning side of the 12 kV overhead and underground distribution systems, as well as electrical planning for high-rise buildings in central Chicago.

He joined San Diego Gas & Electric as a Substation Engineer in 1981. In 1985, he joined the System Protection group, where he is now a Principal Relay and Protection Engineer. One of his major accomplishments was the coordination of the transmission and sub transmission systems of the Island of Guam. He has written an article on 500 kV Series Capacitors for T&D Magazine (1987). He was one of the speakers at the 30th Western Protective Relay Conference held in Spokane, Washington, and also the 57th Annual Protective Relaying Conference at Georgia Tech, in Atlanta, Georgia. The presentation, and published paper, was titled Transformer Test to Calculate Z_0 For Interconnected Winding Transformers. He also presented the paper to the IEEE Transformer Committee and it has been accepted for implementation into the IEEE Standards. He is a member and former Chairman of IEEE/PES Society San Diego Chapter, and a Registered Professional Engineer in the State of California.

Previously presented at the 2005 Texas A&M
Conference for Protective Relay Engineers.

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