Resolving Digital Line Current Differential Relay Security and Dependability Problems: A Case History

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INTRODUCTION

Interfacing teleprotection equipment and digital multiplexers for the purpose of line current differential protection as well as transfer trip functionality has historically posed challenges for both protection and communications engineers. This paper documents a case history of a problematic three-terminal current differential protection scheme utilizing transfer trips to remotely clear bank faults.

The scheme was originally put into service in July 1996 over a SONET OC-1 communications infrastructure. Excessive bit error rates were immediately prevalent in the relay system as a result of the utilization of an unproven communications interface device intended to provide the optical/V.35 electrical signal conversion required between the differential relay and the SONET multiplexing equipment. The bit error rates were high enough to cause the differential relay to declare its communications failed, ultimately disabling the line protection on a regular basis. Various attempts to resolve the interface/bit error/protection scheme failure issues were unsuccessful.

After the protection scheme began to misoperate and unnecessarily trip industrial customers for disturbances on the SONET system, Tacoma Power decided to investigate alternative technologies for product replacement.

This paper covers Tacoma Power's research, evaluation, and installation of a new line current differential relay utilizing a new multiplexer channel interface unit. This new system utilizes the IEEE C37.94 Standard for Optical Fiber Interfaces Between Teleprotection and Multiplexer Equipment [1]. We include an explanation of the added security and dependability gained with a new method of current differential relaying, and discuss the details of the IEEE C37.94 standard and the benefits it affords. We conclude with a summary of the protection and communications system performance to date.

BACKGROUND

Tacoma Power's service territory covers the City of Tacoma as well as various outlying towns, cities, and regions of Pierce County, including a major industrial area commonly referred to as the Tideflats. The Tideflats portion of the Tacoma Power system includes two three-terminal, 110 kV transmission lines: Pioneer–Simpson–Alexander and Pioneer–Tideflats–Pennwalt. These three-terminal lines do not encompass any tapped load and have historically been protected by

current-differential relays with direct transfer-tripping capability for clearing transformer bank faults. This is Tacoma Power's preferred relaying principle for its transmission lines that are less than 10 miles long. The combination of electromechanical relays and pilot wire functioned well on these lines from the mid 1960s to the early 1990s, until frequent ground potential rise (GPR) misoperations due to insulation breakdown of the aged pilot wire forced Tacoma Power to reconsider the protection scheme.
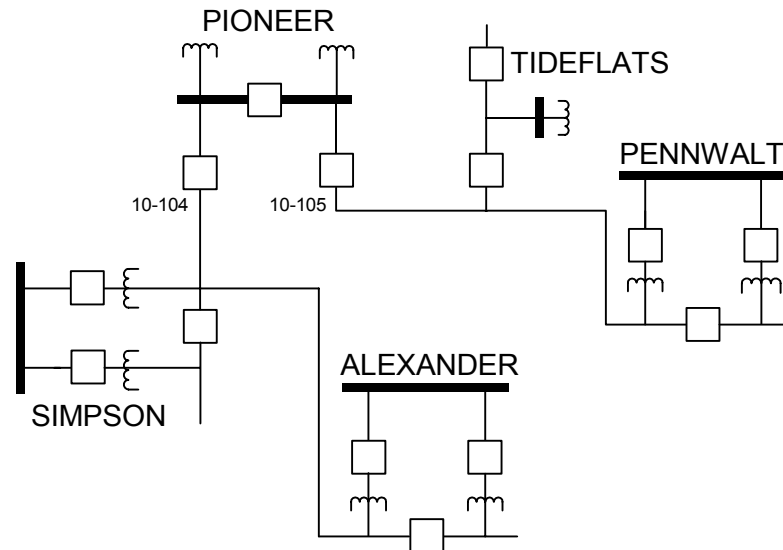
Figure 1   Tacoma Power 110 kV Tideflats Region

The Tacoma Power communications staff decided to replace the old metallic cable with a multiplexed fiber-optic Synchronous Optical Network (SONET) system operating at 51.84 Mbps (OC-1). The network was later upgraded to 155.52 Mbps (OC-3). This would not only meet immediate teleprotection needs, but would also serve well in the future for a variety of data and telecommunications purposes. As a result, it became evident that the pilot-wire replacement scheme had to not only be configurable for three-terminal lines, but also be capable of interconnection with a SONET OC-1 ring—two requirements that were difficult to satisfy in 1995. After evaluation of available technology, the utility found only one relay capable of meeting both criteria. This relay and the necessary interfacing equipment were purchased and installed on both three-terminal lines in June 1997.

Relay-to-Multiplexer Interface Experienced Many Data Errors

Multiple communications alarms were encountered immediately after installation. The relays reported a high Bit Error Rate (BER), many Cyclic Redundancy Checking (CRC) errors, an overall abundance of communications alarms, and a frequent, complete loss of differential protection.

Tacoma Power logged the frequency of communications channel failures and protection scheme failures to help quantify the various attempts to improve the discrepancies. The SONET cards were reconfigured from synchronous to asynchronous mode. This cut the errors in half, but did not eliminate them. The remaining data error problems and alarms were tolerated as a nuisance until the spring of 2001, when the protection system began to misoperate and trip critical industrial customers.

Three Misoperations Lead To Scheme Replacement

On three occasions, April 14, May 31, and June 4, 2001, after having been in service for over four years, the 87L relays tripped various 110 kV line breakers due to path switching on the loop-protected SONET system. Due to the sensitive nature of the industrial loads in the Tideflats region, the 87L scheme was removed from service while an investigation was launched to examine the cause of the misoperations and to recommend an enhanced three-terminal line differential protection scheme. A short summary of the SONET conditions and the incorrect 87L relay responses to these conditions follows.

April 14, 2001

On Saturday, April 14, 2001, at approximately 3:53 a.m., System Operations determined that the RTU at Lincoln Substation (a node on the Tideflats SONET ring) had lost communications. Upon arrival at Lincoln Substation, the communications technician noted the station battery charger was nonfunctional and that fuses to the RTU and SONET rack had blown. A wire crew arrived at Lincoln Substation shortly thereafter, restored the station batteries, and installed a temporary battery charger. The communications technician then repowered the SCADA and SONET equipment. After the system management program was used to verify the integrity of the SONET system, the substation was turned over to Dispatch for control.

Consequently, at 6:30 a.m., the Pioneer Substation PCB 10-104 circuit breaker was found open with current differential targets, indicating this relay had tripped locally on current differential elements and had also sent trips to the corresponding remote breakers at Simpson and Alexander Substations.

May 31, 2001

On May 31, 2001, at approximately 2:30 a.m., the primary optical loop between the ECC building and Pearl Substation was opened during a scheduled fiber outage. The SONET system responded appropriately to the fiber disruption and switched its communications direction. Within a few minutes, the system destabilized due to a misconfiguration of an external sync-clock module. Without a declared system clock, each node attempted to assume and hold timing. The entire system behaved erratically and unreferenced 1s and 0s were transported between nodes. This particular source of SONET instability will not be a problem in the future as the external sync-clock module is now properly configured, directing the SONET network to no longer search for a second source of external timing. In the future, if the single external clock for the SONET network is lost, the system will default to internal timing.

As a consequence of the SONET instability, at approximately 3:00 a.m., both 87L relays at the Pioneer Substation tripped both 110 kV breakers (PCB 10-104 and PCB 10-105) and corresponding remote end breakers at Alexander, Simpson, Pennwalt, and Tideflats Substations. The fault records of the 87L relays indicate both relays at Pioneer Substation tripped via current differential elements, which initiated differential intertrips that opened breakers to all remote substations. The result of this misoperation created a total outage to Pioneer.

June 4, 2001

On June 4, 2001, at approximately 3:36 a.m., a dc failure occurred at Browns Point Substation, a node on the Tideflats OC-3 ring. A communications technician arrived at Browns Point and found that power was lost to the SONET rack due to station batteries dropping below 24 V on a

48 V system. After the dc problem was corrected, the SONET equipment was powered-up and proceeded through a seemingly normal startup procedure. Upon further investigation, it was determined that the correct startup procedure had not been followed in bringing a dead node into operation on a live SONET network. This error caused temporary instabilities on the SONET system.

Consequently, at approximately 8:49 a.m., the 87L relay at Pioneer Substation tripped the local PCB 10-104 breaker and the corresponding remote breakers at Pennwalt and Tideflats Substations.

Replacement Objectives

Tacoma Power began to search for a new three-terminal current differential scheme that would meet the following objectives:

- Utilize the existing fiber-optic multiplexed communications infrastructure (SONET).
- Avoid integration of the historically problematic optoelectric media converter required by the previous scheme for interfacing the teleprotection equipment with the relay.
- Incorporate a plug-and-play relay to multiplexer interface that offered few or no data errors, traditionally caused by:
  - Incorrect wiring of the clock polarity—if the clock polarity is reversed, the data may appear correct but the jitter margin disappears. These connections are often poorly documented
  - Clock-phase issues that are also often poorly documented
  - Susceptibility to the noisy electrical environment of substations
  - GPR issues
- Provide a secure and dependable relay system that properly adapts to the changing system conditions and propagation time delays inherent to a switched optical network.
- Provide an overall cost-effective, long-term protection solution.

To ensure the replacement scheme did not suffer the same problems as the original equipment, we took the following approach:

- Understand why the original scheme misoperated and why the continuous data errors occurred.
- Seek equipment immune to the conditions that caused the misoperations.
- Test the new equipment in realistic scenarios to ensure it would not also misoperate or be subject to continuous data errors.

RELAY MISOPERATION ANALYSIS

Each of the 87L inadvertent trips were associated with SONET switching or SONET instabilities. It was evident during the outage investigation that none of the SONET outages triggered any communications alarms in the line differential relays. The inability of the 87L relays to properly disable the differential elements upon loss of a reliable communications infrastructure ultimately allowed the misoperations to occur.

The relay manufacturer attributed the misoperations to a difference in transmit and receive delays through the SONET system during the switching or instability episodes described above.

According to the manufacturer, differences as small as 1 ms are capable of producing a misoperation.

CHANNEL DELAY COMPENSATION ON A SONET SYSTEM

Normal Operation Gives Equal Transmit and Receive Delays

In the top of Figure 2, Relay A and Relay B exchange current differential information over an example 5-node SONET ring. The SONET node at Site #1 receives data from Relay A, and transmits it in both clockwise and counter-clockwise directions around the ring to Site #2, where Relay B is located. The node at Site #2 is configured to route the data received on the L, or "Left" port to Relay B. Site #2 effectively ignores the data received on the R, or "Right" port. This establishes the shortest possible connection from Relay A to Relay B.

Likewise, the SONET node at Site #2 sends data received from Relay B in both directions around the ring to Site #1. The SONET node at Site #1 is configured to route data received on the R port to Relay A.
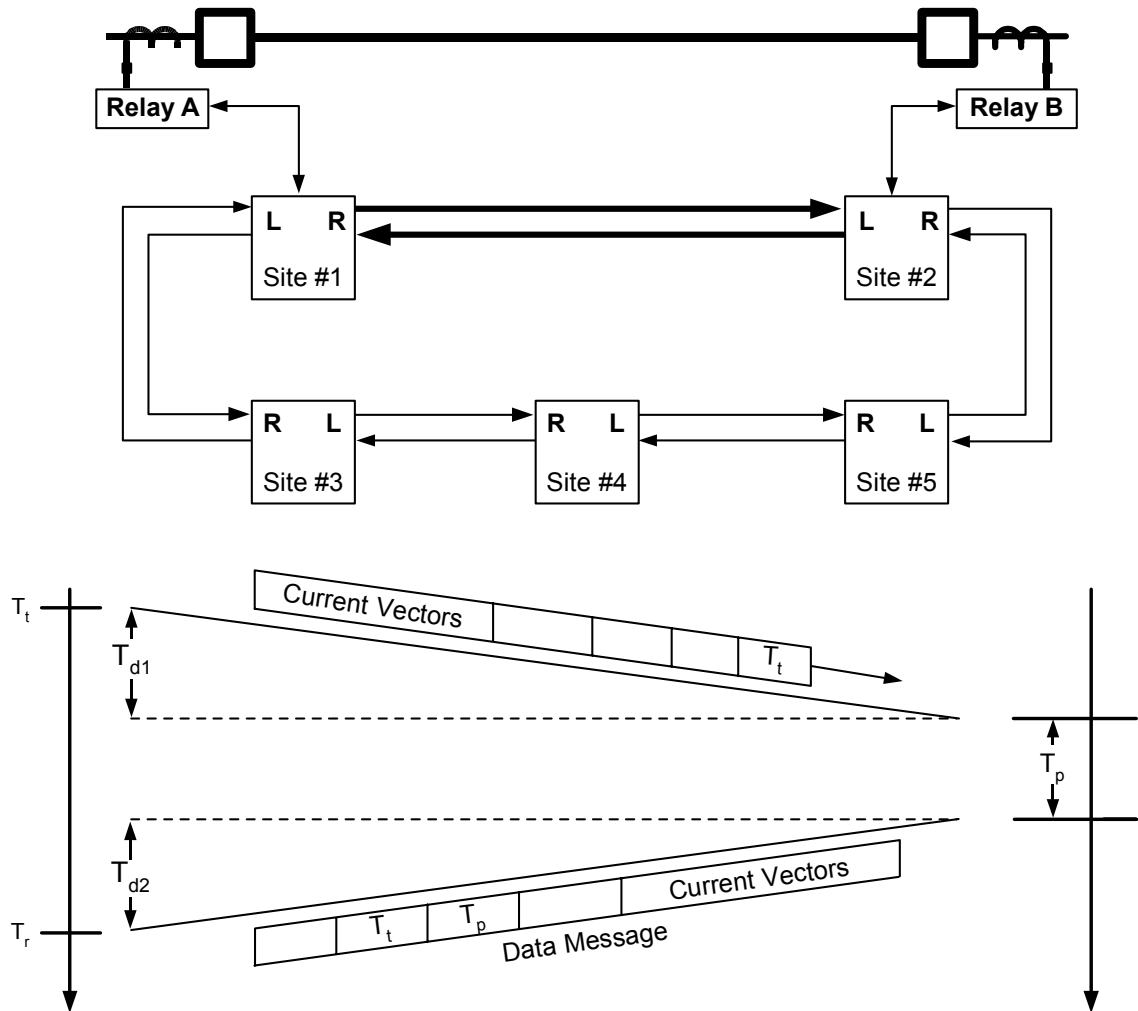
Figure 2 Normal SONET Operation Has Equal Transmit and Receive Delays

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Data sent from Relay B to Relay A uses the same path, and passes through the same equipment, as data passed from Relay A to Relay B. This causes the transmission delay from Relay A to Relay B to be very nearly equal to the delay from Relay B to Relay A. The relays use this fact to compensate for the transmission delays, as shown at the bottom of Figure 2.

To compensate for the transmission delay from Relay B to Relay A, Relay A must know the delay from Relay B to Relay A. When the transmission delays are equal, $T_{d1} = T_{d2,}$ as shown in the bottom of Figure 2. In that case, Relay A can simply measure the round-trip time from Relay A to Relay B and back to Relay A ($T_r - T_t$), subtract any processing delay at Relay B (T_p), and divide by two, as shown in Equation 1.

$$T_d = \tfrac{1}{2}(T_r - T_t - T_p) \qquad\qquad \text{Equation 1}$$

Where:

T_d is the calculated one-way transmission delay.
T_t is time when the tagged message departed Relay A bound for Relay B.
T_r is the time when the tagged message returned to Relay A.
T_p is the time Relay B took to process the message before returning it to Relay A.

This is called the ping pong method, and it works very well when the transmission delays are equal, i.e., when $T_{d1} = T_{d2}$. From inspection of Figure 2,

$$T_r - T_t = T_{d1} + T_{d2} + T_p \qquad\qquad \text{Equation 2}$$

Substituting Equation 2 into Equation 1 gives,

$$T_d = \tfrac{1}{2}(T_{d1} + T_{d2}) \qquad\qquad \text{Equation 3}$$

When $T_{d1} = T_{d2}$, then the calculated $T_d = T_{d1} = T_{d2}$. In other words, when the transmission delays are equal in both directions, both relays can accurately calculate the one-way transmission delay, and compensate for it.

Fiber Cut Forces Unequal Transmit and Receive Delays

In Figure 3, the fiber carrying data from Site #2 to Site #1 is cut. The SONET node at Site #1 quickly detects the cut and reconfigures to route data received on the L port to Relay A. Data from Relay B to Relay A now flows the long way around the ring, passing through all five SONET nodes. Data from Relay A to Relay B still passes through only two SONET nodes. This causes the transmission delay from Relay A to Relay B to be shorter than the transmission delay from Relay B to Relay A, as shown in the bottom of Figure 3. Now T_{d2} is larger than T_{d1}, so $T_{d1} \neq T_{d2} \neq T_d$ by Equation 3. The T_d calculated by each relay is not equal to either T_{d1} or T_{d2}. Each relay uses T_d to time align the received current samples with the local samples, but T_d is in error. Under steady state conditions (i.e., load current) the error causes an apparent phase shift between the local and remote currents in each relay. The phase shift operates on the load current to produce a false difference current, which can cause some current differential relays to misoperate.
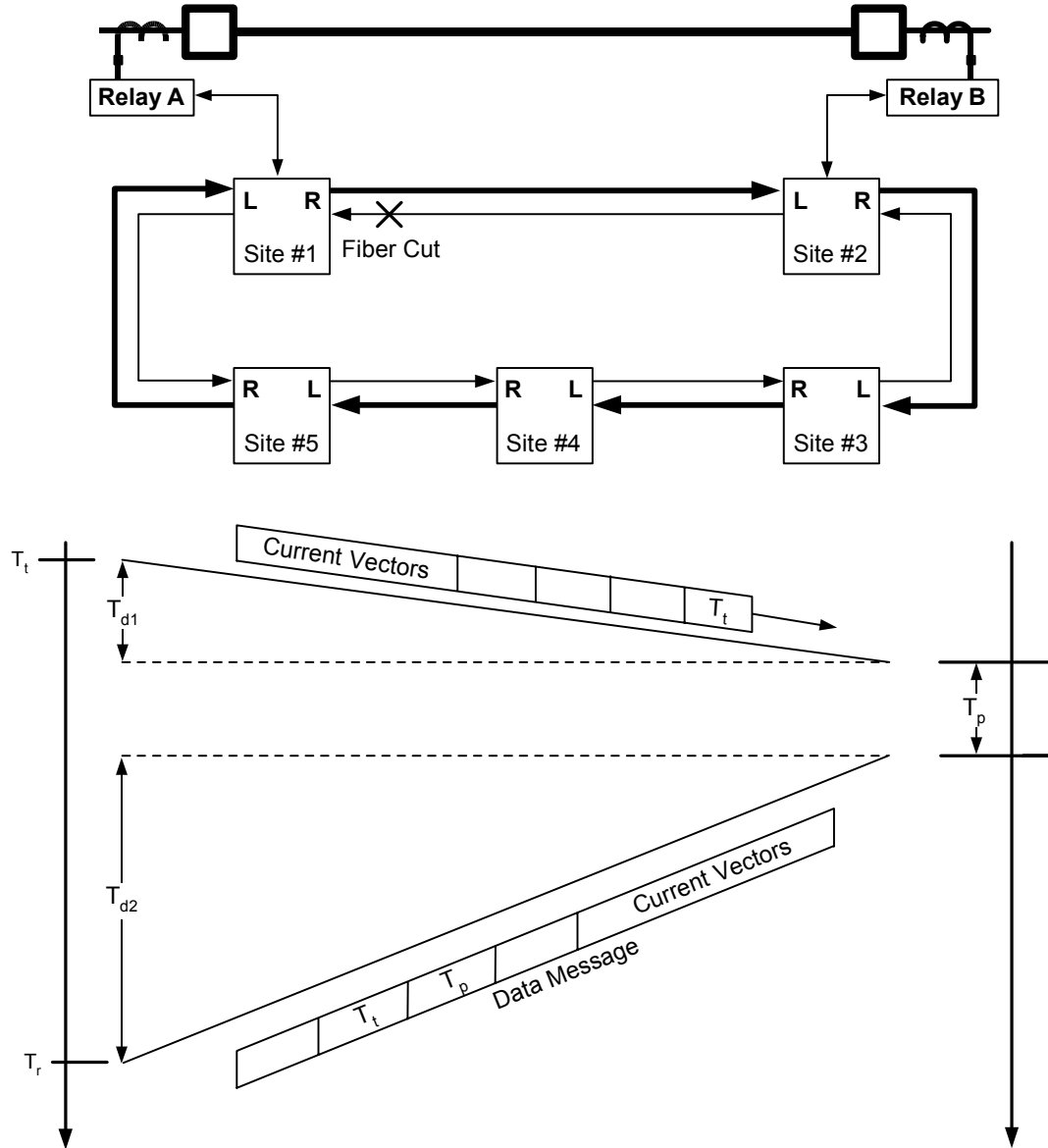
Figure 3   Fiber Cut Forces Larger Delay from Relay B to Relay A

To quantify the effect, assume the fiber cut causes the delay from Relay A to Relay B to increase from 1 ms to 4 ms. Substituting T_{d1} = 1 ms and T_{d2} = 4 ms into Equation 3 gives

$$T_d = \tfrac{1}{2}(1 \text{ ms} + 4 \text{ ms}) = 2.5 \text{ ms}$$

T_d is larger than T_{d1} by 1.5 ms, and smaller than T_{d2} by 1.5 ms. Relay A will process the local and remote currents assuming they are misaligned by 2.5 ms, when in fact they are misaligned by 4 ms. Likewise, Relay B will process the local and remote currents assuming they are misaligned by 2.5 ms, when in fact they are misaligned by 1 ms. Both relays will experience a 1.5 ms current misalignment, which will cause the following phase shift at 60 Hz:

$$1.5 \text{ms} \cdot \frac{360°}{16.7 \text{ms}} = 32.3°$$

In reality, fibers are typically routed in pairs. A mishap that cuts a fiber probably cuts both fibers in the pair. The unequal transmit and receive delays shown in the bottom of Figure 3 still exist momentarily when both fibers are cut. The time scales of interest in Figure 3 are on the order of 100 μs. The time between cutting one fiber, and breaking or cutting the other fiber in a pair can easily exceed 100 ms. The delay gives the SONET system time to reroute, creating a temporary difference in transmit and receive delays as discussed previously.

Even if both fibers are lost at exactly the same instant, it is still possible to get an effective difference in transmit and receive delays. When both fibers are interrupted simultaneously, Site #1 senses the loss of incoming data from Site #2. Site #1 routes data received on port L to Relay A. That data was constructed as a response to messages received by Relay B over the Site #1 to Site #2 connection before the fiber cut. Thus, the first few messages received by Relay A after the fiber cut essentially experience a different transmit and receive delay. A similar argument exists for Relay B. Both relays experience a momentary difference in transmit and receive delays even if both fibers between Site #1 and Site #2 are cut at the same instant.

Switch On Yellow

In the spring of 2001, the communications links used by the current differential relays on the Tacoma Power SONET system were configured to "switch on yellow." In the example system shown in Figure 4, the fiber cut is detected by the SONET node at Site #1, which causes it to send a "yellow" indication back to Site #2. If the SONET node at Site #2 is configured to switch on yellow, receipt of the yellow bit from the node at Site #1 causes the node at Site #2 to reconfigure so data received from the R connection are routed to Relay B. Notice that the data sent from Relay A to Relay B and from Relay B to Relay A now go through the same equipment. The delay from Relay A to Relay B is once again the same as the delay from Relay B to Relay A. This eliminates the apparent phase shift and difference current after the SONET system finishes reconfiguring.

Relay Misoperation Conclusions

Even when the SONET system is configured for "switch on yellow," an apparent current phase shift and consequential difference current still exist temporarily during and immediately following a SONET system switch. When the SONET system is not configured to "switch on yellow," the errors can exist permanently. According to the relay manufacturer, this temporary apparent difference current caused the misoperations experienced by Tacoma Power.
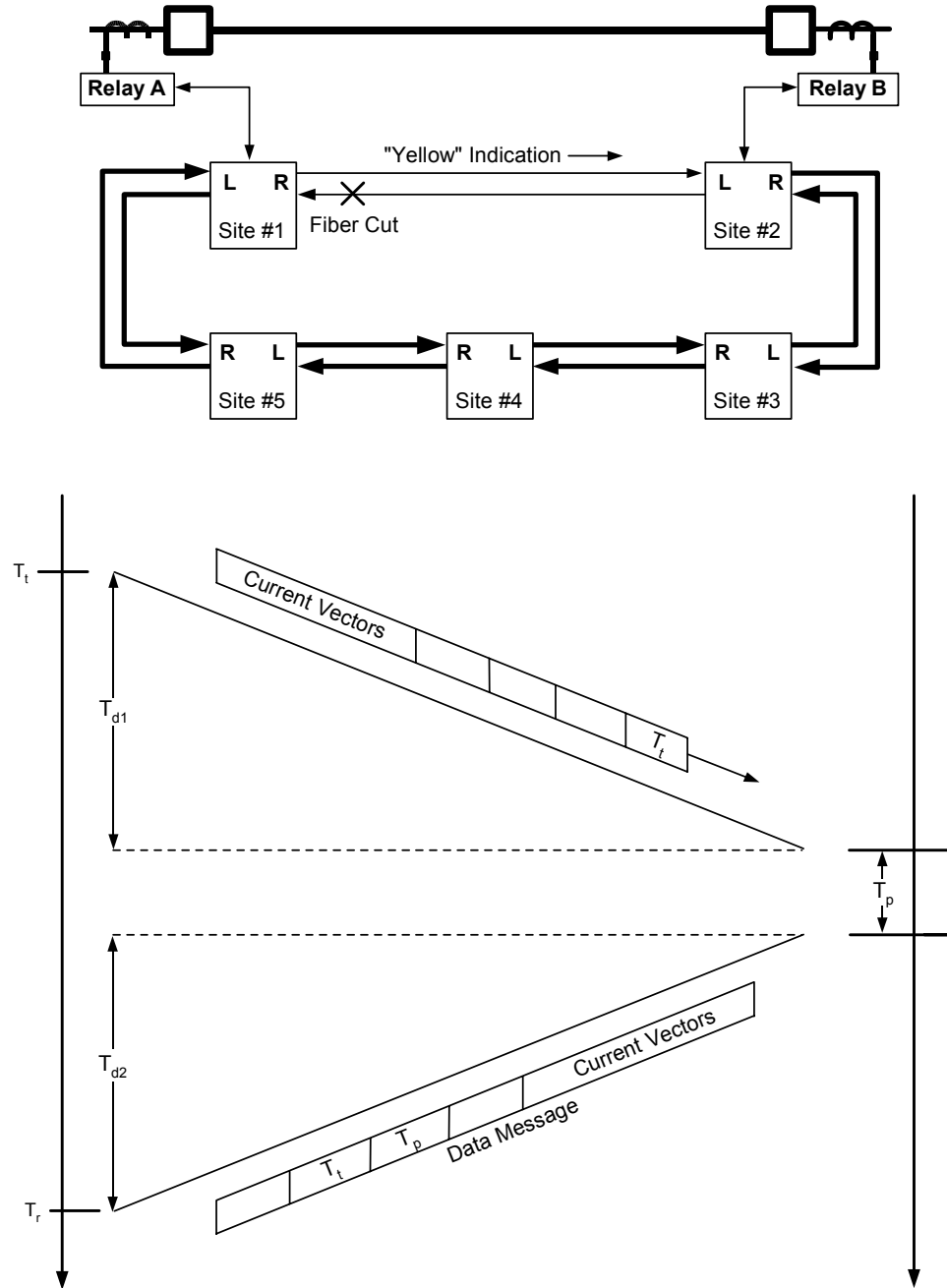
Figure 4   Switch on Yellow Equalizes Transmit and Receive Delays After a Fiber Cut

RESOLVING THE RELAY MISOPERATIONS

To resolve the relay misoperations, we selected a new current differential relay designed to work over SONET systems. Its current differential algorithms were designed to distinguish between internal faults and temporary or permanent differences in transmit and receive delays caused by SONET switching. The relay performs this without the use of GPS synchronization or other external timing references. The current differential algorithms of the new relay operate directly on the alpha plane [2], [3], [4].

The Alpha Plane

The alpha plane is a complex ratio of two currents. In the case of two-terminal current differential protection, it is the complex ratio of remote to local current ($\vec{I}_R / \vec{I}_L$).

As shown in Figure 5, the ratio has real and imaginary parts, or in polar coordinates consists of a magnitude or radius, r and an angle, θ. There is a separate alpha plane for every possible current (phase, sequence, etc.).
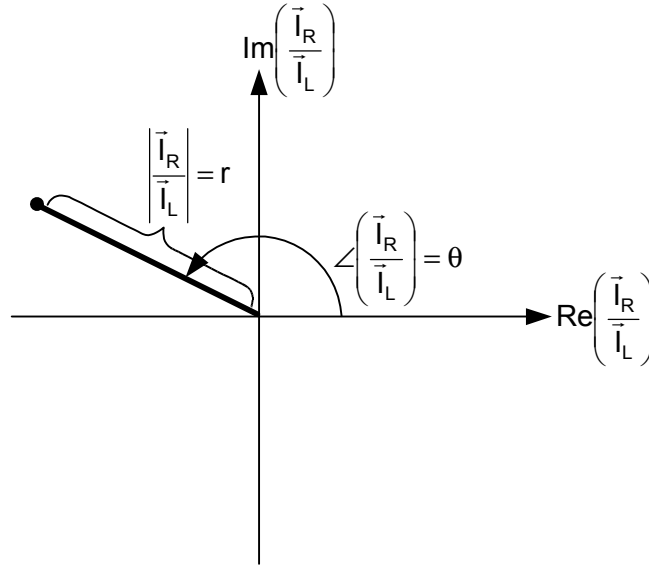
**Figure 5**   The Alpha Plane

Consider a two-terminal line with load current as shown in Figure 6. Taking the convention that current entering the protected line is positive, and momentarily ignoring the effects of line charging current, if $\vec{I}_{AL} = 5\angle 0º$, then $\vec{I}_{AR} = 5\angle 180º$. Taking the complex ratio gives:

$$\alpha = \frac{\vec{I}_{AR}}{\vec{I}_{AL}} = \frac{5\angle 180°}{5\angle 0°} = 1\angle 180°$$
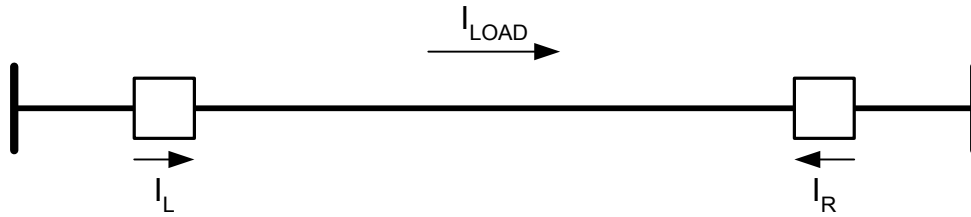
Figure 6   Two-Terminal Line With Load Current

The ratio plots one unit to the left of the origin on the alpha plane as shown in Figure 7. In fact, the ratio plots one unit to the left of the origin regardless of the magnitude or phase of the load current. The same argument holds for external faults. The ratio of $\vec{I}_R$ to $\vec{I}_L$ is always $1\angle 180°$ for external faults, ignoring errors.
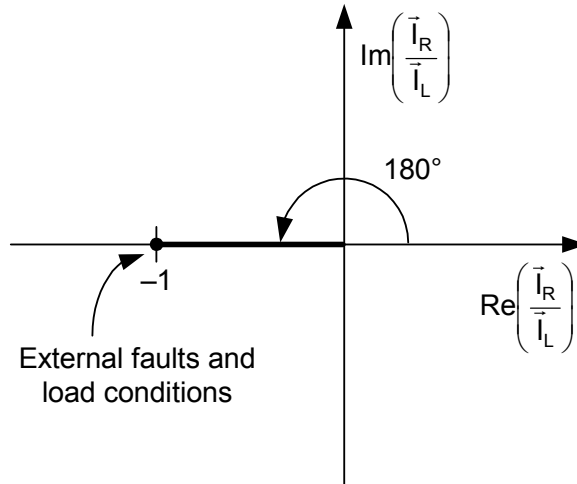
Figure 7   Alpha Plane Ratio for Load and External Fault Current

## **Effect of Channel Delay Difference on Alpha Plane Ratio**

As mentioned earlier, a difference between transmit and receive delays causes an apparent time shift and phase shift of the remote current. For example, a 3-ms difference between transmit and receive delays causes a 1.5 ms current misalignment, which introduces an apparent phase shift of $32.3°$.

If the ratio normally plots at $1\angle180°$, this phase shift rotates the complex ratio around the origin on the alpha plane to $1\angle\pm147.7°$, as shown in Figure 8. The sign on the angle depends on which delay (transmit or receive) is larger.
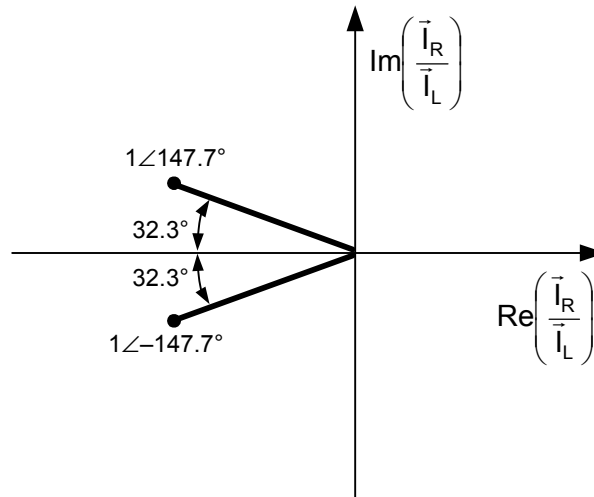

Figure 8   Load Current Phase Shifted by 1.5 ms Current Alignment Error

Is this rotation enough to cause a relay to misoperate? A typical current differential relay operates on a dual slope characteristic. Figure 9 shows the operate characteristic and settings of the relays that misoperated at Tacoma Power in the spring of 2001.
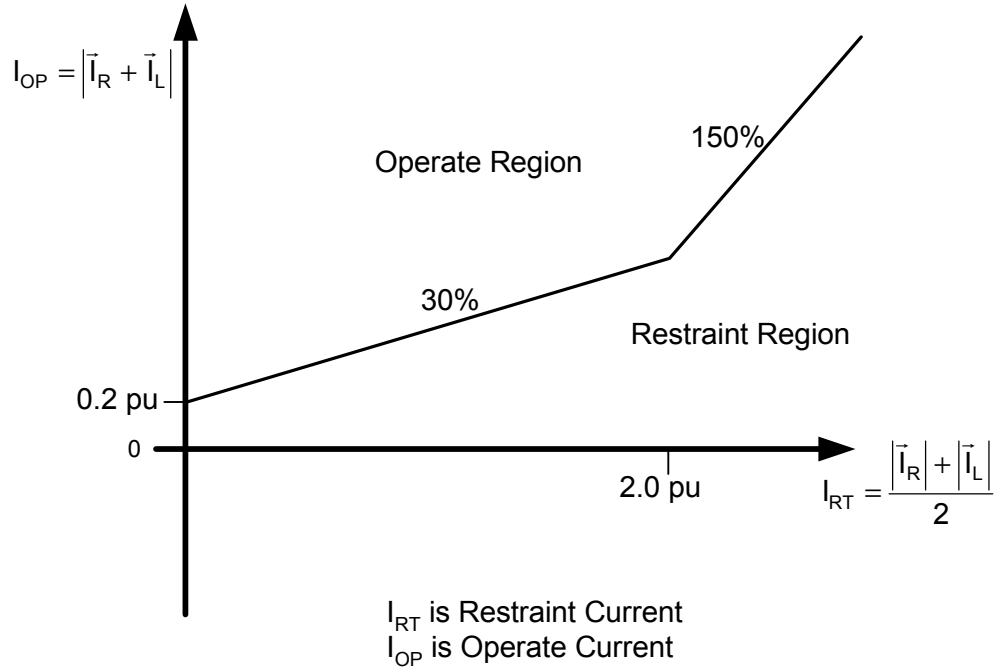
Figure 9   Operate Characteristic of Relays In Service in Spring 2001

The method described by Roberts et al. [5] translates the operate characteristic shown in Figure 9 to a restraint region on the alpha plane, as shown in Figure 10. Figure 9 and Figure 10 are different representations of the same characteristic. In Figure 9, the relay trips if the locus moves above the line. In Figure 10, the relay operates if the locus that normally resides at –1 moves outside the restraint region shown by the black circles. The size and shape of the restraint region of this relay is a function of local current as shown in Figure 10.
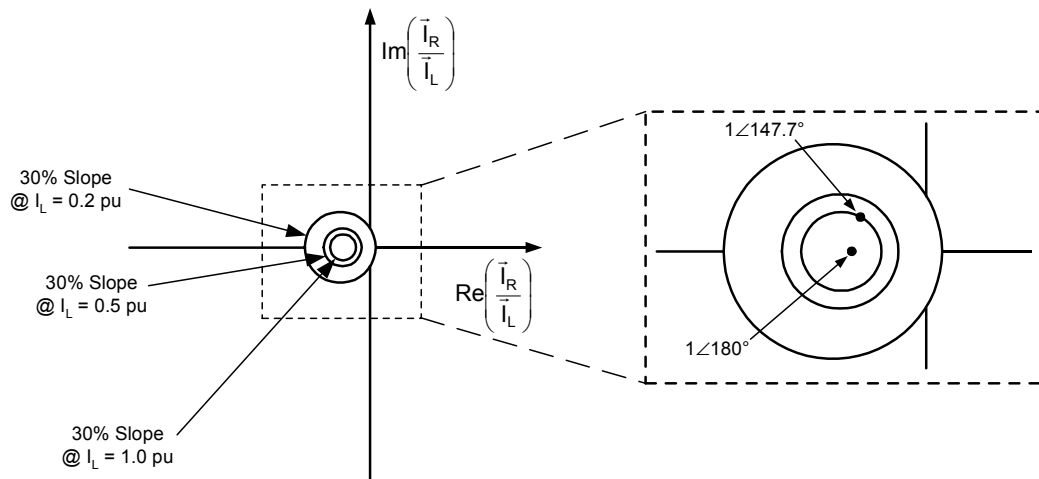

Figure 10   Operate Characteristic of Figure 9 Represented on the Alpha Plane

As the local current increases from 0.2 per unit to 1.0 per unit of nominal current, the restraint region shrinks, decreasing the relay tolerance to differences in transmit and receive delay. At a load current of 1.0 per unit nominal, the restraint region no longer surrounds the point $1\angle\pm147.7°$.

The relay is expected to trip on 1.0 per unit load current given a transmit to receive delay difference of 3 ms, even if no other errors exists.

## New Relay Tolerates Large Channel Delay Difference Without Need for GPS Clocks

The relay selected to replace the dual slope relays operates directly on the alpha plane (patents pending). It defines a static restraint region, independent of current levels, around the point $1\angle 180°$, as shown in Figure 11. The relay does not trip when the complex ratio of remote to local current lies within that region. If the ratio travels outside the restraint region and the difference current exceeds a pickup setting, the relay trips.
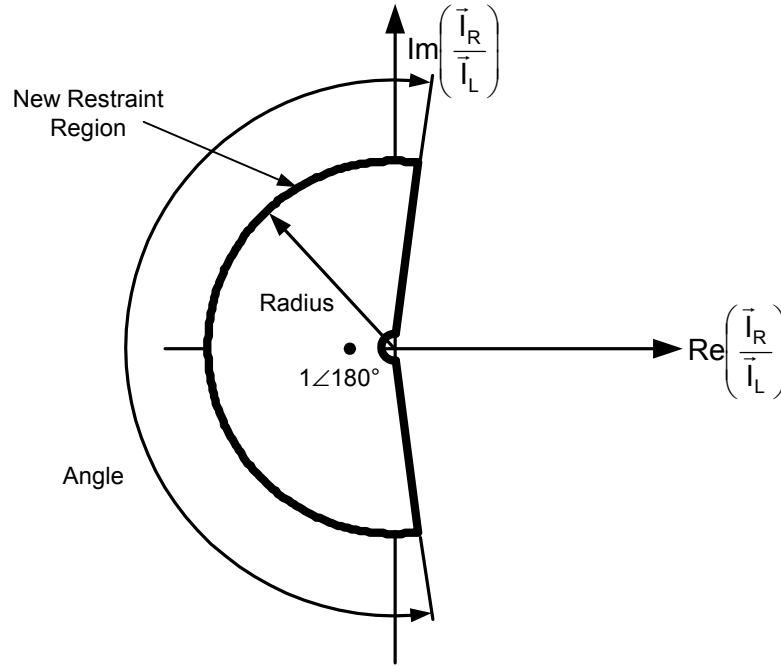
Figure 11   Static Alpha Plane Restraint Region of New Relay

The restraint region is defined by two settings: 1) the outer radius, and (2) the angle subtended by the restraint region. The inner radius is the reciprocal of the outer radius. The size and shape of the restraint region does not change as a function of load current or any other power system condition. The manufacturer recommends setting the radius at 6 and the angle at 195°. With those settings the relay remains secure as the complex ratio of remote to local current moves 97.5°, from $1\angle 180º$ to $1\angle 82.5º$. This makes the relay secure to transmit and receive delay differences of over 9 ms, assuming no other errors, without the need for precision clock synchronization.

Other sources of error, such as line-charging current, CT errors and saturation can also produce a rotating effect on the alpha plane [4]. It would be unwise to apply the relays depicted in Figure 10 and Figure 11 on a system with transmit and receive delay differences as large as this analysis indicates is possible. As Figure 12 illustrates, the new restraint region better tolerates those sources of error because it is larger.
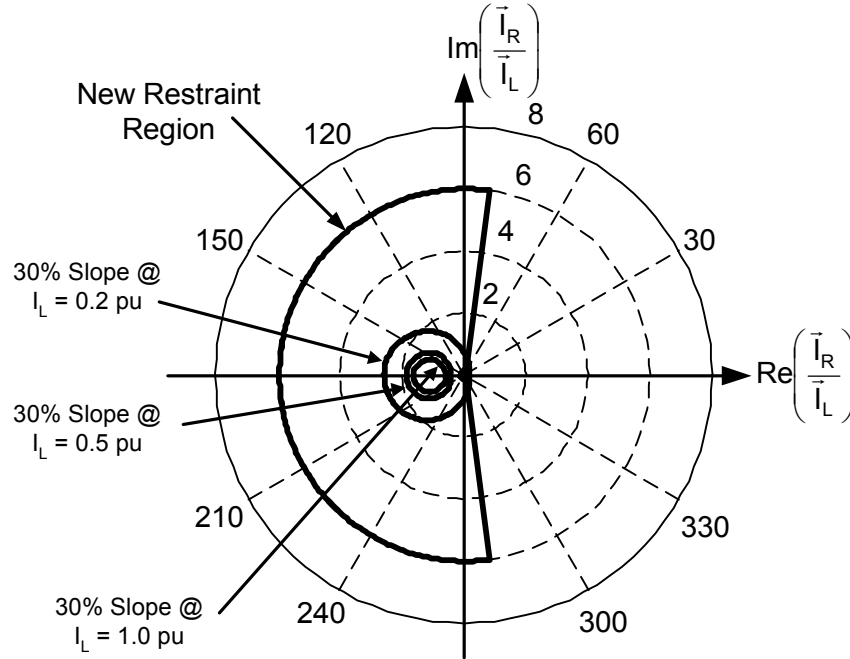
Figure 12   Larger Restraint Region of New Relay Is More Secure

The analysis above assumes a two-terminal line. Roberts et al. [5] shows how to use the alpha plane to analyze and protect three-terminal lines by decomposing them into three two-terminal lines.

New Restraint Region Allows More Efficient Use of SONET Bandwidth

SONET bandwidth is broken into Virtual Tributaries, or VTs. Each VT consists of several (e.g., 24) 64 kbps channels. Typically a VT is the smallest subdivision that may be routed point-to-point on a SONET system. Even if the end equipment uses a single 64 kbps channel, the entire VT is consumed. During the replacement investigation, Tacoma Power became aware that the SONET manufacturer supported a special mode of operation that allowed a VT to be shared among several nodes. This mode of operation effectively allows individual 64 kbps channels to be routed between nodes, without consuming the entire VT. This is up to 24 times more efficient than the normal mode of operation.

There are two limitations to the shared mode of operation. When a VT is shared among several nodes, the delay through each node is higher. Also, the "switch on yellow" configuration is not available in the shared mode of operation.

Higher through-delay at each node means that the channel delay is larger, which slows the current differential protection. For example, the delay through 16 SONET nodes in normal mode might be 400 µs. The same equipment using shared mode would have a delay of 2000 µs. The speed difference between the faster replacement relay and the slower misoperating relay is more than enough to cover the increased delay. The new scheme still trips faster, despite the increased through-node delay experienced in the more efficient shared mode of operation.

Higher through-delay also creates a larger difference in transmit and receive delays. Since switch on yellow is not available in this mode of operation, the larger difference in transmit and receive

delays is permanent. However, the new restraint region shown in Figure 11 has sufficient tolerance to even these larger delay differences.

Using shared mode, Tacoma Power saves two VT, or forty-eight 64 kbps channels.

DATA ERROR ANALYSIS

Figure 13 shows the entire three-terminal communications arrangement in place in the spring of 2001. The relay was supplied with a multimode fiber optic interface. The SONET manufacturer did not offer a channel card that would directly connect to this proprietary relay interface. A media converter on each channel converted from the proprietary relay fiber interface to the standard V.35 electrical interface supported by the 56 kbps high speed data card in the SONET channel bank.

Immediately after installation, multiple communication alarms occurred. A thorough examination of the transmit and receive timing on the SONET channel card revealed an incompatibility with the relay and the media converter. Figure 14 shows the interface in more detail.

Alexander

87L Relay

CH 1   CH 2

RX   TX   RX   TX

Fiber

Media
Converter

V.35

High
Speed
Data
Unit
56 kbps

High
Speed
Data
Unit
56 kpbs

Sonet OC-1

High
Speed
Data
Unit
56 kpbs

High
Speed
Data
Unit
56 kpbs

High
Speed
Data
Unit
56 kpbs

High
Speed
Data
Unit
56 kpbs

V.35

Media
Converter

V.35

Media
Converter

Fiber

Fiber

RX   TX   RX   TX   RX   TX

CH 1   CH 2   CH 1   CH 2

87L Relay   87L Relay

Simpson   **Pioneer**
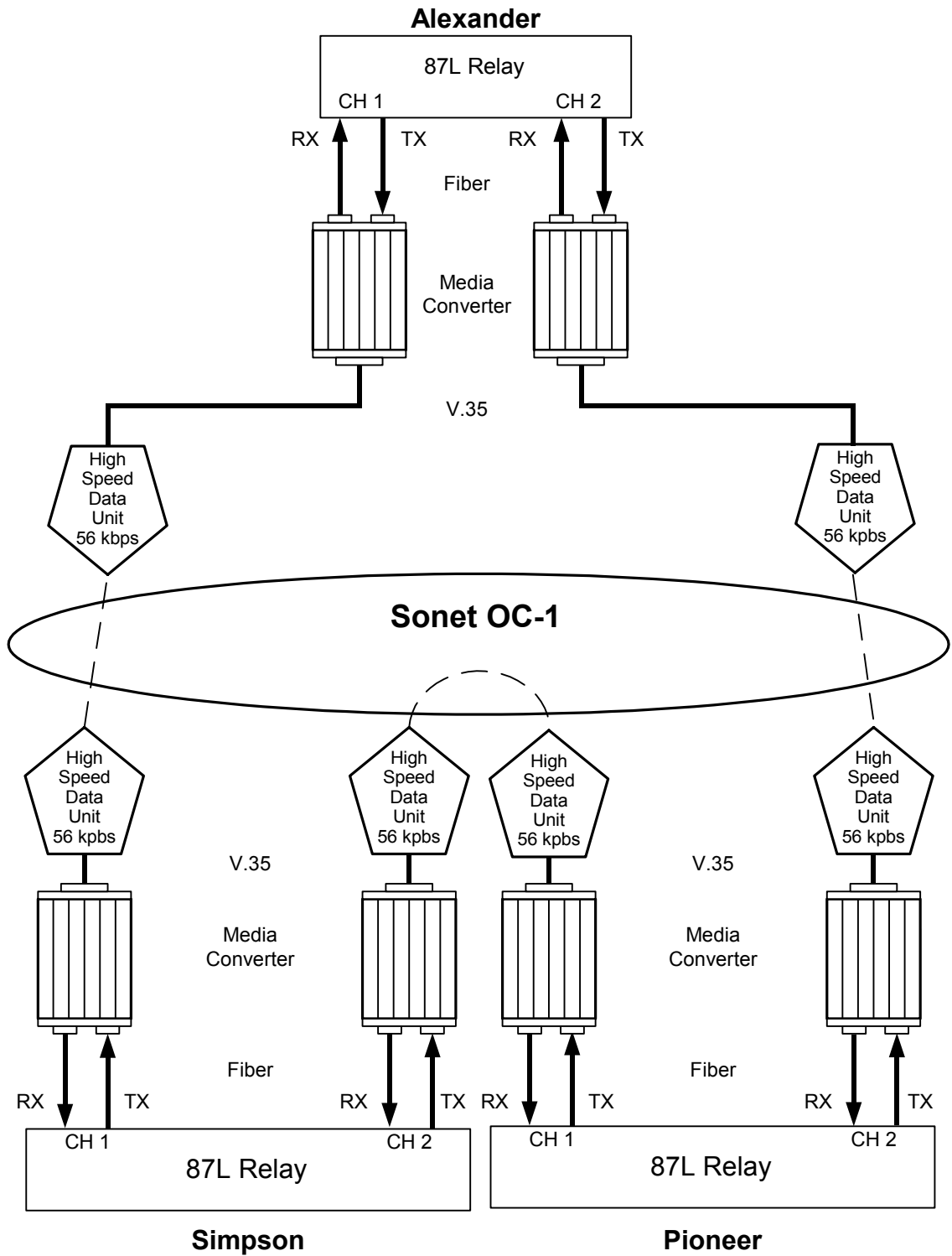
Figure 13   Original Communications Connections Employing Media Converters
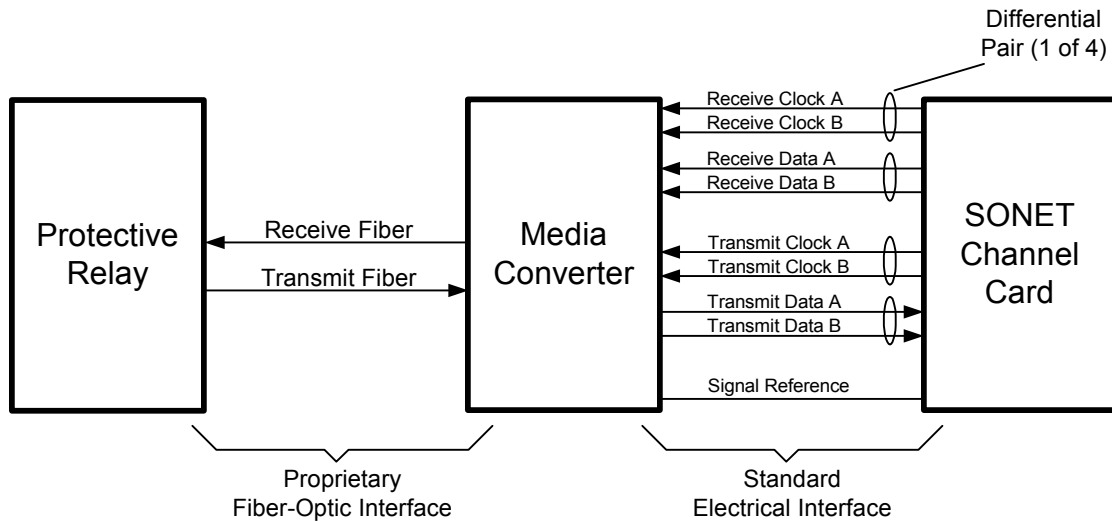
Figure 14   Details of One Relay and Media Converter Interface From Figure 13
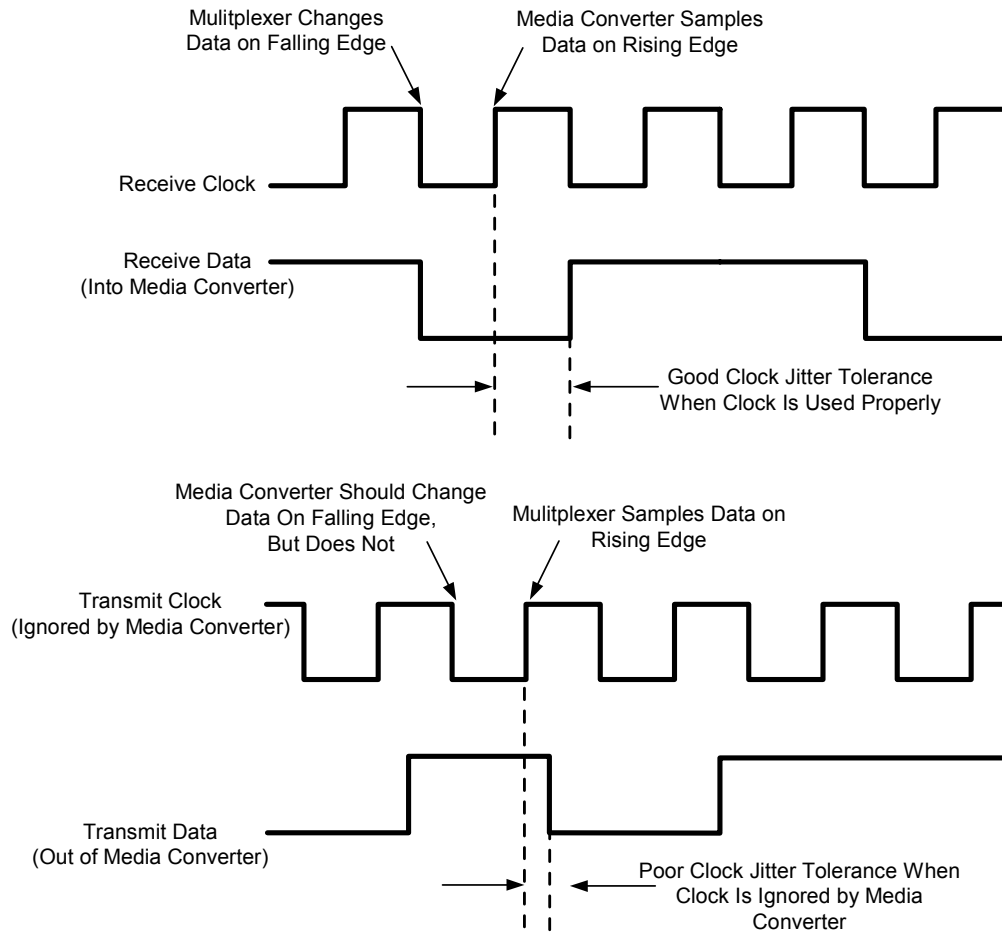
In synchronous mode, the SONET channel card supplies the media converter with two clocks. The receive clock is phase-synchronous with the receive data output from the SONET channel card, and essentially tells the media converter when to sample the bits in the serial receive data stream. The SONET channel card also supplies the media converter with a transmit clock. The transmit clock tells the media converter when to change the transmit data output from the media converter. If the media converter does not sample the incoming receive data on the appropriate edge of the receive clock, or does not change the outgoing transmit data on the appropriate edge of the transmit clock, the interface does not work properly.

In this case, the media converter does not properly use the supplied transmit clock as shown in Figure 15. This causes the SONET channel card to sometimes sample the transmit data at almost the same instant the data changed. Even a small amount of jitter on the transmit clock or transmit data causes data errors.

The SONET channel card supplies two clocks because the phase relationship between transmit data and receive data on the SONET system is arbitrary and changes after each network disturbance. The interface performance changed after each SONET system switch because the media converter ignored the transmit clock. Successful communications were hit and miss.

Mulitplexer Changes
Data on Falling Edge

Media Converter Samples
Data on Rising Edge

Receive Clock

Receive Data
(Into Media Converter)

Good Clock Jitter Tolerance
When Clock Is Used Properly

Media Converter Should Change
Data On Falling Edge,
But Does Not

Mulitplexer Samples Data on
Rising Edge

Transmit Clock
(Ignored by Media Converter)

Transmit Data
(Out of Media Converter)

Poor Clock Jitter Tolerance When
Clock Is Ignored by Media
Converter

Figure 15   Media Converter Did Not Properly Use the Transmit Clock,
Causing Poor Clock Jitter Tolerance

RESOLVING DATA ERRORS USING THE NEW IEEE STANDARD C37.94

Early in the replacement investigation, Tacoma Power discovered that a working group of the
IEEE Power System Relaying Committee had nearly finished development of a new standard,
IEEE C37.94, which offered much hope as a plug-and-plug relay-to-SONET multiplexer
interface. This standard describes the interconnection details for Nx64 kbps connections of
teleprotection equipment to digital multiplexers using optical fiber. For normal 64 kbps
applications, N=1. The standard supports up to 768 kbps with N=12, to allow more bandwidth-
intensive relay algorithms in the future. Existing interface standards for teleprotection equipment
to multiplexers prior to the C37.94 were electrical only and offered no assistance in resolving the
timing problems caused by the old system utilizing the media converter.

The new standard eliminates the clock phasing problems experienced with the existing
installation of relays and media converters, because the relay and multiplexer must tolerate an
arbitrary phase relationship between transmit and receive data to be compliant with the new
standard. The standard also has the potential to completely eliminate the media converter,
provided the SONET and relay equipment manufacturers support it. A description of other
important benefits of the new standard follows.

New IEEE C37.94 Standard Eliminates Clock Polarity Selections

As mentioned previously, with a typical standard electrical interface channel card, the SONET multiplexer supplies a transmit and receive clock. The connected equipment, whether media converter or protective relay, must use the appropriate edge of the receive clock to sample the receive data, and must change the transmit data on the appropriate edge of the transmit clock. This poses several challenges for the end user.

To ensure compatibility with all types of equipment, most multiplexer manufacturers allow the end user to select which edge of each clock should be used. Likewise, many relay manufacturers allow the user to select each clock edge to ensure compatibility with those few models of multiplexers that do not allow the selection. The clock edge settings often have names such as "normal/inverted," or "rising edge/falling edge," but there is little agreement among equipment manufacturers concerning what each setting means. The definitions of the settings are often poorly documented or are not documented at all.

The end result is that the user is presented with four settings or selections that are often not well defined or documented. The settings offer 16 possible combinations. Eight of the 16 possible combinations are equally correct, and eight are incorrect. To make matters more confusing, most of the 8 incorrect settings combinations probably work perfectly at installation and commissioning time, but they have drastically less jitter tolerance than the correct settings combinations. Further adding to the confusion, each of the four signals—transmit data, receive data, transmit clock, and receive clock—are split into a differential pair on the interface cable, as shown in Figure 14. If a differential pair is inadvertently swapped in the cable, the associated signal is inverted. Inverting a clock signal invalidates even the most carefully selected clock edge settings, and again may not be detected during commissioning tests.

The new standard combines clock and data into one signal, so there are no associated clock settings that may be set incorrectly. If the fibers are swapped, the interface cannot work, so the error is easily detected and fixed.

New IEEE C37.94 Standard Eliminates GPR Problems and Ground Loops

Most electrical interface standards are not isolated from the frame of either piece of equipment. Even differential standards such as V.35 and EIA-422 contain a signal reference conductor in the cable. That reference conductor must be connected to the ground pin on the differential driver and receiver in each piece of equipment. If the conductor is not connected, the interface will probably work properly at commissioning time, and will fail only when disturbed by some outside noise source.

If the manufacturer does not isolate the interface, then the signal reference conductor is often connected to the equipment frame at both ends of the cable. This allows ground loops that disrupt communications and introduce operational and safety concerns due to ground potential rise.

Even given a properly designed and constructed electrical interface using optoisolators, the electrical interface cable must be carefully routed to prevent induced noise from causing data errors.

The new interface standard directly connects the relay to the multiplexer with fiber as, shown in Figure 16, eliminating all of these concerns.
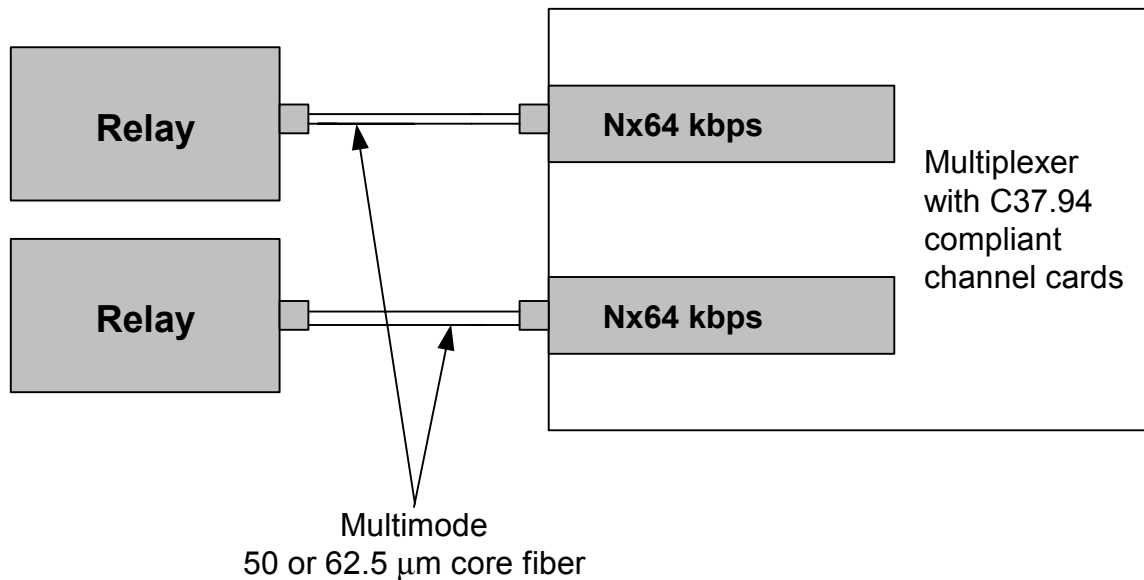
Figure 16 The IEEE C37.94 Standard Connection Does Not Require Media Converters

Inquiries with the manufacturer of Tacoma Power's existing SONET equipment and the proposed replacement relay verified they both supported the new standard, allowing a direct relay to multiplexer fiber connection with no media converter. In fact, the two manufacturers had worked together as the first companies to implement the new standard, and had already verified interoperability.

BENCH TESTING THE NEW RELAY

Tacoma Power set out to verify that the relay/multiplexer combination would indeed deliver all of our replacement objectives. All three misoperations of the old relay experienced a certain degree of clock synchronization problems. In some instances, this was initiated by loss of dc to the SONET equipment; in other instances, it was due to an incorrect setting on the external sync module. Nevertheless, we wanted to replicate the events causing the loss of clock signal. We also wished to compare the performance of the new interface standard with existing electrical standards. A complete assessment of this new relay system required tests on an actual SONET system. We preferred to test on an OC-3 ring with at least 15 nodes to simulate the Tideflats SONET system. Tacoma Power could set up only an OC-1 loop with 9 nodes. So we made arrangements to visit the R&D facility of the SONET system manufacturer to perform these tests.

Test Setup

As shown in Figure 17, the SONET equipment at the manufacturer's R&D facility was configured as a single OC-3 SONET ring with 16 nodes (sites) and one master clock located at the headend node, or Site #1. Some of the relays were equipped with EIA-422 interfaces and others used the new IEEE C37.94 fiber interface.
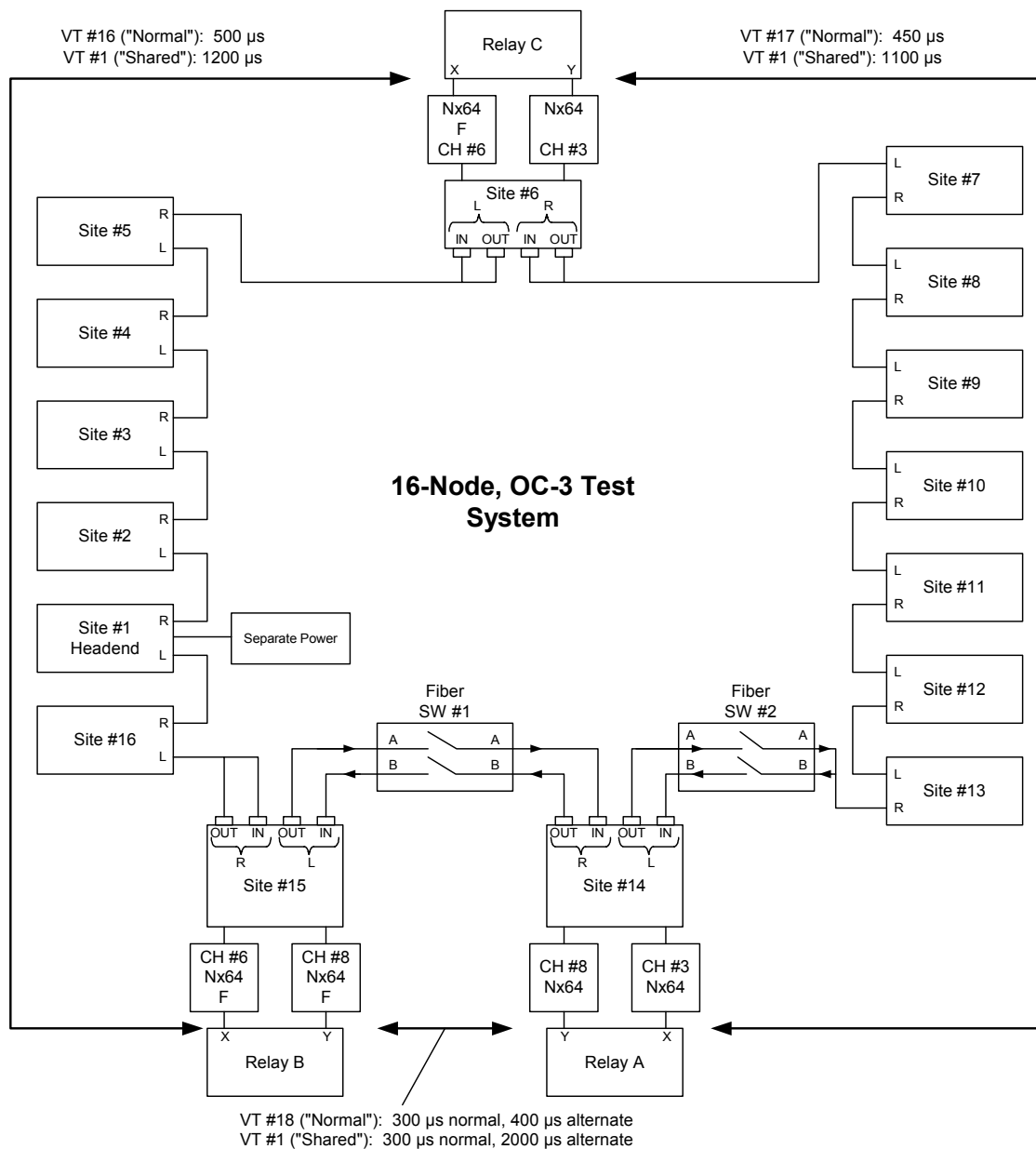
Figure 17 16-Node SONET System With Fiber Switches to Simulate Fiber Cuts

To simulate loss of power at the headend, we equipped the headend node with a separate power supply. To most accurately test the configuration of the Pioneer–Alexander–Simpson Line, two of the three-terminal nodes were adjacent and the third node was a distance of six nodes away.

Test Summary

The test results verified that the new relay overcame the communications shortcomings of the old relay. An outline of the 11 tests we conducted and the result of each test is given below. In each case, the relay and SONET system performed as expected with no misoperations or unexpected loss of protection. During the tests, secondary current was injected into the relays to simulate

1.0 per unit nominal load current on the three-terminal line. In every case, the relay properly noted the loss or restoration of communications.

1. Loss of SONET clock via dc power loss and restoration

    This test simulated a gradual loss of dc power at a SONET node other than the nodes active in the three-terminal current differential scheme (similar to the events of April 14 and June 4). After a complete loss of dc to this node, dc was reapplied immediately, but the power-up procedure defined by the SONET manufacturer was not followed. This simulated a node improperly inserted into the ring.

2. Loss of external synchronizing clock

    This test simulated the loss of the external clock to the SONET system (similar to the events of May 31, after the fiber cut). The headend node was reconfigured as a timing slave, and we allowed the SONET system to search for a clock source for at least two minutes.

3. Fiber pair loss

    This test simulated a total failure of both fibers between the two adjacent nodes on the SONET. We used Fiber SW #1 to simulate breaks in both fibers, forcing the SONET system to reroute traffic between Relay B and Relay A the long way around the ring. We verified the relays disabled protection and then re-enabled protection after the SONET system had stabilized in the alternate direction around the fiber cut.

4. Fiber pair loss and replacement

    This test simulated a total failure and immediate restoration of the fiber path on both channels between Relay A and Relay B. This forced the SONET to reconfigure itself in the non-preferred direction and then immediately reconfigure itself back into the preferred or normal direction after the fibers were replaced. We verified that the relays were stable and re-enabled protection after the fiber was restored.

5. Single fiber loss

    This test simulated the loss of Fiber A carrying data from Site #15 to Site #14. We used Fiber SW #1 to simulate the fiber break. This caused a temporary difference in transmit and receive delays when the network was configured to switch on yellow. It caused a permanent difference when the network was operated in shared mode. We verified that the relays were stable and re-enabled protection after the channel was rerouted.

6. Single fiber replacement

    This test simulated restoration of the fiber break of Test 5. In both normal and shared modes, this restored communications to the preferred path between Relays A and B. We verified that the relays were stable and re-enabled protection after the channel was rerouted.

7. Single fiber loss

    This test simulated the loss of Fiber B carrying data from Site #14 to Site #15. We used Fiber SW #1 to simulate the fiber break. This caused a temporary difference in transmit and receive delays when the network was configured to switch on yellow. It caused a permanent difference when the network was operated in shared mode. We verified that the relays were stable and re-enabled protection after the channel was rerouted.

8. Single fiber replacement

   This test simulated restoration of the fiber break of Test 7. In both normal and shared modes, this restored communications to the preferred path between Relays A and B. We verified that the relays were stable and re-enabled protection after the channel was rerouted.

9. Loss of a folded loop—islanded scenario

   This test simulated the interruption of a node connected to the SONET by a folded loop. This node (substation) would be totally isolated, with no alternate path for communication on the SONET system. We used Fiber SW #1 and Fiber SW #2 to isolate Site #15 from the rest of the network. We verified that the protection scheme disabled and remained stable during the interruption.

10. Restore the folded loop—undo the islanded scenario

   This test simulated the restoration of a node that was islanded from the SONET system. We used Fiber SW #1 and Fiber SW #2 to restore Site #15 to the loop. We verified that the protection scheme enabled and remained stable during the restoration.

11. Initiate a trip to Relay A, B, and C

   This test verified that all three relays trip and were not disabled during or as a result of the previous tests. We simulated an internal fault and verified that all three relays tripped and targeted properly.

FINAL RELAY SELECTION AND INSTALLATION

The relays were installed with C37.94 direct interfaces to the multiplexers on the Alexander–Simpson–Pioneer line. They were commissioned January 16, 2002.

Each of the three relays uses two communications channels when protecting a three-terminal line and is capable of logging every bit error on either channel. Five of the six interfaces have operated without a single bit error from installation to late August 2002, a span of over 7 months. As a comparison, one of the original relays that remained in service on the SONET system utilizing media converters lost over 40,000 messages in a period of 118 days.

The sixth interface on the new relay system experienced a 200-ms loss of communications on May 24, 2002, as reported by the relay. The relays are capable of protecting a three-terminal line during loss of a single communications channel. Since the interruption occurred on only a single channel, the protection scheme was never unavailable. Protection has been available 100 percent of the time on the Alexander–Simpson–Pioneer line since commissioning the new relay system.

SUMMARY

Tacoma Power was the first to successfully implement a digital line current differential relay over a SONET system utilizing the new IEEE C37.94 Standard for Optical Fiber Interfaces Between Teleprotection and Multiplexer Equipment.

The entire investigation process to find and test this new interface along with a new digital line current differential relay was a great educational opportunity and learning experience for all Tacoma Power team members involved. A great synergy developed between the Tacoma Power

protection engineers, communications technicians, relay technicians, and the manufacturers of the digital line current differential relay and the SONET system. The security and dependability of Tacoma Power's three-terminal line current differential teleprotection scheme was improved immensely by implementing this new relay into the existing SONET system infrastructure.

Since the installation of this new teleprotection scheme in January 2002, Tacoma Power has not experienced any of the security and dependability problems and issues that were frequently occurring on the historically problematic three-terminal lines in the Tideflats area.

CONCLUSIONS

1. Teleprotection that interfaces with a SONET system must tolerate an arbitrary phase relationship between transmit and receive data. Failure to properly utilize the separate transmit and receive timing signals from the multiplexer results in dropped messages and routinely disables current differential protection.

2. Teleprotection operating on a SONET system must tolerate a permanent or temporary difference in transmit and receive delays. The magnitude of the difference depends on the SONET equipment and the size of the network, and can easily exceed 1 ms. The duration of the difference depends on the configuration of the SONET system. If it is configured to switch on yellow, then the difference is temporary. If the system is not configured to switch on yellow, then the difference can be permanent.

3. Failure to tolerate the difference in transmit and receive timing can cause a current differential relay to misoperate during quiescent power system conditions.

4. The alpha plane helps visualize how differences in transmit and receive delays affect the security of current differential relays.

5. Utilizing a restraint region defined on the alpha plane that is not a function of any power system current allows the new relay to tolerate very large differences in transmit and receive delay without the need for external time references such as GPS. The differences can be temporary or permanent.

6. The new relay allows Tacoma Power to operate their SONET system in a more efficient shared mode. The new relay is fast enough to make up for the increase in delay through each SONET node, and the new relay can tolerate the permanent large differences in transmit and receive delays generated by this more efficient mode of operation. Operating in this mode saves Tacoma Power forty-eight 64 kbps channels per three-terminal line.

7. Prior to the IEEE C37.94 standard, existing interface standards between teleprotection equipment and multiplexers were electrical only and they were susceptible to intra-substation electromagnetic interference (EMI). The use of dedicated optical fibers for communications links between teleprotection equipment and multiplexers to eliminate the data corruption common to electrical connections has been tried, but problems arising from the proprietary nature of these interfaces has been a major issue.

8. The new IEEE C37.94 standard communications interface allowed Tacoma Power to provide a clean and simple fiber-optic interface between their relays and their multiplexing SONET equipment, eliminating the many possible sources of settings and connection errors that are difficult to detect during commissioning tests. Those errors can disable current differential protection when noise is introduced onto electrical communications circuits.

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9. Installation of the new line current differential relays on the three-terminal lines on the Tideflats 110 kV subtransmission system is the first step in the overall improvement of Tacoma Power's primary relaying schemes for its short transmission lines (<10 miles).

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BIOGRAPHIES

Debra Carroll received her Bachelor of Science of Electrical Engineering from Seattle University in 1995. Debra started her career with Occidental Chemical Corporation in Tacoma, Washington where her assignments included installation and maintenance of plant control, alarm and electrical systems. In 1997, Debra joined the T&D Technical Services Department of Tacoma Power where her activities have focused on protection and teleprotection engineering on both the distribution and transmission system. Debra is now expanding into new areas including analog and digital microwave and SONET system design and utilization. Debra is a member of IEEE Power Engineering Society and a former president of the Seattle Section IEEE, Power Engineering Society.

John E. Dorfner, P.E., received his Bachelor of Science Degree in Electrical Engineering from Washington State University in 1981. He joined Tacoma Power upon graduation as an Electrical Engineer where he designed underground residential distribution (URD), overhead distribution, and overhead transmission projects. In 1984, he began his power system protection career and is presently the Senior Protection Engineer of the T&D Technical Services Group at Tacoma Power. He has experience with generator, transmission, and distribution protection. Presently, he designs protective relay circuits for application on the distribution and transmission systems, utilizing several communications media, including direct fiber-optic cable, SONET multiplexed channels, and digital microwave radio. John is a registered Professional Electrical Engineer in Washington State and is a member of the IEEE Power Engineering Society.

Tony J. Lee received his B.S. degree in electrical engineering from Washington State University in 1987. He worked for Texas Instruments in Dallas, Texas from 1987 through 1991, when he joined Schweitzer Engineering Laboratories, Inc. as a hardware design engineer. He presently holds the position of Principal Systems Engineer at SEL.

Ken Fodero is a Senior Product Engineer for Schweitzer Engineering Laboratories, Inc. Before coming to work at SEL he was a product manager at Pulsar Technology for four years in Coral Springs, Florida. At RFL Electronics he held various positions over 15 years, including director of product planning. He has also worked for Westinghouse Electric as a relay system technician. Fodero is chairman of the Communications Subcommittee for IEEE PSRC. He graduated from RETS Technical School in New Jersey.

Chris Huntley, P.Eng., received his M.A.Sc. in Engineering Physics from the University of British Columbia in 1960. After a two-year Athlone Fellowship in the U.K. Chris joined the R&D group of GTE Lenkurt Electric in Burnaby, B.C. where he has remained, now serving as the R&D manager as well as continuing to design products. Huntley's legacy includes the 46A3C FDM mux, the 937B Protective Relaying system, the 8400 Analog LightWave product, and more recently, the Junglemux Sonet mux. The R&D group has seen many owners from GTE and B.C.Tel through Nortel and now GE. Chris is an active member of the IEEE, IEC, Cigre, and AES professional groups.