APPLICATION OF A
SINGLE POLE PROTECTION SCHEME
TO A DOUBLE-CIRCUIT
230 KV TRANSMISSION LINE

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ABSTRACT

This paper describes the application of a single pole protection scheme to a double-circuit 230KV transmission line. Because the 230KV line is the only link between a three-unit generating station and a copper and gold mine located approximately 60 miles from the station, the primary and secondary protection systems were required to satisfy strict continuity of service and system stability criteria while keeping the protection system equipment as simple as possible. Additional challenges during the protection scheme design and calculation of equipment settings include the problems of weak in-feed, neutral and negative sequence unbalance, and cross-country fault conditions on the power system. The interaction between the single pole protection scheme and the automatic reclosing and breaker failure protection scheme is also described as it relates to power system stability and continuity of service.

The fiber-optic communication system used by the protective systems will also be presented. The paper will include channel requirements for both protective systems, SCADA, direct transfer trip, loadshedding and voice communications.

INTRODUCTION

The expansion of P. T. Freeport Indonesia's copper and gold mine near the top of a 14,000 foot mountain in Irian Jaya, Indonesia, required additional generation to power the mining and processing equipment. An engineering and economic analysis performed by Duke/Fluor Daniel determined that the best alternative was to build a 195 MW coal-fired generating plant at sea level and electrically transmit the power up the mountain. This required the building of a new 60 mile 230kV double-circuit transmission line to connect the generating plant to the milling operation near the top of the mountain. The line started at the coast, crossed a major river, ran through mangrove swamps, went under-ground near an airport, then wound up a mountain ridge to the mill processing site at an elevation of 9,500 feet. Duke/Fluor Daniel was selected to design and build the generating plant. Duke Engineering & Services and Walk, Haydel, and Associates were selected to design the 230 kV Switchyards at the generating station and the minesite, respectively. Power Technologies, Inc. designed the transmission line and served as the electrical system coordinator, and designed and installed the high-speed loadshedding system. The transmission line and power system presented several formidable challenges to the protection engineers, including continuity of service, system instability, and effective management of the complexity of the protection system. A power system study confirmed the probability of system instability during a 230kV line fault. A business case study confirmed that the application of a single pole tripping scheme was a lower cost option to reduce the probability of system instability, and to reduce circuit outages for direct or nearby lightning strikes to the transmission lines.

Two high-speed pilot relay protection schemes were required for primary and secondary protection of the transmission line. Each relay scheme required a secure communications channel in order to accurately identify the fault type and trip the correct phase. The fiber-optic communications network, designed by Commtech Industries provided redundant dedicated channels of the desired clarity and speed for the two pilot relay schemes. Additionally, the fiber-optic communications equipment could also switch to backup pilot channels on the mining company's microwave communications system, should both of the fiber optic channels be lost.

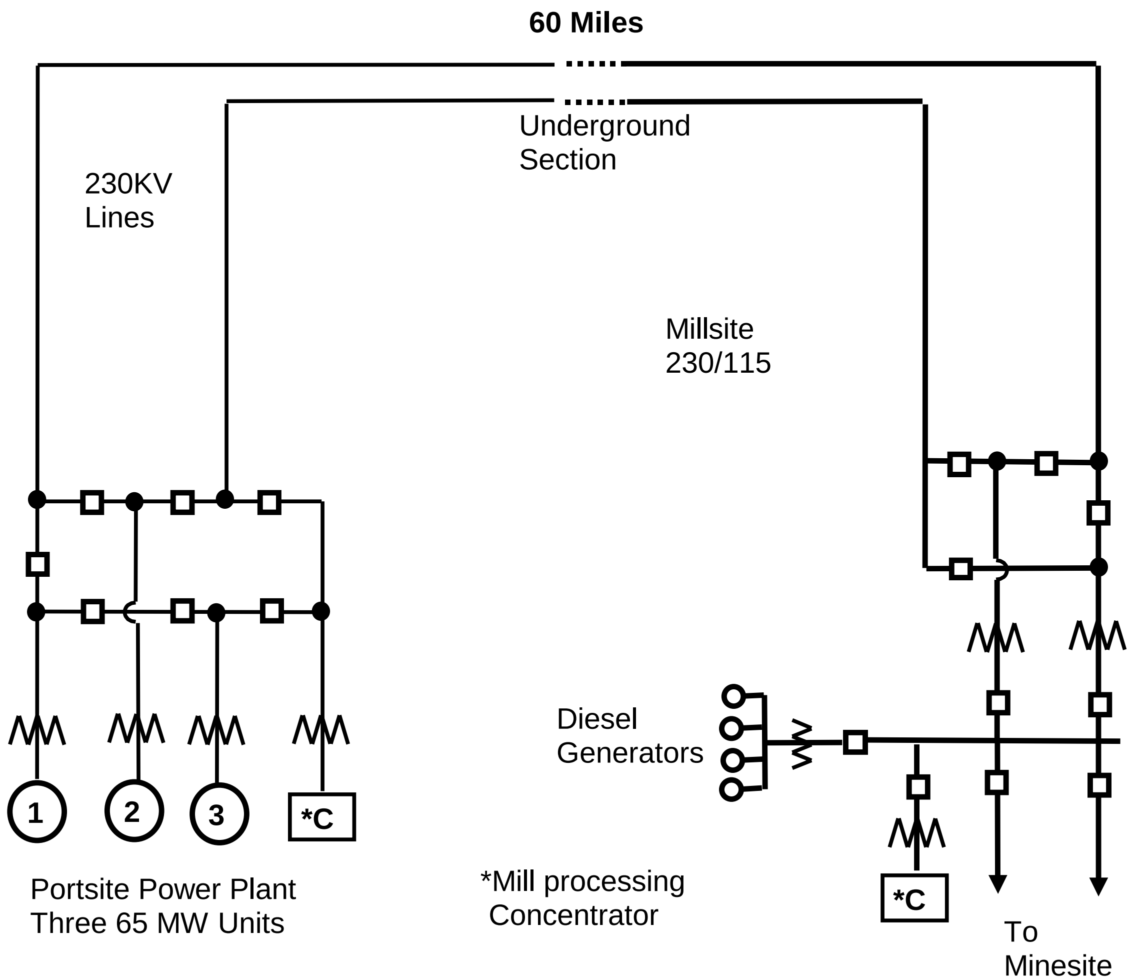


Figure 1: One-Line Diagram of the Power System

With a dependable communications network in place, the primary and secondary protection systems for the parallel 230 kV lines could be selected to provide as much redundancy and reliability as possible. The two systems were made by different vendors and operate on different principles in order to minimize the risk of common mode failures. The primary system operates on the segregated phase comparison principle. It also has step-distance, direct transfer trip, and single-pole reclose initiate functions. A permissive overreaching transfer trip (POTT) system was selected as the secondary protection system for the transmission line. The POTT system also has step-distance, direct transfer trip, and single-pole reclose initiate functions. Backup overcurrent relay protection was also applied in the unlikely event that both the primary and secondary protection systems were temporarily out of service.

SINGLE POLE TRIPPING SCHEMES

ADVANTAGES OF SINGLE POLE TRIPPING SCHEMES

Many factors can affect system instability. Systems that have generation and load separated by relatively long lines are most susceptible to transient instability because of the large angular difference across the line under normal conditions. Faults and subsequent line tripping aggravate this situation by increasing the angle even further. Reducing load and the transfer impedance are the most direct and effective methods of reducing the probability of transient instability. Paralleling transmission lines, bundling line conductors, or adding series capacitors also reduces the transfer impedance.

The 230 kV lines were designed to present as low an impedance as possible between the generation and the mining operation. The other options mentioned previously were too expensive, either singly or in combination. A relatively inexpensive solution to reduce the probability of transient instability and to ensure maximum continuity of service was the application of a single-pole tripping and reclosing scheme using independent pole operated breakers and selective phase tripping relays. This option reduced the probability of transient stability, did not significantly add to the cost of the existing breakers or protective relays, and eliminated the need for expensive primary power system improvements.

PROBLEMS ASSOCIATED WITH SINGLE POLE TRIPPING SCHEMES

Although the application of single pole tripping and reclosing enhances the reliability and stability of the power system, single pole tripping and reclosing requires attention to a number of details that are not normally considered for three-pole tripping schemes. Some of the problems that require special consideration include:

- Complex protective relay schemes and relay communication equipment may be required to communicate relay logic status between the two terminals.
- Undesired three-pole tripping may occur during simultaneous line to ground faults on two different phases of a double circuit line. These faults are called “cross-country faults“.
- Longer reclosing intervals are generally required for successful reclosing after a single-pole trip since more time is required for the secondary arc to extinguish.
- Special consideration must be given for zero-sequence and negative-sequence currents flowing during the “single pole open” interval due to the single-pole trip.

SINGLE-POLE TRIPPING SCHEME APPLICATION

SEGREGATED PHASE COMPARISON (SPCR)

The operation of a segregated phase comparison system is similar to that of a line differential system in that the relay at each terminal monitors the currents going into and out of the line. If the currents monitored at the two ends of the line are not equal and opposite, the relays recognize an internal fault and trip their respective breakers. The system is called “segregated” because the comparison is performed separately for each of the three phase currents and the ground (or residual) current. This scheme includes several other features that make it a reliable system for single-pole tripping. These features include:

- Comparison of each phase to enable the system to perform single-pole tripping.
- A current only scheme, phase comparison does not rely on line voltages.
- Insensitivity to system swings.
- Ability to properly detect cross-country faults.
- Provides reliable fault detection and tripping for lines with weak sources.

The relays in a segregated phase comparison scheme compare the phase relationship at each end of the line. This is done on a per-phase basis and starts when the rate of change detector in the relay detects a change in line current. The relay digitizes the data and sends it to the remote relay. The relay then compares local and remote end signals, after compensating for the phase shift caused by the propagation time delay in the communications channel. If the two signals match and their magnitudes are above the minimal current setting, then a trip signal is issued at each end of the line. If the signals are out of phase then the relay does not trip. Figure 2 is a diagram of the local and remote end signals seen on one phase for an internal and an external fault.

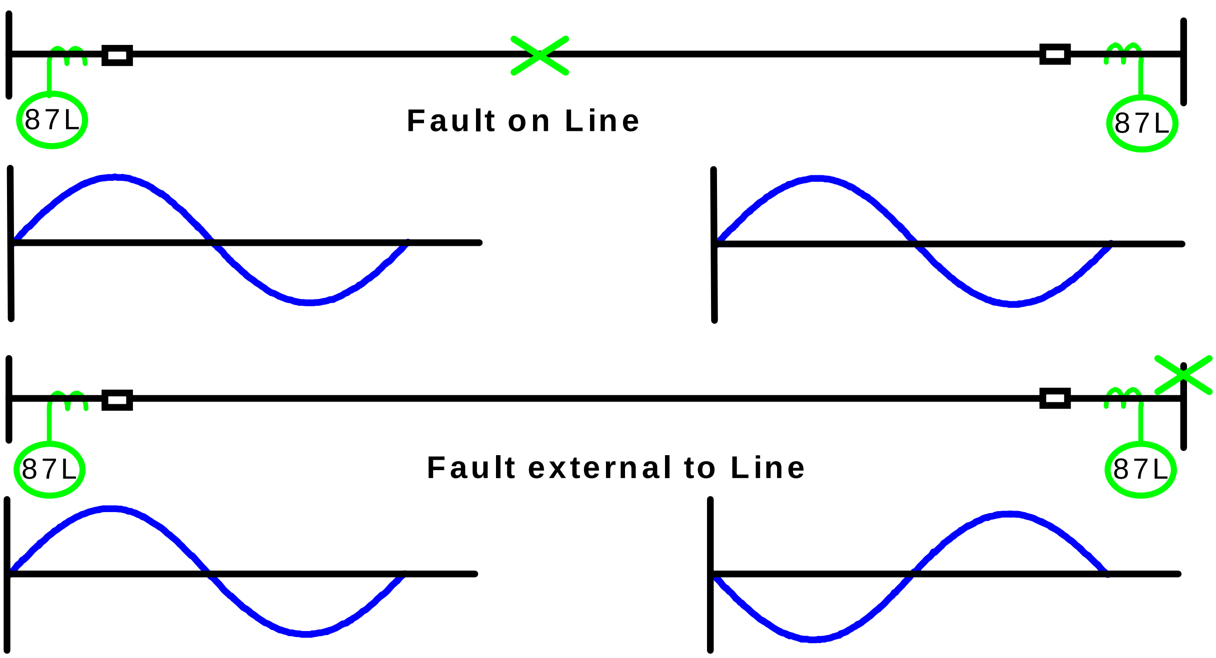


Figure 2: Segregated Phase Comparison Signals

COMMUNICATIONS CHANNEL REQUIREMENTS

The segregated phase comparison relays use a 64 kbps digital data link over a T1 communications channel on the fiber-optic network to enable each relay to compare its local current readings with the remote relay's current readings. The data link also provides a path for transfer trip signaling, remote breaker status information, local and remote system monitoring, and communications channel information.

Line Differential relays such as segregated phase comparison relays are subject to any change in the absolute delay between terminals. Therefore it is important to know the absolute point to point delay and the new set of channel delay parameters if switched onto a second path. Continuous time measurement of the absolute delay is built into the segregated phase comparison relay to compensate for path switching. The segregated phase comparison relay utilizes a 32-bit data word for communications operating at either 56 kbps or 64 kbps. The 32-bit data word has a Sync Bit, Unit ID, Data, Time Delay Information and a CRC bit. Critical information to measure and protect each line phase is data encoded into NRZI (Non-Return to Zero Inverted) format. The relay communications output is ported through an industry standard 25-pin D-Subminiature Connector. A metallic cable connects the relay output to Channel 1 of the twenty-four DS0's (Digital Signal 0) available in the intelligent T1 multiplexer via a synchronous data module. The synchronous data module converts the relay data word into a DS0, which is 64 kbps, to provide full duplex communications at either 56 kbps or 64 kbps.

BACKUP PROTECTION FUNCTIONS FOR THE PHASE COMPARISON SYSTEM

Incorporated in the segregated phase comparison package are two zones of back up phase and ground directional distance elements. The distance elements are only in service when the communication channel fails or is removed from service. The backup protection will only initiate three-pole tripping. Since voltage inputs are required to provide the backup directional distance functions, the segregated phase comparison package also provides fault location, loss of potential detection, loss of current detection functions and oscillographic event records.

SEGREGATED PHASE COMPARISON SYSTEM INPUTS AND OUTPUTS

The proper application of a single-pole tripping scheme requires a much greater number of inputs and outputs than a three-pole tripping scheme to ensure correct operation. The single-pole tripping scheme requires additional inputs to indicate the status of each breaker pole. It also requires additional output contacts to trip the individual breaker poles and provide additional alarm and annunciation functions. Most of the relays used in single-pole tripping schemes are equipped with at least two outputs per phase to allow direct activation of the breaker trip coil(s) and to initiate auxiliary tripping or signaling functions. This feature eliminated most of the auxiliary tripping relays and thereby reduced the fault clearing time. Typical inputs and outputs used in the segregated phase comparison scheme are listed below.

<u>INPUTS</u>

- Breaker contact, “A” Phase
- Breaker contact, “B” Phase
- Breaker contact, “C” Phase
- Direct Transfer Trip Keying
- Pilot Trip Enable

- Single Pole Trip-Enable/Disable

OUTPUTS

- Trip “A” Phase
- Trip “B” Phase
- Trip “C” Phase
- Breaker Failure Initiate, “A” Phase
- Breaker Failure Initiate, “B” Phase
- Breaker Failure Initiate, “C” Phase
- Single-Pole Reclose Initiate
- Three-Pole Reclose Initiate

Relay settings

Settings for the the segregated phase comparison relay are very minimal with most being standard factory settings. Some of the settings the protection engineer must decide are:

• Key starting	Starts on ΔI or ΔV
• Phase comparison count	Extends comparison for more security
• Very low set phase current	Set below line charging current
• Low set phase current pickup	Set above line charging current
• Low set ground current pickup	Minimum setting of 0.5 amps
• High set phase current pickup	High set instantaneous tripping
• Single pole trip timer	Open pole trip timer
• Phase distance setting	Zone 2 and 3 line distance setting.

PERMISSIVE OVERREACHING TRANSFER TRIP (POTT)

A permissive overreaching transfer trip (POTT) system was selected as the secondary protection scheme for the transmission line. The POTT system utilized numerical distance relays with direct relay-to-relay logic communication to reduce the complexity and cost of both the relay scheme and the communications equipment. Forward-looking distance elements of the relays at both ends of the line are set to overreach the line in a POTT system. An RS-232 data link over a T1 communications channel on the fiber-optic network is used to control tripping of the relays, such that the relays on both ends must agree that they see the fault in the tripping direction before a trip can occur. Permission to trip is sent on one channel for both single phase or multi-phase fault types, while another channel is used for multi-phase faults only. If the communications channel is lost, the relays block the communications-assisted tripping function and revert to a basic step-distance scheme with three-pole tripping only.

If the segregated phase comparison relay (i.e., the primary system) fails or is removed from service, the POTT system still provides complete line protection as well as single- pole tripping and reclosing through its logic. Similarly, if a relay in the POTT system fails or is removed from service, the segregated phase comparison relays still provide complete line protection as well as single-pole tripping and reclosing through their logic.

APPLICATION OF RELAY-TO-RELAY LOGIC COMMUNICATIONS FOR SINGLE POLE TRIPPING SCHEMES

The POTT logic was implemented using relay-to-relay logic communication. Programmable relay logic equations allow the numerical relays to send trip permission on one channel for both single phase and multi-phase fault types and on another channel for multi-phase faults only. The resulting system is simpler and more economical than traditional single-pole tripping relay systems.

In the traditional POTT scheme, the teleprotection equipment consisting of an audio tone transmitter, receiver and output relays is separate from the protective relays. This equipment serves as the interface between the protective relays and the communications channel. In the relay-to-relay communications scheme of Figure 3, the protective relays are directly connected to the communications channel, thereby eliminating the external audio tone interface.

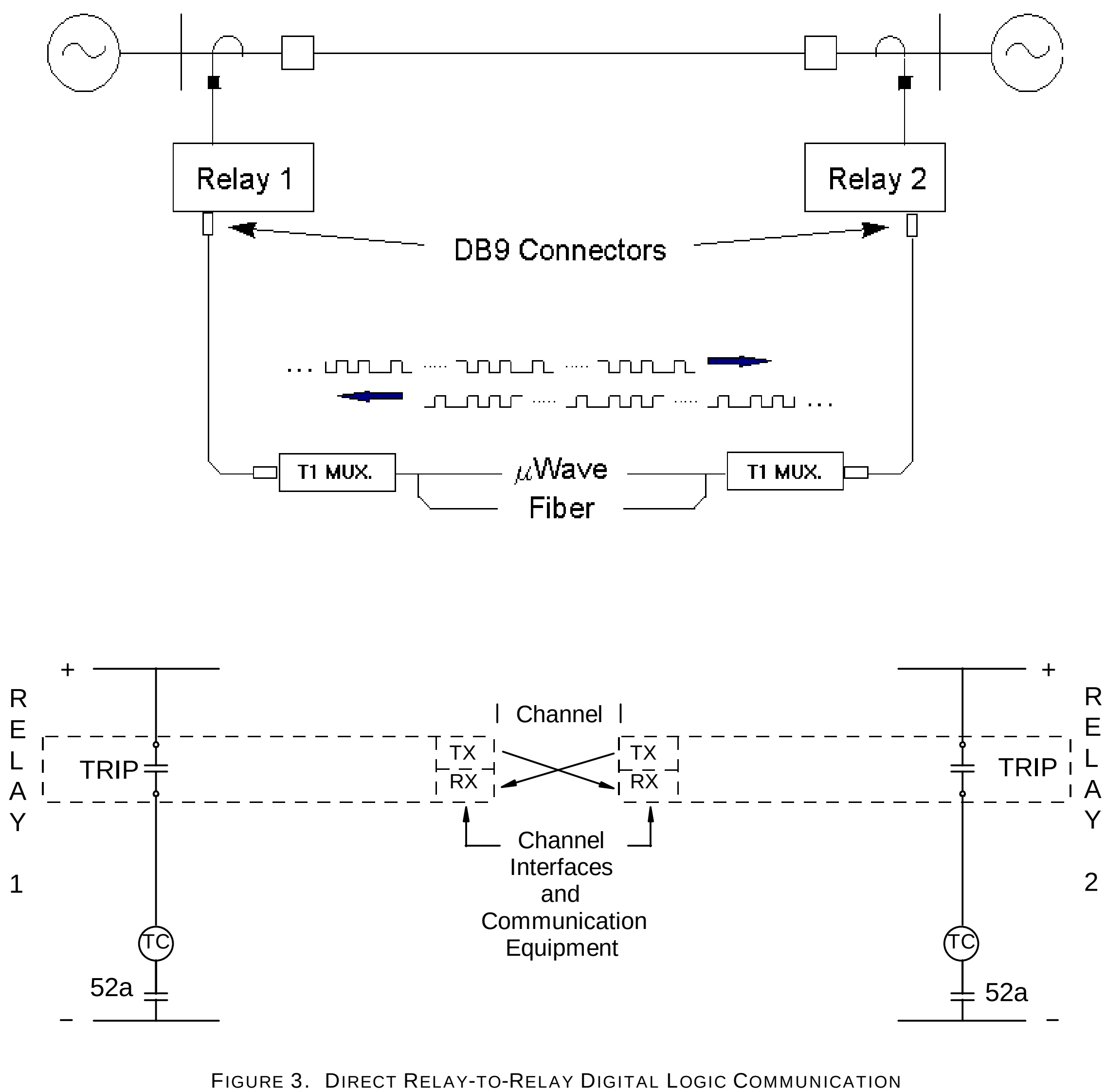
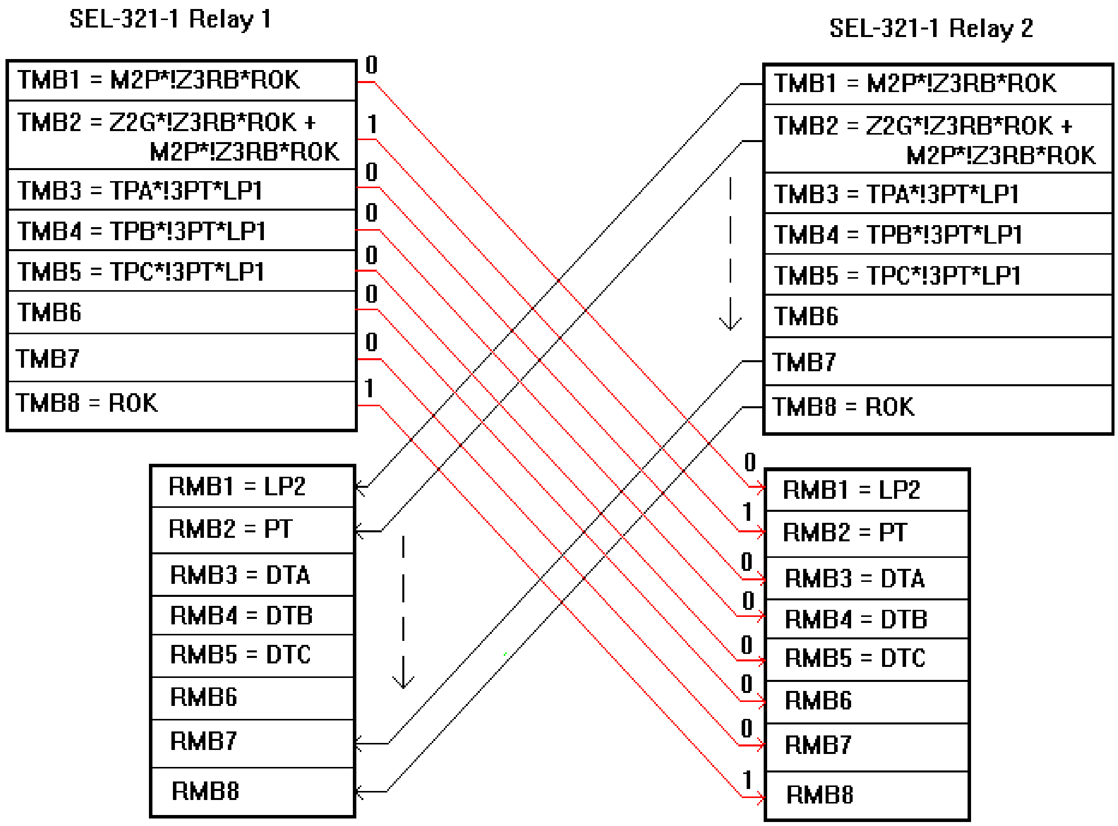


FIGURE 3. DIRECT RELAY-TO-RELAY DIGITAL LOGIC COMMUNICATION

Relay-to-relay logic communication repeatedly sends the status of eight programmable internal relay elements, encoded in a digital message, from one relay to the other through an RS-232 serial communication port. In Figure 4 the status of each of the eight transmit bits (TMB1 - 8) in the local relay is sent to the eight receive bits (RMB1 - 8) in the remote relay, and vice versa, via the communication channel.



TMB1 - MULTI-PHASE FAULT INDICATION
TMB2 - PHASE-GROUND OR MULTI-PHASE FAULT INDICATION
TMB3 - SEND TRANSFER TRIP PHASE A
TMB4 - SEND TRANSFER TRIP PHASE B
TMB5 - SEND TRANSFER TRIP PHASE C
TMB6 - NA
TMB7 - NA
TMB8 - CHANNEL MONITOR

RMB1 - THREE POLE TRIP RECEIVE
RMB2 - SINGLE POLE TRIP RECEIVE
RMB3 - TRIP PHASE A
RMB4 - TRIP PHASE B
RMB5 - TRIP PHASE C
RMB6 - NA
RMB7 - NA
RMB8 - CHANNEL MONITOR

FIGURE 4. RELAY-TO-RELAY LOGIC COMMUNICATION

Each transmit mirrored bit (TMB) is programmed as an output contact with a programmable logic equation that represents the status of an internal relay element, control input, or any combination of these using AND gates, OR gates, or inverters (eg., permission sent). Similarly, each Receive Mirrored Bit is assigned as an input (eg., permission received) to be used in the trip and report logic words. For example, the communications aided trip word (MTCS) in the two relays in Figure 4 would be:

MTCS = Z2G* ROK + M2P*LP2*ROK + M2P*ROK*!SPTE,   where:

MTCS = Communications aided trip word requires logic in its equation to be satisfied as well as an input (PT) from the remote relay to activate the logic equation. When the equation is satisfied, the relay determines the type of fault and trips the appropriate breaker pole for a single phase fault or three-pole for a multi-phase fault.

Z2G*ROK = Trip single-pole, with Zone 2 ground (Z2G), channel in service (ROK), and a permissive trip (PT) received.

M2P*LP2*ROK = Trip three-pole, with Zone 2 phase (M2P), a multi-phase fault bit received from the remote end (LP2), channel in service (ROK), and a permissive trip (PT) received.

M2P*ROK*!SPTE = Trip three-pole, with Zone 2 phase (M2P), channel in service, single-pole trip disabled (!SPTE), and a permissive trip (PT) received. The !SPTE is a local blocking switch to disable single pole tripping.

As shown earlier in Figure 3, the relay-to-relay logic communications is interfaced to the network communication multiplexer through an RS-232 card inserted in the multiplexer rack ("T1" in Figure 3). In this application, the relay communications output is ported through an industry standard 25-pin D-Subminiature connector. A metallic cable connects the relay output to Channel 2 of the twenty-four DS0's available in the intelligent T1 multiplexer via an asynchronous data channel module. The asynchronous data channel module is capable of multiplexing up to either four 9600 bps or two 19.2 kbps RS-232 data signals into one or two DS0s. High speed sampling rates keep the jitter for each data signal to within 16 uS p-p for the 9600 bps POTT channel. One of the four sub rate channels are utilized for the POTT function.

If the multiplexer is located more than 15 meters from the protective relays, the relay serial communication port may be connected to the asynchronous data channel module with a fiber-optic cable and fiber-optic transceivers. Fiber-optic communication is recommended between the relay and the T1 multiplexer equipment to eliminate any effect of electrical interference from the substation environment.

BACKUP PROTECTION, INPUTS, AND OUTPUTS FOR THE POTT SYSTEM

The POTT relay system also contains a complete three-zone stepped directional distance scheme with back up phase and ground overcurrent elements. The distance elements are in service along with the POTT scheme logic and remain in service even if the POTT communications channel fails or is removed from service. Both the stepped distance and backup protection will only initiate three-pole tripping. In addition to the directional distance and backup overcurrent functions, the POTT system also provides fault location, loss of potential detection, and loss of current detection functions. The number of inputs and outputs required to implement single pole tripping with the POTT system is comparable to the number used in the phase comparison relay system.

THE "CROSS-COUNTRY FAULT"

In double-circuit line applications requiring single-pole tripping, problems can arise for the simultaneous ground faults shown in Figure 5. Both lines experience single phase faults near Millsite, but on different phases. Highland #1 has a phase B-to-ground fault, while Highland #2 has a phase C-to-ground fault.

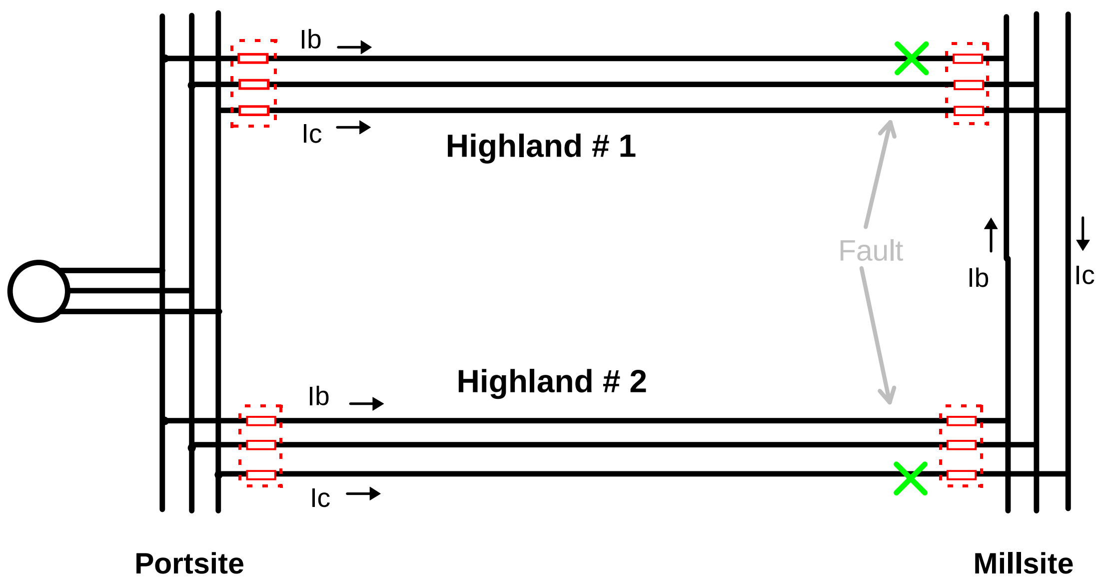


FIGURE 5: DOUBLE-CIRCUIT LINE WITH SIMULTANEOUS GROUND FAULTS

Because the segregated phase comparison system monitors the currents at each line terminal on a per-phase basis, it will correctly recognize the system disturbance as separate single-line-to-ground faults and trip the appropriate pole of the breakers. To the POTT system, the faults appear phase-to-phase-to-ground to the distance relays located at the left hand station, but they appear as single phase-to-ground at the right hand station due to the current distribution. This problem diminishes as the fault moves towards the middle of the line. Since the distance relays at the right hand station correctly identify the faults as single phase and are within the reach of Zone 1, tripping at both terminals is instantaneous and independent.

The difficulty arises with the distance relays at the Portsite station prior to the single pole opening of the breakers at the Millsite station. The distance relays for Highland #1 and #2 identify the fault as BCG at the Portsite station. (See Figure 6.) A multi-phase fault requires tripping of all three breaker poles. If a permissive trip signal from the right hand station arrives while an overreaching Zone 2 phase distance element is picked up, then an undesirable three-pole trip results for both line breakers at the left hand station.

FIGURE 6: HIGHLAND #1 LINE RELAY PHASOR DIAGRAMS FOR SIMULTANEOUS GROUND FAULTS ON BOTH LINES

To avoid this problem, a provision must be made to identify the mismatch in fault type identification between the distance relays at both ends of either line. This requires at least two communication channels, ie., one for transmitting three pole trip permission for multi-phase faults only (KEY1) and another for transmitting permission for any fault type (KEY2). Logic in the distance relay is set up to allow single pole tripping only for the receipt of KEY2 and detection of a single line to ground fault. Three pole tripping is only allowed for receipt of both KEY1, KEY2 and detection of a multi-phase fault. The logic for this is shown in Figure 7. For example, if the local relay receives permission to trip all three poles and identifies the fault type as SLG, then the local relay issues a single pole trip for the phase identified by the phase selection logic. However, if the local relay identifies the fault as multi-phase and does not receive the required three pole permissive trip signal, then tripping is suspended until one of the following events occurs:

1. The relay receives a three pole permissive trip signal.
2. The local relay phase identification logic changes to SLG.

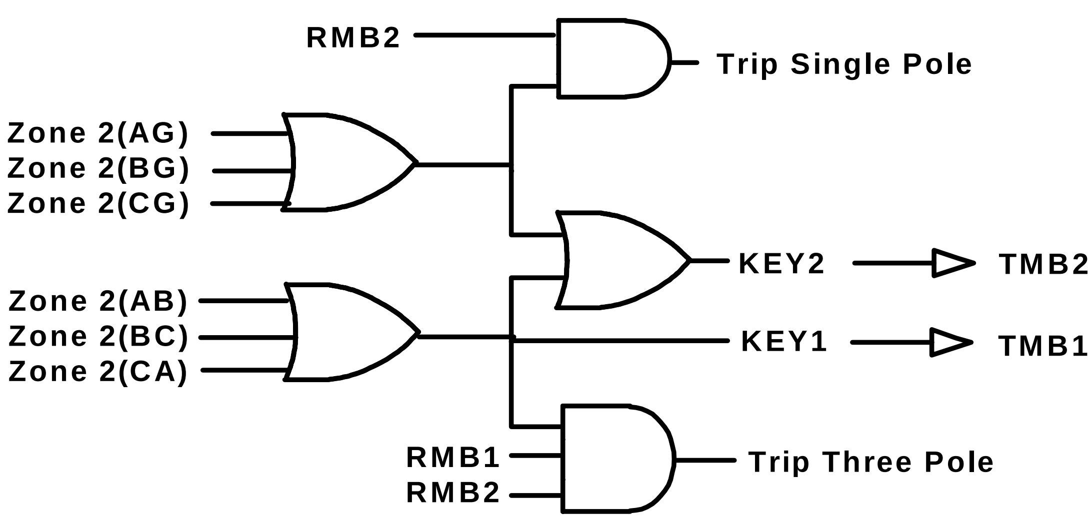


FIGURE 7 RELAY KEYING AND TRIPPING

A third condition was also added to increase the single-pole trip speed of the system by reducing the time required for the remote terminal to recognize a SLG fault. It was implemented as shown in Figure 8 by programming three unused TMBs such that when the relay recognizes a SLG fault it will send a direct transfer trip signal to the remote terminal to trip the corresponding phase of the breaker. This is very similar to a permissive under reaching transfer tripping scheme, except this will only operate for SLG faults.

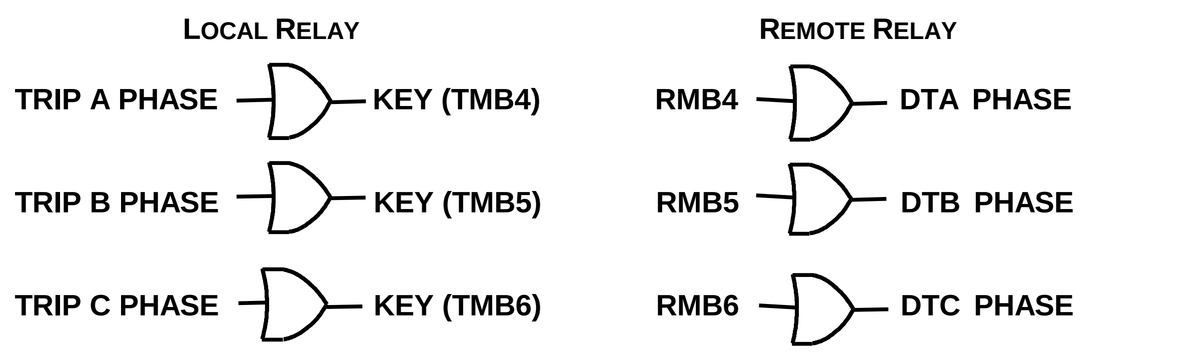


FIGURE 8: SLG UNDER-REACHING LOGIC

POTT Settings

The relay applied for this application was microprocessor based with phase and ground distance elements, programmable internal logic, and relay-to-relay communications. The settings were derived based on the line impedances, load current, communications channel, and logic needed to perform single pole tripping.

Because the single pole open interval following a single pole trip is very similar to an open conductor fault, the system voltage and current become unbalanced. The voltage unbalance typically causes zero-sequence voltage to appear in the relay VT circuits. At the same time, zero-sequence currents appear in the residual circuit of the line CTs. The combination of zero-sequence voltage and current can cause some directional relay elements to misoperate. Non-directional ground overcurrent relays connected in the residual circuit of the CTs must be set above the maximum unbalance current for an open-phase condition, or they must be blocked.

SINGLE POLE AND THREE POLE AUTOMATIC RECLOSING LOGIC

Single pole tripping helps maintain system stability due to the synchronous power flowing through the remaining two phases. However, it generally requires a longer period of time before the open phase can be restored to service. The longer open pole interval, or “dead time”, is required because the electrostatic and electromagnetic coupling between the open phase and the two energized phases prolongs the arc on the faulted phase. Thus, more time is required to allow the ionized gases in the vicinity of the fault to dissipate after a single pole trip than if all three poles had tripped. For example, the dead time after a three pole trip on a 230kV line at 60Hz is typically 20-22 cycles. The minimum dead time after a single pole trip calculated for the 60 mile 230kV line described in this paper was 30 cycles. Therefore, 40 cycles was chosen for the single pole reclose interval to allow some margin for error while limiting the open interval period to as short a time as possible. Simultaneous single pole reclosing at both line terminals is presently permitted. In the event of a three pole trip, three pole reclosing of the faulted line is permitted, as long as the other line does not also trip. The single pole and three pole reclosing logic for the 230kV line can be summarized as follows:

With either or both channel aided schemes (Phase Comparison or POTT) in service,

a) A single phase-to-ground fault causes an instantaneous trip of the faulted phase only. A single pole reclose follows with a 40 cycle intentional delay to allow time for arc dissipation. If the fault is there after the first reclose, then all three poles of the breaker are tripped, and no further reclosing is initiated.

b) A fault involving two or more phases causes an instantaneous trip of all three poles. If only one line tripped and the other line is in service, all three poles of the line breakers that tripped can be reclosed in 30 cycles. The Minesite end could reclose after a 1.5 second delay for live bus - dead line. If the fault is there after the first reclose, the breaker would be tripped again, and no further reclosing would be initiated. The Portsite end (where the generators are) could then reclose 1.5 seconds after the Minesite end by synchronism check only. If both lines tripped, or if one of the lines was already out-of-service when the faulted line tripped, no three pole reclosing would be initiated. Although provision was made in the reclosing design for Option b, the decision was made to implement only Option a at the present time.

Part of the Portsite ring bus appears in Figure 9. Since the line breakers at the Portsite are connected in a ring bus design, one breaker will reclose first and if successful, the second breaker will close. The reclose logic can also detect if one line breaker is out of service and will transfer the reclose to the second line breaker.

A microprocessor relay was chosen to implement the logic described above. The reclosing relay includes standard and user programmable logic and allows control of two breakers. Some of the standard features include:

- Two-breaker control.
- Voltage checking/sync check for each breaker.
- Separate timers for single pole and three pole reclosing.
- Auto swap to breaker in service.
- Manual close supervision.
- Single pole reclose over-ride if a three pole trip is issued after a single pole trip.

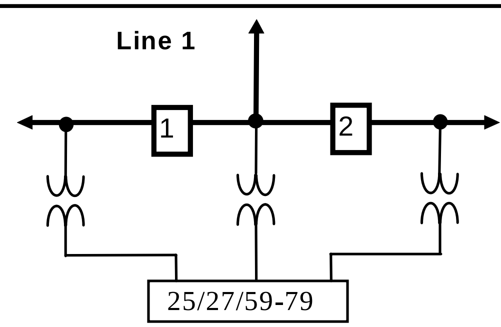


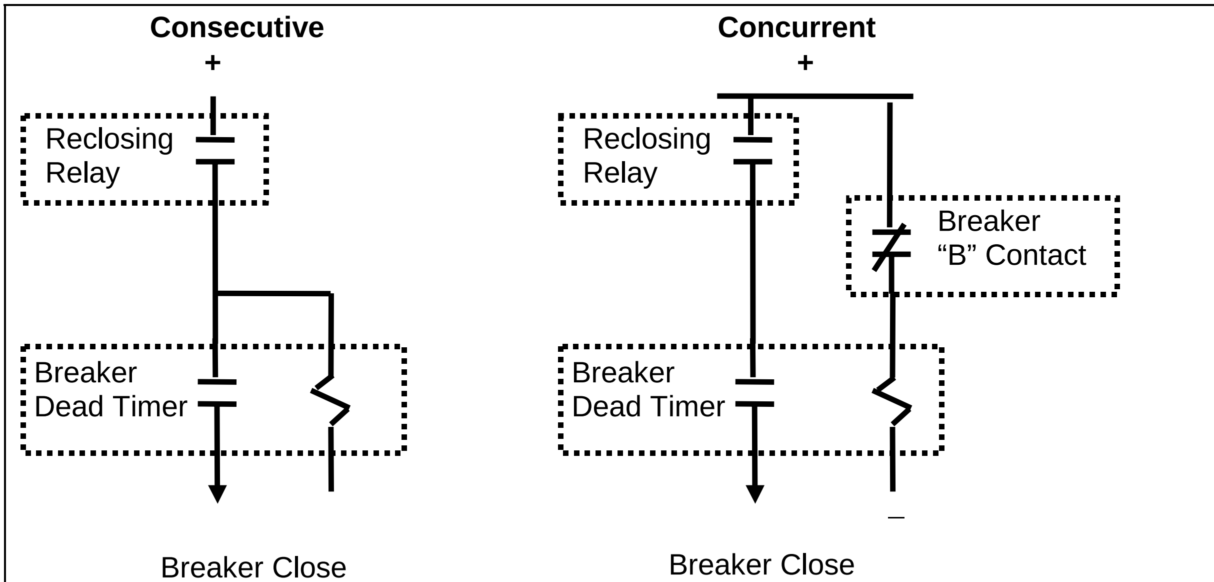
Figure 9: VT CONNECTIONS TO RING BUS FOR RECLOSING RELAY

Additional logic was programmed to perform the following:

- Block three pole reclose if line 2 is out of service.
- Block single pole reclose if both line pilot schemes are out of service
- Allow reclose blocking of one breaker with the other breaker recloser still in service.
- Reclose blocking of both breakers will disable single pole tripping.

BREAKER DEAD (CLOSE) TIMER

In most breaker control schemes the close circuit includes a dead timer. The timer is intended to prevent premature closing of the breaker after a fault has occurred. As discussed earlier in the paper, the dead timer setting for a 230KV line is typically 20-22 cycles. The activation of this dead timer and the reclose timer must be coordinated to achieve the desired line reclose time for a proper reclose. This timing is even more important when employing a single pole tripping scheme. To calculate the proper coordination time, the user must first determine if the two timers operate consecutively or concurrently by reviewing the breaker control scheme. In most breakers, the dead timer is controlled by a breaker close (most common) or by a breaker “b” contact, as shown in Figure 10.



Consecutive		Concurrent	
Reclosing Relay Time	= 20 Cycles	Reclosing Relay Timer	= 40 Cycles
Breaker Dead Timer	= 20 Cycles	Breaker Dead Timer	= 20 Cycles
Total Reclose time	= 40 Cycles	Total Reclose Timer	= 40 Cycles

FIGURE 10: CONSECUTIVE AND CONCURRENT BREAKER RECLOSE

BREAKER POLE DISAGREEMENT

In breakers where the three poles (contacts) are not mechanically connected, a pole disagreement scheme is used to detect an open phase condition. An open phase condition can generate substantial negative-sequence currents in rotating machinery on the power system. These currents cause excessive heating of the rotors, which can lead to premature machine failure if the currents persist. Thus, care must be taken not to allow an open phase condition to exist for a long period of time. A general solution to this problem is to apply one or more breaker pole disagreement schemes. In a single pole tripping scheme one of the phases will be open for a longer time than is normally required for a three pole trip scheme. This additional time must be set up to allow the open pole to reclose but still be set to provide protection for an open pole condition. The basic operation of such a scheme is that an open phase condition is permitted for a short time period, after which the pole disagreement relay(s) trip the remaining poles of the breaker. The pole disagreement scheme can be implemented in the line protective relays, or hardwired using breaker auxiliary contacts and timers in the breaker control cabinet. In our application there were three pole disagreement schemes. The more common scheme using breaker “a” and “b” contacts was used in the breaker. In addition, each of the line protective relays included a scheme to sense an open pole. The timer in each of these schemes was set longer than the expected reclose time of a single pole operation but short enough to prevent excessive heating in the generators.

BREAKER FAILURE PROTECTION

Because the breaker is an important part of the protective system, the calculations engineer should always include a review of the consequences of a breaker failure condition. In this system the consequences of a breaker failure severely affect system stability and can cause damage to both the transmission line and the generators. In addition, a violent breaker failure can cause catastrophic physical damage to nearby equipment or personnel in the station.

The basic philosophy in designing a breaker failure scheme is to detect a problem in which the “breaker fails to clear” during a trip operation. This could include any of the following conditions:

- Breaker failing to open.
- Control or wiring problems.
- Failure of breaker trip coil.
- Open “a” contact in the breaker trip circuit.
- Re-strike across open breaker contacts.

The scheme designed for this system included the above conditions, plus considerations for single pole tripping, ring bus design, generator faults and low fault currents. Traditional breaker failure relays using two phase elements and a residual ground element for overcurrent detection often cannot be used because the residual ground element cannot be set above the maximum unbalance current. In such cases, a breaker failure relay having three separate phase units should be applied. The relay chosen was microprocessor based and included the ability to use multiple schemes to provide the best protection. In this application two schemes were used. The first scheme uses a fault detector and timer to detect faults on the transmission line, bus or generator. This timer is set to allow other breakers to clear the fault before the system goes unstable. The second scheme uses a very low set fault detector to detect problems in the generator or the failure of the breaker to interrupt load current. The timer for these faults can be set longer, without regard to system stability.

In order for the breaker failure scheme to operate properly for single pole tripping, the relay must operate on a per phase basis. This requires a separate trip input for each phase, single phase fault detectors and a timer for each phase. The separate trip inputs were provided by three outputs from each line protective scheme. This allowed the line relays to only activate one phase of the breaker failure relay for single pole trips and to activate all three for a three pole trip. Outputs from the generator relays also provided three-phase trip inputs to the breaker failure relays.

Since the station breakers are connected in a ring bus, the fault currents flowing through individual breakers can be low for line or bus faults due to the split of the current between the two breakers and the low magnitudes of available fault current. This may cause the line relays to operate before the fault current in the breakers can exceed the breaker failure overcurrent detector setting. Once the first breaker is open, the fault current in the other breaker may be seen by the breaker failure relay's fault detector. Since this may extend the time of the breaker failure trip, a scheme was selected to start the 62B timer when the trip input is activated. This is performed by using an additional timer (62T). The 62T timer is started when a trip input is activated, but it is set to drop out before the 62B timer operates. This allows the breaker failure relay system to start timing, but it will also cause the 62B timer to stop if the 50B detector does not pick up before the 62T times out.

Figure 11 shows the logic diagram for Breaker Failure Scheme 1.

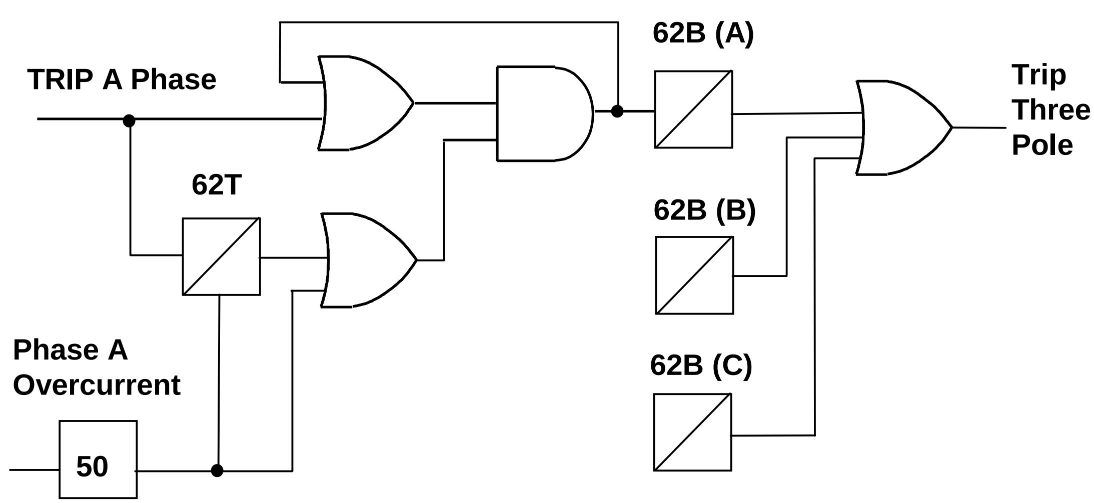


FIGURE 11: BREAKER FAILURE TRIP SCHEME

The second breaker failure logic scheme shown in Figure 12 uses a more sensitive overcurrent fault detector and operates a timer with a longer delay setting. In this scheme the concern is sensitivity and not stability. The overcurrent fault detector is set below line charging current, and it will detect if the breaker fails to interrupt load current. It also provides sensitive protection for low-value faults in the generator.

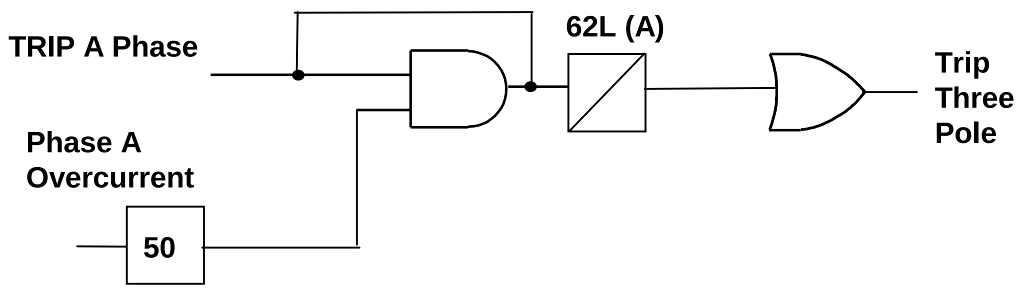


FIGURE 12: SENSITIVE BREAKER FAILURE SCHEME FOR LINE CHARGING AND LOAD CURRENT INTERRUPTION

COMMUNICATIONS SYSTEM

FIBER OPTIC PROTECTION NETWORK DESCRIPTION

Two 12-fiber singlemode optical ground wire (OPGW) cables transport the communication signals and serves as a backbone communications path. The mining company's digital microwave system is also available as an alternate path to serve the communication requirements described herein. This section concentrates on the fiber-optic communications used by the two high-speed protective relay schemes for the Highland #1 and #2 primary and secondary line protection.

Figure 13 depicts the Portsite end of the point-to-point fiber-optic protection network application. The communications channel for the primary protection system for the Highland #1 Line interfaces into the first channel of a dedicated intelligent T1 multiplexer. The communications channel for the secondary protection system for the Highland #1 Line interfaces into the first channel of a second independent intelligent T1 multiplexer. Similarly, the communications channels for the primary and secondary protection for the Highland #2 Line interfaces into the second channel of the two T1 multiplexers. Additional communications functions such as a voice service channel, 9600 bps asynchronous data channel, four-wire RTU (Remote Terminal Unit), direct transfer trip (DTT), and load shedding are also multiplexed together with the primary and secondary protective relaying communications, as shown in Figure 14a.

Each of the intelligent T1 multiplexers has an electrical DS1 (1.544 Mbps) interface card for the T1 - Binary Eight Zero Substitution (B8ZS) signal that connects into an intelligent line switch (ILS). Four fibers are dedicated for each ILS; two for primary fiber path communications and two for the backup fiber path communications. An ILS can be provisioned to interface into the digital microwave system by selecting the electrical DS1 interface unit or via an optical interface adapter (OIA). The OIA requires a 1550 nm wavelength laser to meet the sixty mile point-to-point communications requirements without a repeater.

Failure of the fiber, a splice junction, laser, detector, or a poor bit error rate will automatically be detected by the ILS and switched to the available backup fiber pair in as little as 1 mS. The ILS will revert to the primary fiber pair upon restoration of the failure.

The design concept of Protection Communications Network #1 and #2 provides protection for a catastrophic failure in either network. In Figures 14a and 14b, a complete fiber cable failure in Communications Network #1 (primary and backup - all four fibers) will still leave the primary protection for the Highland # 2 Line and the secondary protection of Highland #1 Line intact over on Communications Network #2. Figures 14a and 14b represent an overall system description of everything introduced above, and will serve as a reference for the following auxiliary functions section.

AUXILARY FUNCTION CHANNELS

<u>Voice Service Channel:</u> An automatic ring-down (A.R.D.) voice service channel provides the technician with telephone voice communications between each site. A built-in ring generator allows off-hook detection to cause the telephone to ring. Voice communications is obtained over the FXS (Foreign Exchange Service) channel that converts voice into 64 kbps in channel three of the twenty-four DS0's.

<u>Four Wire Remote Terminal Unit (RTU):</u> A four-wire voice channel module is included for the existing supervisory control and data acquisition (SCADA) master to poll a Remote Terminal Unit (RTU) modem.

<u>Direct Transfer Trip 1 and 2 :</u> The Portsite terminal of the DTT tone system is shown in Figure 15. The teleprotection channel (designated as DTT Teleprotection Terminal 1 and 2) selected for this scheme is a four-channel, frequency-shift audio tone device programmable for direct transfer trip (DTT) applications. Channels 1 and 2 and Channels 3 and 4 for the Highland #1 Line provide DTT redundancy to enhance both security and dependability. Each terminal has two separate four-wire interfaces which enable Channels 1 and 2 to operate over T1 multiplexer Network 1 and Channels 3 and 4 to operate over T1 multiplexer Network 2. The second DTT Teleprotection Terminal provides the same type of protection for DTT tripping of the Highland #2 Line.

The DTT teleprotection channel can be applied with 56 kbps or direct fiber; however, in this application audio tones were selected for several human engineering reasons, such as trip and guard interposing relay indications, multi-channel routing, and testing. Each module adapter is capable of six voice channel interfaces. The dual-channel, four-wire voice channel module utilizes two DS0 time slots in the intelligent T1 multiplexer, thereby providing the two independent interfaces for the DTT teleprotection terminals.

<u>Load Shedding Scheme:</u> A modular teleprotection system (MTS) card can provide up to four functions in each direction that can transfer a contact status. The MTS card is a direct module that plugs into the intelligent T1 multiplexer and occupies one 64 kbps DS0. Two of the MTS cards are used for generator off-line load shedding. A second function for the MTS card is to allow access from a remote location via network management software to interrogate the system's absolute delay. The MTS has an event record that can be triggered

when the measured delay exceeds a predetermined value. An alarm and event record will be produced if the delay approaches the 4.0 mS delay tolerance for the segregated phase comparison relay.

COMMUNICATION SYSTEM TIMING CONSIDERATIONS

Recovery Time: An important aspect of the fiber optic network is its ability to heal itself after a failure. This healing takes a brief period of time while the protection communications channel is out of service. The time from the loss of the protection communications channel to the restoration of the channel through an intelligent line switch (ILS) is called the recovery time. The duration of the recovery time will depend upon the complexity of the system. In Figure 16, the total recovery time for the Portsite to Millsite system consists of the following individual times:

Switch Time: The time from a catastrophic communications link failure to the injection of DS1 traffic onto the backup fiber path. Switch time is made up of two components; Failure Detection Time and actual switch-over time. The intelligent line switch used on this system can switch based on a path or fiber failure in less than 1 mS.

Reframe Time: The time for a T1 multiplexer to reframe upon appearance of valid data. The intelligent T1 multiplexer utilizes a DS0 time slot to provide a "Fast Reframe Channel" to speed up the recovery process to reduce the reframe time to within 1ms. The typical reframe time of a channel bank with no special means of fast reframing is 5 - 50ms.

Resynchronization Time: The time from a catastrophic communications link failure to the reappearance of valid data from the multiplexer DS0 channel cards.

Protection Resynchronization Time: This time applies to digital protection channels which must frame to their own word structure once the DS0 data is available. This depends on the type of protective relay.

Protective Guard Time: This refers to the time a protection device squelches its output while ensuring that no misconnection has occurred. Typically addressing or guard before trip delay is the major component of this time.

In the event of a trip simultaneous with a communications failure, the total recovery time should be taken into consideration when estimating the total trip time. Figure 16 shows the recovery time to include resynchronization time, protection resynchronization time, and protection guard time. A poor bit error rate (BER) on protection network 1 will enable a switch over to protection network 2 (known as recovery time defined herein) in approximately 4 mS.

DETERMINING TOTAL SYSTEM COMMUNICATIONS DELAY

In Figure 14a the absolute (one-way) delay of a data word from the segregated phase comparison relay can be traced from the Portsite to the Millsite. The segregated phase comparison relay's data message word will take 187.5 uS to frame into the DS1 Extended Super Frame (ESF) code. The DS1 code will have a 25 uS delay through the intelligent line switch (ILS).

The propagation delay by definition is the delay of the optical communications signal at the speed of light through the fiber, measured as 8 uS per mile. Therefore, the total propagation delay is 480 uS.

The same delays take place as the signal passes through the ILS, the intelligent T1 multiplexer, and the DS0 channel card to the input of the segregated phase comparison relay at the Millsite terminal. The total absolute (one-way) channel delay is therefore the sum of the above delays and is equal to 905 uS.

Each segregated phase comparison relay takes approximately 1.6 mS to encode or decode its data message word. Therefore, the inherent delay of the segregated phase comparison relays is 2 x 1.6 mS = 3.2 mS. The total SPCR system delay from end to end is therefore:

1. SPCR Inherent Delay = 3.2 mS
2. Fiber Channel Delay = 0.905 mS

Total SPCR system delay = 4.1 mS

The absolute delay of the relay-to-relay communications channel for the POTT relay system can also be traced in Figure 14a. At the multiplexer, the asynchronous data channel module encodes the POTT data signal into the DS1 in 250 uS. The same process takes place at the remote location for a total DS0 contribution delay of 500 uS. The total propagation delay of the fiber path is the same as for the segregated phase comparison relay, namely, 480 uS. The total absolute (one-way) channel delay is therefore the sum of the above delays and is equal to 1030 uS.

If the relays used in the POTT system are connected back-to-back in the lab via an RS-232 cable, the total time required to initiate an input at the transmitting relay is approximately 2.1 mS. The time required by the transmitting relay to send the logic status changes to the receiving relay and assert the required elements in the receiving relay is 4.2 - 6.3 mS at 9600 bps. Therefore, the total time to send a signal between two relays connected back-to-back is 6.3 - 8.4 mS. The total POTT system delay from end to end is therefore:

1. Relay - Relay Communications Inherent Delay = 4.2 - 6.3 mS
2. DS0 - DS0 Communications Inherent Delay = 0.5 mS
3. Fiber Path Propagation Delay = 0.48 mS

Total POTT system delay = 5.2 - 7.3 mS

The relay engineer can now take the above into the total protective relaying and pilot scheme's delay figure which will include:

1. Fault recognition time by the protective relay.
2. Total absolute delay of the communications system.
3. Interposing trip relay (if necessary).
4. Trip relay operate time.
5. Breaker actuation delay time.

Determining Fiber Optic System Gain, Loss and Margin

The measured signal attenuation delay over the singlemode fiber is 0.483 dB/mile. A splice loss of 0.05 dB/splice will occur and there is a splice located every 1.25 miles. Connector loss is assumed a 1 dB each. The total system gain, total system loss, and total system margin can be calculated for protection network in figure 14a or 14b as follows:

System Gain Calculation:	System Loss Calculation	System Margin Calculation
Laser TX Out = 0 dB	Splice Loss = 2.4 dB	System Gain = 39 dB
(-)Det. RX IN = -39 dB	Atten. Loss = 28.98 dB	(-) System Loss = 33.38 dB
Total Gain = 39 dB	Conn. Loss = 2.0 dB	Total Margin = 5.62 dB
	Total Loss =33.38 dB	

DIGITAL RELAY COMMUNICATIONS AND DELAY ISSUES

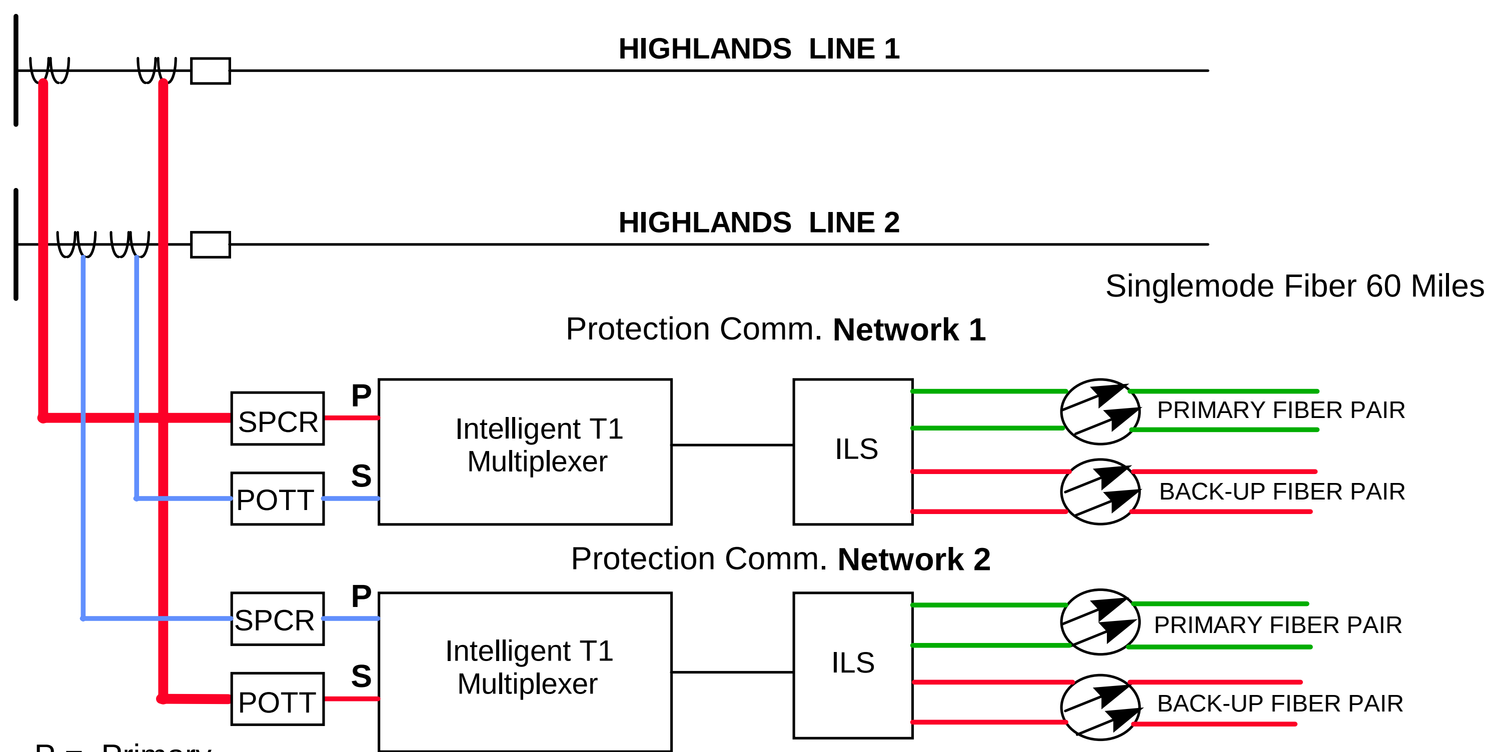
Two protective relays with built-in digital communications are shown in Figure 17. The selection of a communications device and the communications medium can adversely affect the performance of the protection system. For example, traditional POTT relay schemes have been applied with external frequency shift audio tones (such as the DTT teleprotection channel) over leased telephone lines, private cable, analog and digital microwave, spread spectrum microwave, and direct fiber. In recent years this has led to the external digital communications channel that can multiplex both POTT and DTT over a digital microwave, spread spectrum microwave, T1 multiplexers, or direct fiber. The POTT / DTT system has even evolved into the DS0 type modular teleprotection system (MTS) described earlier for load shedding. These industry adaptive changes have led to the built-in relay-to-relay communications applied in the POTT system used for line protection between the Portsite and Minesite Stations.

In all the examples above, one form of inherent delay or another resides in the pilot communications. In the case of audio tone pilot channels, wide or narrow bandwidth filters in audio tone equipment change the delay characteristics of a single channel frequency shift audio tone from 8 mS to 12 mS (340 Hz versus 170 Hz filters, respectively). A digital communications channel can sample the data message word several times such as 3 out of 5 voting, thus introducing an extra 3-5 mS of delay. The MTS card in the intelligent T1 multiplexer encodes the four functions into a data message word that also may take 3-5 mS of delay.

Prior to this technology, relay engineers made a decision to apply a contact closure to an external pilot communications device such as power line carrier, dedicated leased lines, dedicated fiber, etc. The protective relay engineer when applying digital relay communications signals must **consider the effect that the communications medium has on the total absolute delay of the system**. The communications medium may not be dedicated, and therefore the digital relay communications signal must interface with an asynchronous or synchronous DS0 interface card for use over a DS1, line switching device, or perhaps higher order multiplexers such as Synchronous Optical Networks (SONET).

Protective relaying dependability can be severely degraded for communications line switching coincident with a fault. The recovery time in this case can take as long as 60 mS over a SONET system. A recent Bell Laboratories certification entitled “System Test”; documents timing issues relative to applications that utilize a SONET lightwave system as the fiber optic communications media for transporting the protective relaying control. The paper on SONET multiplexers & intelligent T1 multiplexers addresses several of the Recovery Delay issues defined herein as well as the elimination of the 60ms outage associated with the standard SONET path protection switch algorithm.

Portsite Double Circuit 230KV Line
Four Fiber Protection/Communication Network



P = Primary
S = Secondary
SPCR = Segregated Phase Comparison Relay
POTT = Permissive Overreaching Transfer Trip
Line 1 Primary & Secondary Relaying
Line 2 Primary & Secondary

Figure 13

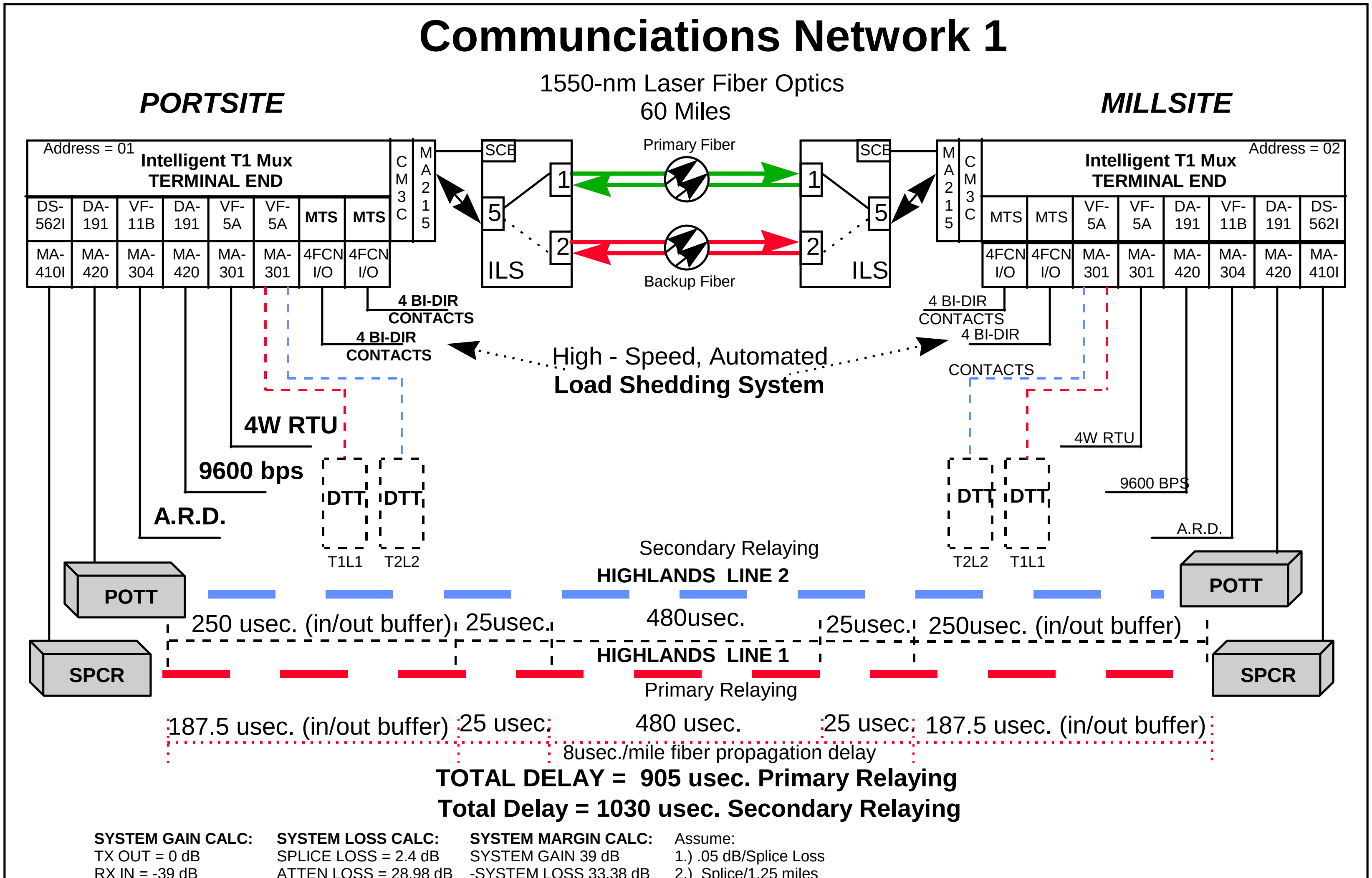
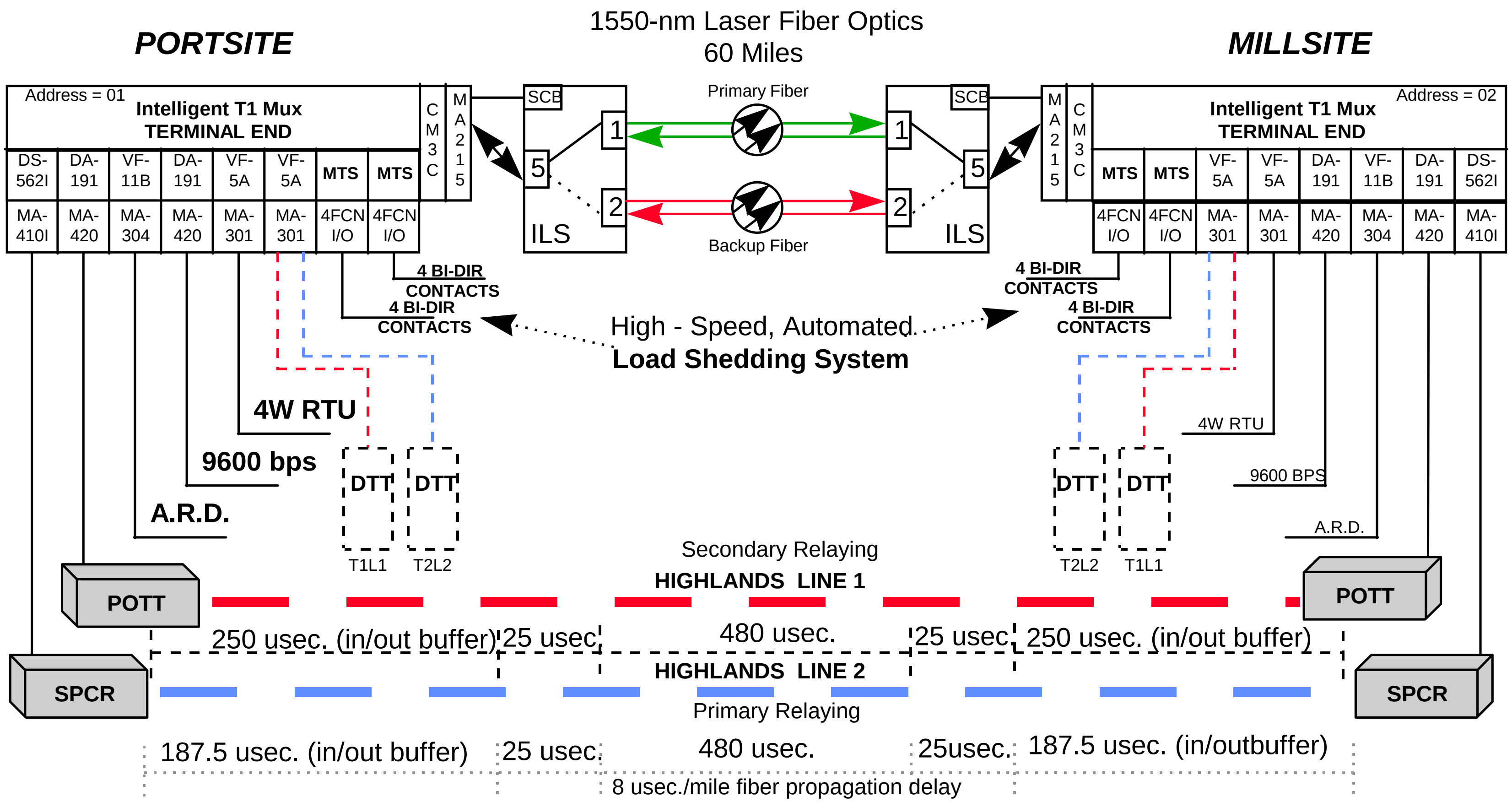

Communciations Network 1
1550-nm Laser Fiber Optics
60 Miles
PORTSITE
MILLSITE
Address = 01
Intelligent T1 Mux
TERMINAL END
DS-562I
DA-191
VF-11B
DA-191
VF-5A
VF-5A
MTS
MTS
MA-410I
MA-420
MA-304
MA-420
MA-301
MA-301
4FCN I/O
4FCN I/O
CM3C
MA215
SCB
ILS
1
2
5
Primary Fiber
Backup Fiber
Address = 02
Intelligent T1 Mux
TERMINAL END
4 BI-DIR CONTACTS
4 BI-DIR CONTACTS
High - Speed, Automated
Load Shedding System
4W RTU
9600 bps
A.R.D.
9600 BPS
DTT
DTT
T1L1
T2L2
POTT
SPCR
Secondary Relaying
HIGHLANDS LINE 2
250 usec. (in/out buffer)
25usec.
480usec.
25usec.
250usec. (in/out buffer)
HIGHLANDS LINE 1
Primary Relaying
187.5 usec. (in/out buffer)
25 usec.
480 usec.
25 usec.
187.5 usec. (in/out buffer)
8usec./mile fiber propagation delay
TOTAL DELAY = 905 usec. Primary Relaying
Total Delay = 1030 usec. Secondary Relaying
SYSTEM GAIN CALC:
TX OUT = 0 dB
RX IN = -39 dB
Total Gain = 39 dB
SYSTEM LOSS CALC:
SPLICE LOSS = 2.4 dB
ATTEN LOSS = 28.98 dB
CONNECT LOSS = 2 dB
Total Loss = 33.38dB
SYSTEM MARGIN CALC:
SYSTEM GAIN 39 dB
-SYSTEM LOSS 33.38 dB
Total Margin = 5.62 dB
Assume:
1.) .05 dB/Splice Loss
2.) Splice/1.25 miles
3.) .483 dB/mi atten. loss

Figure 14a

Communications Network 2



TOTAL DELAY = 905 usec. Primary Relaying
Total Delay = 1030 usec. Secondary Relaying

SYSTEM GAIN CALC:
TX OUT = 0 dB
RX IN = -39 dB
Total Gain = 39 dB

SYSTEM LOSS CALC:
SPLICE LOSS = 2.4 dB
ATTEN. LOSS = 28.98 dB
CONNECT. LOSS = 2 dB
Total Loss = 33.38 dB

SYSTEM MARGIN CALC:
SYSTEM GAIN 39 dB
-SYSTEM LOSS 33.38 dB
Total Margin = 5.62 dB

Assume:
1.) .05 dB/Splice Loss
2.) Splice/1.25 miles
3.) .483 dB/mi atten. loss

Figure 14b

Portsite Power Plant

Direct Transfer Trip Communication Channels

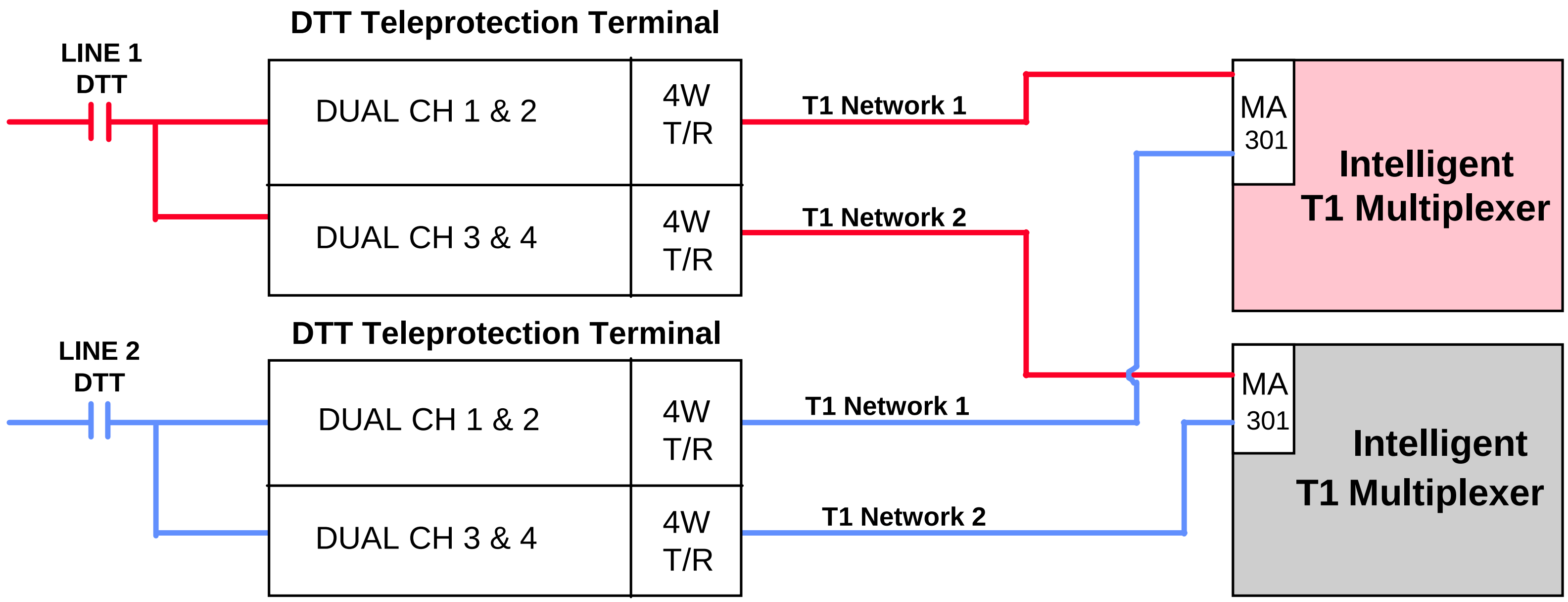


Figure 15

Communications Network

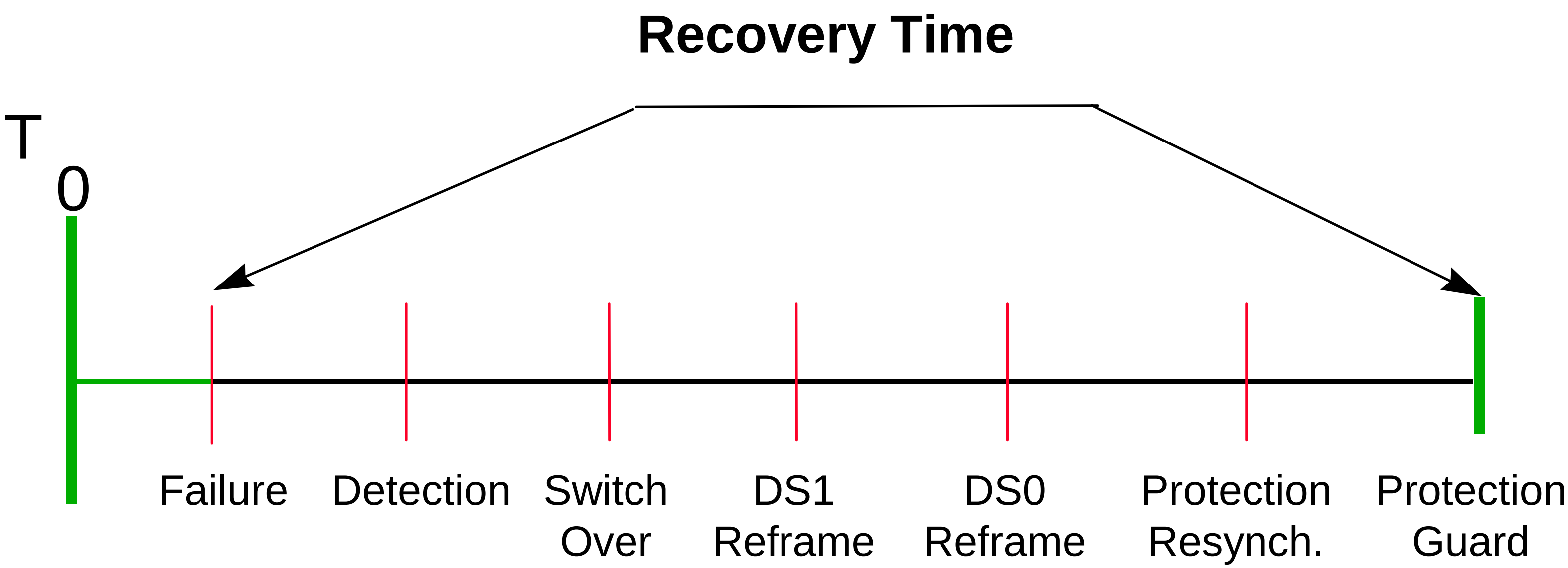


Figure 16

Intelligent T1 Multiplexer - Electrical DS1 (I/O) Multiplexed Protective Relaying & Communications Functions

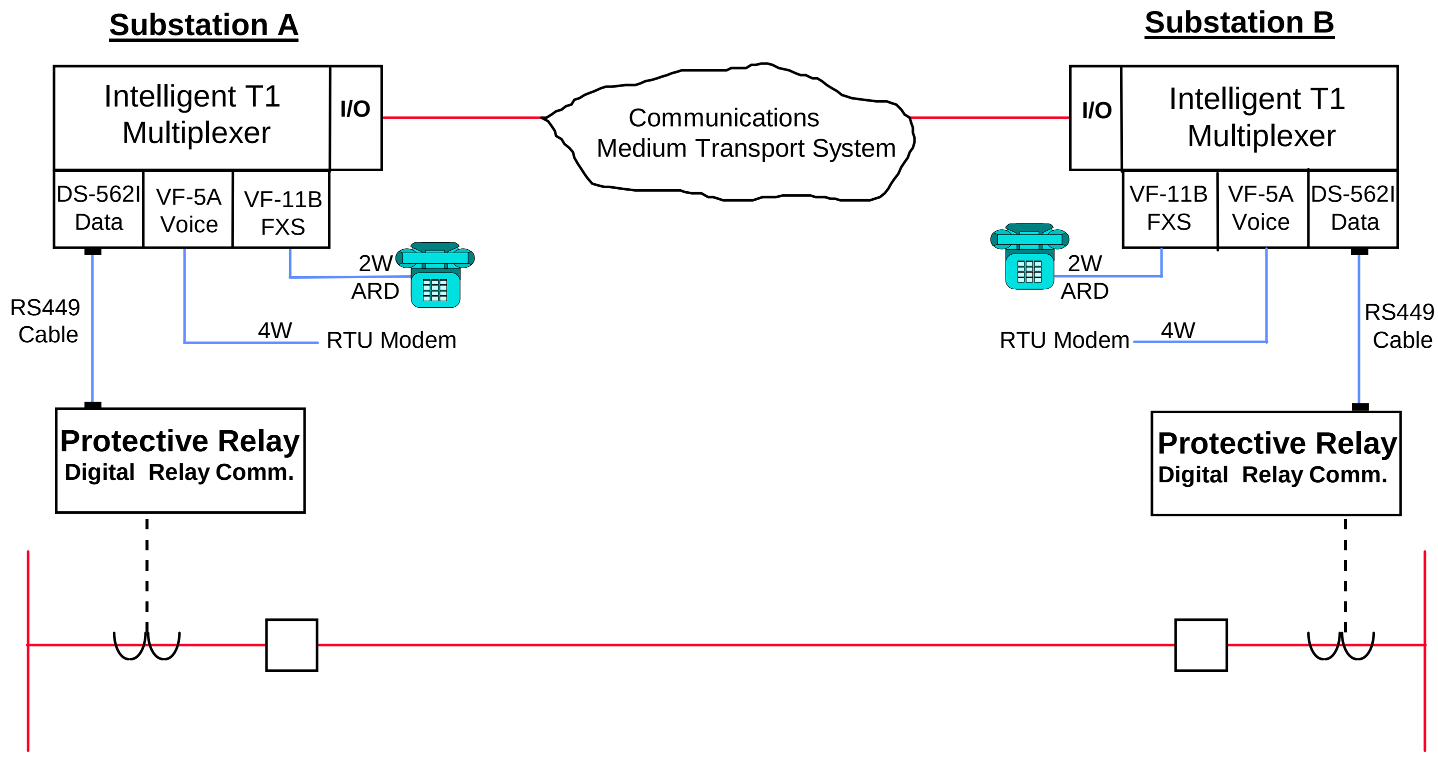


Figure 17

FIELD COMMISSIONING TESTS

Field commissioning tests for a single pole protection system using digital relay logic are simplified because the equipment is numerical; thus, there are fewer pieces of equipment to test and much less external contact logic to verify. As the user gains more experience in applying numerical equipment in protective relay schemes, the number and complexity of commissioning tests in the field decreases. For example, the user's initial practice is generally to test the operation of every function in the numerical relay in the same way that static or electro-mechanical relays are tested. As the user's understanding of numerical relays increases, so does his or her comfort level concerning their ability to operate correctly. At that point, commissioning tests of numerical relays become a matter of verifying that the settings were properly applied, performing a functional check of the inputs and outputs, and verifying that the relay operates correctly in the system or scheme in which it is applied.

Once the relay DC in the panel has been checked for correct polarity and voltage level, the DC can be applied to the numerical relays so that settings can be applied. This is often most easily done by establishing local communications with the relay through a laptop computer and using the appropriate communications software to input the relay settings. An internal relay diagnostics check (CPU status, alarms, I/O status, etc.) is usually done at this time. Each of the relay input circuits (52a, 52b, auxiliary relay, or switch contacts) must then be checked to verify that they will energize the correct input on the relay. The output circuits (trip, close, breaker failure initiate, etc.) are then checked to verify correct operation.

The polarity and connections of the VT and CT inputs to the relay can be checked in a variety of ways using secondary voltages and currents. The metering functions of the relay can also be checked at this time. Sometimes unexpected things can happen while ac inputs to protective relays are being tested. For example, while the relay test set at the Portsite was away for repairs, the test crew was checking the CT inputs and current monitoring functions of the relays by injecting secondary currents on each phase. Rather than blocking the trip outputs of all the relays on the panel, the test crew simply turned off the DC to the breaker (The ring bus had not yet been energized.) and began injecting phase-neutral current at the terminal block on the breaker. When they increased the current to check the metering function of the relays, they exceeded the trip current setting of the backup overcurrent relay, which operated to trip the breaker. Since the breaker had its DC turned off, the breaker failure relay operated and tripped the breaker on each side. After their initial panic, the test crew realized what had happened, and decided that their unplanned breaker failure scheme test had gone well.

Having checked the relay's metering functions and its external input and output circuits, the relay's ability to operate correctly for a power system fault is then tested by applying selected faults to the relay and externally monitoring contact closure. Selected zone impedance settings and zone trip times are verified for impedance elements while the trip times at specified currents are verified for overcurrent elements.

The segregated phase comparison and POTT schemes are tested by first verifying that the relay communication channel is in service and that the relays are communicating with each other. Verification of the segregated phase comparison relay's channel status can be obtained by monitoring the "Channel RX" bit and the channel propagation delay reading from the front panel of the segregated phase comparison relay. The segregated phase comparison relay trip scheme can then be tested by applying an internal fault to one relay terminal and verifying that the relays at both terminals tripped. Verification of the POTT relay's channel status can be obtained by monitoring the "ROK (Receive OK)" bit status of the POTT relay by executing a "Target 20" command. The change in status of the transmitted mirror bits can then be verified via the laptop computer when a Zone 2 phase or ground fault is applied to the relay. For example, if the mirrored bit for a ground fault is sent from the “remote” relay while a forward Zone 2 ground fault is applied to the “local” relay, the local relay should operate to trip the breaker and show “communications-aided trip” targets. The test may then be repeated for a Zone 2 phase fault, then both tests repeated with the “local” relay serving as the “remote” relay.

Testing and verifying the operation of single pole tripping systems can be very confusing at times because of all the details that must be remembered. For example, just to get a correct single-pole breaker trip via the POTT system requires that the pilot channel input to the relay be enabled, that the pole disagreement timer setting in the breaker is coordinated with the pole disagreement time setting in the numerical relays, and that the test current shuts off as the breaker trips. Similarly, verification of the single pole breaker reclosing scheme requires that the reclosing relay receives a reclose initiate signal at the same time that the breaker trips, that the reclose time setting in the relay is coordinated with the “dead time” timer setting in the breaker, and that the pole disagreement timer setting in the breaker is coordinated with the pole disagreement time setting in the numerical relays.

As a rule, the number of periodic maintenance tests for numerical relays is few and far between. As long as the relay failure alarm does not assert, the operability of the relay is assured. When periodic maintenance testing is required, local communications should be established with the relay via a laptop computer. The relay status and monitoring functions, including metering, should be checked. Next, the trip output should be checked, either by applying a fault to the relay or by executing a trip command from the laptop computer. If the relay passes the above tests, it may then be returned to service.

OPERATIONAL EXPERIENCE

The 230 KV lines were commissioned in the fall of 1997. During Plant start-up at Portsite, the system has been operated with the Highlands #1 Line out of service and the Highlands #2 Line in service to improve the system voltage regulation. The performance of the line protective system so far has been excellent.

During the rainy season in Irain Jaya, we have had four line trips to date. In all of the trips, the protective system operated as expected, and the line breakers reclosed as designed. Of the four trips, three were phase-to ground faults and the fourth was a multi-phase fault. The following are details on the four trips as detected by the Portsite relays:

- Phase A to ground - Distance to fault 44 miles, auto reclosed.

- Phase A to C to ground - Distance to fault 40 miles, did not reclose. (By design there is no auto reclose for multi-phase faults.)

- Phase B to ground - Distance to fault 39 miles, auto reclosed.

- Phase C to ground- Distance to fault 40.2 miles, auto reclosed.

In Figure 18, the graph shows the event report from the Portsite relay for the last fault. The fault occurred during a lightning storm. As indicated by the phase currents, Ic increases during the fault to just over 1000 amps and is cleared in 3.5 cycles when "C" pole of the breaker opens. The graph also shows the other two phases continuing to supply the load, and the current on those phases increases by 20%. The source of the voltages shown on the graph is a set of line side CVTs. The graph shows a depressed "C" phase voltage during the fault followed by a much lower level of voltage after the breaker "C" pole opens. With the "C" pole open, a small "C" phase line voltage is still present due to coupling from the other two energized phases.

The digital channels shown in Figure 18 were selected to best illustrate the protective elements, communications channel bits, and tripping of the breaker. As indicated by the graph, the first element in the relay to sense the fault is the instantaneous ground overcurrent (50G) used to supervise the distance elements. This is followed by the distance ground zone 2 (21G-2) element around a cycle after the start of the fault. Since this is a permissive tripping scheme, the 21G-2 element also sends a transmit bit (TMB2) to the other end of the line. (Logic for this is in figure 7.)

When the permissive receive bit (RMB2) is received by the local relay with the 21G-2 element still picked-up, the relay issues a trip signal (TPC) to breaker pole "C" . When the breaker "a" contact of "C" pole opens, relay input IN3 drops out, indicating that the breaker pole has opened.

The last digital point on the graph is RMB5. This is the bit used in the permissive under-reaching transfer tripping scheme (Figure 8). This logic is performed when the remote relay trips single pole and sends a transmit bit to trip the local breaker pole. As indicated by the received signal, the remote relay tripped by "C" phase and transfer tripped to the local relay as indicated by RMB5. RMB5 is a direct trip for the breaker "C" pole.

CONCLUSION

A single-pole protection scheme was the most cost-effective and reliable solution to the problem of clearing power system faults quickly while maximizing the stability and continuity of service of the power system. While the logic required for single-pole tripping and reclosing can be quite complicated, the use of numerical protection relays and digital relay communications greatly reduces the parts count and wiring required to implement the system. However, the protection engineer must be careful when applying digital relay communications schemes to consider the nature of the communications medium and equipment. The protection engineer can no longer assume that the signal delay between two relay terminals will always be short or the same at all times.

The use of numerical relays in protection schemes can also offer the added benefits of real-time metering and sequence of events recording, either as primary systems on their own or as backup equipment. While the value of real-time metering during normal power system operation is obvious, real-time metering can also be of great value during system commissioning as a final check of instrument transformer connections, ratios, and polarity. The relay's sequence of events recording function is an invaluable tool for use in determining how well the relays and breakers performed during a power system disturbance. Additionally, the event histories of the other numerical relays in the station can be correlated to yield a surprisingly complete and accurate snapshot of what all the major pieces of substation equipment saw at the time of the system disturbance.

The same microprocessor technology that permits protective relays to do communications and communications equipment to do relay protection has also changed the way that we view protection, communications, control, and data acquisition systems in general. It is no longer enough to simply be a relay engineer or a communications engineer. The protection, communications, control, and data acquisition systems we design and specify must work together as an integrated system, and we as engineers can expect to find ourselves learning whatever we must in order to be good system integrators as well as good relay engineers.

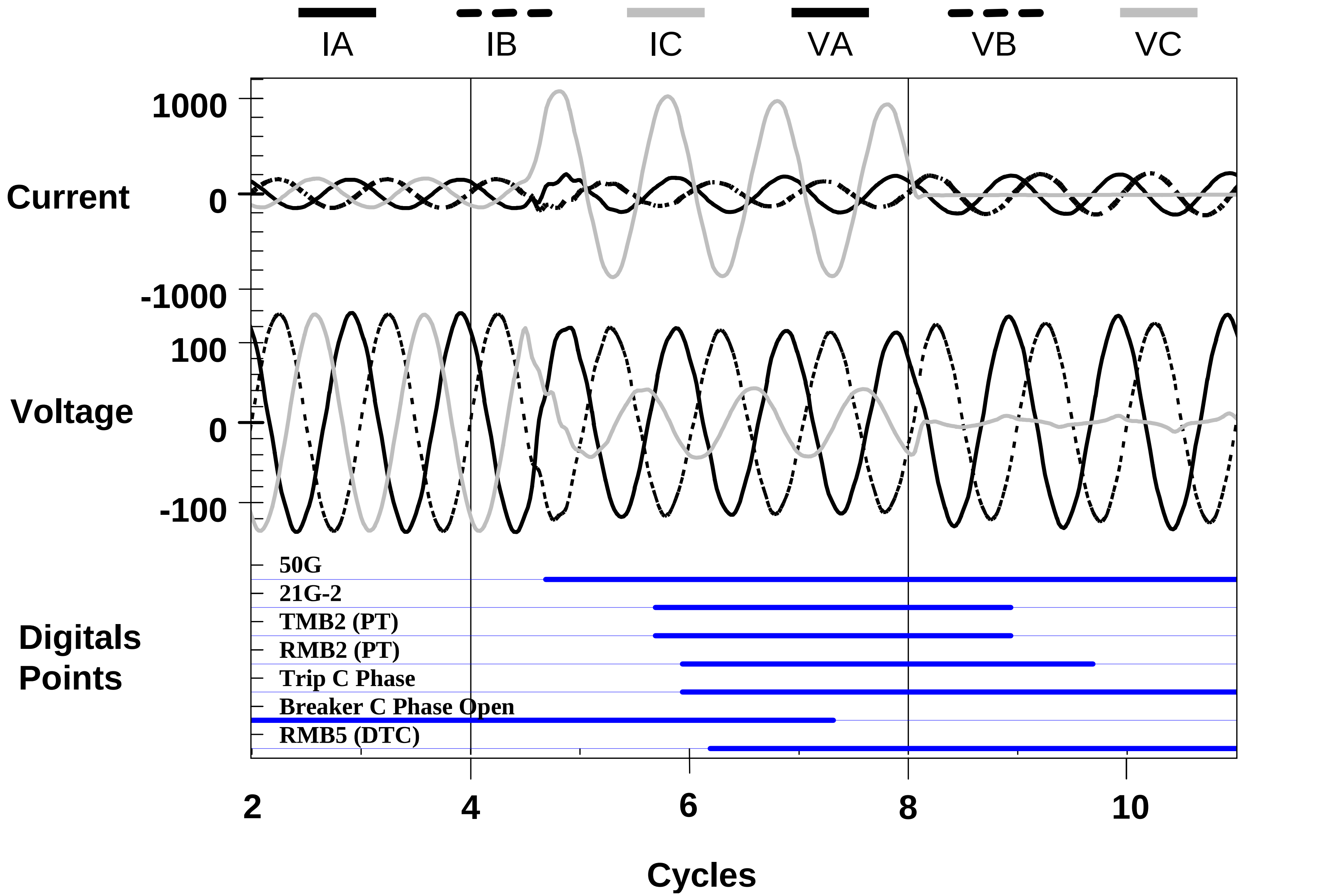


Figure 18 Graph of Single Pole Trip

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BIOGRAPHICAL SKETCH

Barry W. Jackson received his BSEE from North Carolina State University in 1973 and is a registered engineer in North and South Carolina. He started work at Duke Power Company in the area of protective relaying and has held various positions in the protection area for the last 25 years. He is presently a Sr. Engineer in the Provide Technical Direction group of the Plan the System Process. Barry's responsibilities include new equipment evaluations, development of new standards, engineering support and analyses of equipment performance. He is a member of IEEE and has written several technical papers on protective relaying.

Martin F. Best received his BSEE degree from North Carolina State University in 1976 and joined the Protective Relay Engineering Group of Duke Power Company in June of that year. He is presently a Senior Engineer in the Protective Relay Engineering Group of Duke Engineering and Services. Martin has over 20 years of experience in protective relay, control and instrumentation systems for transmission, distribution, and industrial installations, including relay setting calculation, power system fault analysis, relay equipment evaluation and problem solving, testing procedures, and protective relay, control, and instrumentation standards. He is a member of IEEE, holds one U.S. patent, and is a registered Professional Engineer in North Carolina, South Carolina, and Virginia.

Ron Bergen served four years in the U.S. Navy. He attended Aviation Electronics School and served as an Electronic Counter Measure Technician aboard the EC121K Super Constellation and as a Target Drone Launch Operator on the P2V. He attended Ventura County College and Morris County College.

Ron Bergen began his 31 year career at RFL Electronics Inc. as a Final Test Technician. He has worked as a Customer Service Engineer, Sales and Systems Engineer, and Teleprotection Product Manager.

Ron served as the National Sales Manager responsible for sales representatives and regional managers prior to moving to Charlotte, NC in 1990. His present position is Eastern Regional Manager.

Ron has written over six technical papers for presentations at various universities and trade shows. Ron is a member of the IEEE Society.