JUSTIFYING PILOT PROTECTION ON TRANSMISSION LINES

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Abstract

This paper concerns the justification of the use of pilot protection on transmission lines.

Members of the working group

Gary Kobet - chair
Bogdan Kasztenny - vice-chair
Mark Allen
Art Buanno
Albert N. Darlington
Alla Deronja
Hyder DoCarmo
Jerry Finley
George Gresko
Larry Henriksen
Mike Jensen
Bill Kennedy
Kazik Kuras
Vahid Madani
Walter McCannon
Mike McDonald
John Miller
Mukesh Nagpal
Jim O'Brien
Frank Plumptre
Elmo Price
Sam Sambasivan
Mark Simon
Jian Cheng Tan
Ilia Voloh
Solveig Ward
Ray Young

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1 Introduction

Pilot protection schemes use communication channels to send information from the local relay terminal to the remote relay terminal, thereby allowing high-speed tripping for faults occurring within 100% of the protected line.

This document is intended as a tool for protection engineers to assist in determining when pilot protection should be installed for transmission line protection, in addition to a communications-independent system. The emphasis is not on which pilot scheme to use, but rather if pilot protection is necessary. (Note: The document does not purport to provide a comprehensive list of all considerations that may be used in making this determination or in determining redundancy requirements.)

It is evident that it would be less expensive to only install non-pilot step-distance protection since no communication equipment would be necessary (estimates as high as $150K per terminal for the addition of pilot protection). It is prudent to provide engineering considerations that would aid in justifying the installation and future maintenance costs.

This report explores this issue by providing the following:

- Considerations to determine the need for, and benefits of, pilot protection such as high-speed reclosing, improved system stability and power quality, easier coordination, better resistive coverage, and regulatory issues.
- Alternatives to pilot protection and fall back strategies when the channel is lost or degraded, or when temporary configurations are entered. Options include stepped distance, ground inverse time overcurrent, Zone 1 extension, and taking the line out of service.
- Considerations to determine pilot system redundancy for a given application depending on the voltage level, regulatory issues and economics, role of voting schemes and redundant channels, dependability vs. security, etc.

2 Definitions

(Note: It is not intended that this section be comprehensive in defining all possible forms of pilot protection. Refer to the bibliography for more detailed description of pilot schemes. "**PSRC**" indicates the term is included in the IEEE Std C37.100 Dictionary of Terms.)

directional-comparison protection: A form of pilot protection in which the relative operating conditions of the directional units at the line terminals are compared to determine whether a fault is in the protected line section (**PSRC**). (Directional comparison schemes include phase, ground distance as well as directional ground overcurrent elements.)

directional comparison blocking (DCB): Transmit a block trip signal by a reverse looking element, with or without non-directional overcurrent start. Trip when blocking signal is not received and with supervision from a local terminal forward overreaching element.

directional comparison unblocking (DCUB): Send a blocking signal continuously, switch to permission from a forward overreaching element. Trip upon receiving permission, or temporarily after the loss of reception of the blocking signal, with supervision from a local terminal forward overreaching element.

direct underreaching transfer trip (DUTT): Operation of a local underreaching relay element initiates the transmission of a trip signal with no additional supervision.

direct transfer trip (DTT): Operation of a local control event initiates the transmission of a trip signal with no additional supervision.

line current differential (LCD): Remote and local terminal currents or composite currents are summed via data shared over fiber or other communication media. If the summation is above a threshold, fast tripping occurs. No need for potential devices.

permissive (as applied to a relay system): A general term indicating that functional cooperation of two or more relays is required before control action can become effective (**PSRC**).

permissive overreaching transfer trip (POTT): Transmit from an overreaching element, trip upon receiving permission with supervision from a local terminal overreaching element.

permissive underreaching transfer trip (PUTT): Transmit from a forward underreaching element. Trip upon receiving permission from the remote terminal and local fault detection element.

phase-comparison protection: A form of pilot protection that compares the relative phase-angle position of specified currents at the terminals of a circuit (**PSRC**).

pilot protection: A form of line protection that uses a communication channel as a means to compare electrical conditions at the terminals of a line (**PSRC**). (Line current differential and directional comparison fall under this category.)

pilot wire protection: Pilot protection in which a metallic circuit is used for the communications channel between relays at the circuit terminals. (These are older traditional schemes which are analogous to modern line current differential schemes.)

transfer trip: A form of remote trip in which a communication channel is used to transmit a trip signal from the relay location to a remote location (**PSRC**).

weakfeed trip: Transmit from a strong terminal, trip with low voltage supervision at weak terminal.

3 Background

Unlike most power system elements (e.g., transformers, capacitor banks, buses), the zone of protection for a transmission line is somewhat unique in that the limits of the zone generally extend to geographically separate locations. Those elements that are entirely contained at one location, along with their relay input sources, can have instantaneous tripping configured with few coordination problems. In order to effect high-speed tripping for 100% of a transmission line, each terminal of the protected line must communicate with the other terminal(s) in some fashion.

Selectivity of any protective relaying system is based either on measuring, directly or indirectly, signals at all boundaries of the intended zone or on measuring signals at one boundary only and depend on time coordination of protective relays to discriminate between in-zone and out-of-zone faults. In the case of protecting power lines, a time coordinated stepped distance scheme provides for instantaneous clearance of approximately 60% of internal faults assuming an average Zone 1 setting of 80% of the line, leaving the remaining 40% to be cleared with time delayed protection (typically 0.3 – 0.6 sec.). See Figure 1.

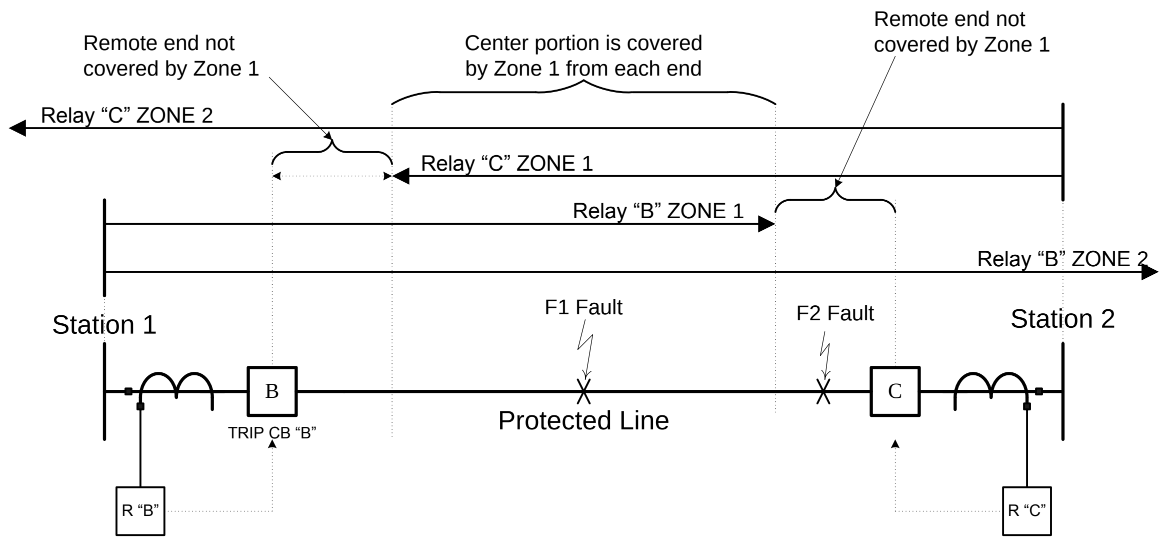

Figure 1. Step distance protection scheme

When comparing the measurements at all line terminals, high speed fault clearing is provided for the entire line. The only additional delays beyond a typical single measurement instantaneous operation are those associated with communicating data between terminals, which will almost never exceed one or two cycles and may be near zero in the case of some schemes and communication paths. This is the main benefit of pilot protection. However, as the zone boundaries are geographically dispersed, a communication medium is required to consolidate measurements from all line terminals. The capabilities of the applied communication channels may constrain the type of communication-aided protection scheme applied. Generally, either analog (continuous) or binary (discrete) signals are exchanged.

The use of analog or continuous signals is referred to as a “unit protection scheme” [1], and includes line current differential in the form of a pilot wire analog scheme or a microprocessor-based system based on digital communications. The use of binary or discrete signals is referred to as a “non-unit protection scheme” [1], or a “pilot assisted scheme” [2]. The local analog information is processed to a simple binary indication so that it can be communicated to the remote zone boundary using a single binary signal. The signal reports in-zone faults for a “permissive scheme”; or informs of out of zone faults or no faults for a “blocking scheme”.

Phase comparison relays use binary signals to encode continuous information regarding absolute phase of currents at the zone boundaries. Because the time coincidence of the binary signal exchanged between phase comparison relays is the encoding of an analog value for the relative angular direction of zone currents, phase comparison schemes are historically classified as “unit protection schemes”.

Each pilot assisted scheme is comprised of analog measurements and binary logic to drive the transmit signal as well as measurement and logic for tripping in response to the local measurements and received signal(s).

From the measurement point of view, pilot assisted schemes are classified as follows (see section 2 for definitions):

- Phase-comparison
- Directional-comparison
- Pilot-wire protection

From the point of view of transmit and trip logic, pilot assisted schemes are typically classified as follows (see section 2 for definitions):

- Directional comparison blocking
- Directional comparison unblocking
- Permissive overreaching transfer trip
- Permissive underreaching transfer trip
- Direct underreaching transfer trip
- Line current differential

Hybrid combinations are possible in both the measurement and logic parts as well as enhancements such as current reversal, weakfeed, zone acceleration or echo logic [2].

Practical applications of pilot assisted schemes require addressing several key issues associated with communications such as channel monitoring, channel redundancy, communication path routing, and desired response of the scheme under loss of channel.

4 Considerations to Determine Need for Pilot Protection

When considering the need for pilot protection for a transmission line, there is a difference between goals and means. Improved stability is a goal, while short fault clearing time is a means of achieving that goal. Utilities do not reduce clearing time on transmission lines just for the sake of it, but rather for technical reasons such as to improve stability, reduce equipment damage, improve power quality, etc. This section addresses several technical reasons for which a utility may require pilot protection on a transmission line.

4.1 Generator Angular Stability

Angular stability concerns itself with the transfer of real power across a power system. The classic equation

$$P = E_s E_r * \sin\delta / X$$

demonstrates that it is easier to increase transmitted power across the system by changing the angle between the equivalent sources than it is to change the sending and receiving end voltages. Dunlop et al in their classic development of the St Clair Curve showed the curve was in reality two curves in one: voltage drop and angle. Depending upon the short circuit strength at the sending and receiving ends, voltage drop takes precedence within the first 200 miles of line and angle across the whole system takes precedence above the 200 mile limit.

Typically, a transmission line can be loaded to about 45^o maximum across the line and the Thévenin equivalent source impedances at both ends. Usually this means the line itself is loaded to between 20^o to 30^o electrical. However, this is contingent upon the fault strengths as expressed by the Thévenin impedances at both the sending and receiving ends. When a fault occurs, the angle across the system will swing to a much larger angle and may exceed 90^o. System restorative forces will bring the system back below 90^o and the system will come to a new angle. For the protection on unfaulted lines, the distance relay sees this as a swing impedance that may or may not enter the tripping zones. However, once the faulted line is tripped, the unfaulted lines will see an increase in angle or increased voltage drop or both.

When a generator loses synchronism, the resulting high peak currents and off-frequency operation cause winding stresses, pulsating torques, and mechanical resonances that are potentially damaging to the generator and turbine shaft [3].

Generator stability can be of particular concern at stations having larger machines (1000 MVA and up), with larger generator per unit reactances and smaller inertia constants. Note that while this is certainly true for transmission lines terminated at generating stations, even faults on lines two or three buses away from generating stations can affect generator stability, depending on the system configuration, line impedances, etc.

The impact of system faults on system stability varies with fault location, fault duration and change in system configuration after fault clearing. Therefore, the critical clearing time to maintain generator stability should be determined by stability studies and compared with the total clearing times provided by both non-pilot and pilot protection. It may be necessary to consider breaker failure and/or remote back-up protection in the calculation of clearing times.

If the critical clearing time for faults on a transmission line in close proximity to a generating station is less than can be obtained with non-pilot time-delayed clearing, pilot protection can be required for stability reasons. This is true even if the machine or transmission line is equipped with out-of-step relaying set to trip on the first slip cycle, since it is prudent to avoid angular instability altogether (given the detrimental effects on the machine and to the power system performance).

4.2 Cascading Issues

Protective relays with the protected zone defined by their "reach" (sometimes referred to as "open-zone" protection) operate when the measured or derived quantity exceeds the pre-set threshold regardless of the systems conditions. The correctness of the operation of open-zone protection relies heavily on detailed system studies and fault level calculations, as well the protection engineer's expertise and familiarity with the protected line and surrounding power system. Setting and designing an open-zone protection system is often a trade-off between security and dependability.

It is interesting to note that distance elements in stepped distance schemes are coordinated in a cascading manner. This may exhibit a potential risk for cascading failures, if overreaching distance zones are employed with time coordination. There is a remote chance that a fault on an interconnected power system may trigger a chain of events, causing the overreaching distance elements to trip under extreme conditions, thus cascading into a large geographical area, eventually lead to a wide spread blackout.

Where cascading failure is of serious concern, pilot schemes with immunity to power swing and overloading conditions such as differential relaying scheme and permissive overreaching schemes may be justified.

4.3 Limit fault damage due to high fault current

Fault currents can cause thermal and mechanical damage to conductors and electrical equipment. There are tools available for the protection engineer to determine what protection is required to minimize damage. For example, transformer through-fault damage curves are provided in C37.91 IEEE Guide for Protective Relay Applications to Power Transformers. Likewise, there are damage curves available for conductors and thermal limits for insulators.

The heating effect of an electrical current is proportional to the square of the current and the length of time the current flows through the conductor (I^2t). Therefore, a thermal damage curve can be established for conductors. Similarly, a minimum I^2t value is established by manufacturers for insulators or other components used for termination of conductors.

On overhead transmission lines, conductor damage from short circuit can occur in two ways: "burn-down" and "annealing".

4.3.1 Burn-down

"Burn-down" refers to a conductor break resulting from the heating effect of an arc or the heat generated in a high-resistance connection, such as a poor splice. Conductor damage increases with the current magnitude and duration, so fast clearing of faults tends to reduce "burn-downs". Small wires burn down more readily than large conductors, and covered wires more readily than bare wire since the arc tends to travel on bare wire.

Another consideration is related to the overhead line equipment through which short-circuit current will pass, such as splices, connectors, switches, etc. Such equipment is generally specified to have thermal capacity equal to, or greater than, the conductor for the respective application. However, because of the long term corrosion or creep of metal, some components may develop high resistance, exceeding that of the conductor, and may be damaged, or become "burned-down" during a fault.

When a new station is constructed, or additional sources (positive or zero sequence) are part of an expansion project, the I^2t impact should be factored in the decision for the type of protection needed for the new equipment and a review of the existing equipment is warranted.

4.3.2 Annealing

An entirely different kind of damage occurs when short-circuit current flows through a line for a period long enough to weaken the wire by "annealing". Annealing could be progressed by slow clearing (for example, relying on sequential fault clearing or on un-fused taps of small wire located near a substation). Conductor damage as a result of annealing could be more extensive than "burn-down" since it may affect the entire line.

The manufacturer's conductor thermal limit or annealing curves assume no heat loss from the conductor during short circuit duration. In addition to the initial fault clearing, heating effects of circuit reclosing must be taken into account when rapid restoration is included as part of the scheme. When clearing is sequential, the I^2t value at the point of fault should take into account the effects of sequential clearing (current magnitude and total clearing time). When automatic restoration is designed and enabled, the total heating effect will be the sum of all clearing operations since no cooling effects are factored in between the clearing of the fault and the reclose. Locations with high fault currents should have protection and reclosing practices carefully evaluated taking conductor thermal characteristics into consideration.

Also, since the steel core does not anneal, an ACSR conductor retains most of its strength at the manufacturer's published values. However, annealing may occur at splices and insulator connections.

4.3.3 Other considerations

In addition to annealing or burning down conductors, high I^2t values during ground faults can fail insulators and, in some cases, damage tower footings.

When an insulator flash-over occurs, ground fault current flows across the surface of the insulator. When the I^2t exceeds 25×10^6 for porcelain or glass insulators, the insulator can be damaged. There are new non-ceramic insulators that the manufacturers claim to have much higher I^2t withstand value, but the published values may be difficult to obtain.

There are additional considerations for underground conductors and cables, such as the metallic shields or the insulation damage.

Optical ground wire (OPGW) is often used on new transmission lines. OPGW consists of optical fibers encased within a metallic conductor and serves the dual purpose of shielding the line from lightning (which includes being a path for ground fault current) and providing a communications path. A number of options for the mechanical structure of OPGW are available from different manufacturers and the individual conductor strands can be made of a variety of materials including aluminum, and aluminum clad steel. OPGW is designed for a maximum I^2t (expressed in kA^2-sec) to avoid damage to the optical fibers and their packaging. The I^2t rating can have a significant effect upon both the cost of the OPGW and the transmission structures themselves, as an increased I^2t rating requires more conductor strands and translates to a larger diameter and heavier OPGW. If the I^2t rating is exceeded, the communications capability of the OPGW will be placed at risk due to overheating and, in a more severe case, the mechanical parts of the OPGW may be damaged as well. To minimize risk of damage to the OPGW, the return current through the OPGW for ground faults during credible contingency cases should be calculated and multiplied by the clearing times to arrive at an I^2t rating for the OPGW. The effect of DC offset should be included in the I^2t calculation. The calculations may require the use of time domain simulation or frequency domain field effects programs. The use of pilot protection may be justified either on economic grounds (by reducing the OPGW and structure costs) or to avoid potential damage to existing OPGW.

4.4 Need for high-speed reclosing

At system equilibrium with no fault, mechanical power (P_m) equals electrical power (P_e), ignoring losses. When a fault occurs, equilibrium is disturbed and the synchronous machines accelerate. Accelerating power P_{acc} is equal to difference between P_m which, ignoring governor action remains the same during the fault, and P_e

$$P_{acc} = P_m - P_e$$

The acceleration of the electrical angle at opposite ends of the protected line is directly proportional to the accelerating power P_{acc} and inversely proportional to the inertia of the equivalent system, which is defined by the stored energy of the machines. Precise calculations of the electrical angle change during the fault and after the fault involves step-by-step procedures and determining all values at each interval of the calculations. From power-angle diagrams using equal-area criteria, the transient stability limit angle can be found. Comparing results of the electrical angle change from step-by-step calculations against transient stability limit angle would dictate critical fault clearing time for the protected line.

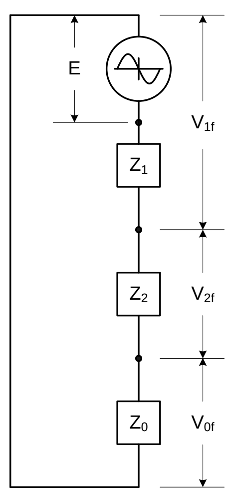

Figure 2. Phase-to-ground fault

V_{lf} is defined as the positive sequence voltage immediately after the fault. V_{lf} can be used to estimate requirement for high-speed tripping as P_e is proportional to V_{lf} (Figure 2). During normal conditions, i.e. no fault, V_{lf} is equal to P_e. Accelerating power (P_{acc}) is further proportional to the difference between prefault and fault positive sequence voltages at the point of fault. The smaller V_{lf} is, the faster the system is accelerating and the faster the system needs to isolate the fault. Typically, for $V_{lf} < 0.85$ pu, high speed tripping is required, and between 0.85 pu and 0.95 pu, normal tripping is sufficient. Acceleration continues until the breaker trips, at which time it changes to a new value, which typically is lower. During this time, termed the line dead time, the system continues to accelerate at a reduced rate. If the system in question is heavily networked, slow speed clearing may be acceptable (> 1 second). However, for higher voltage lines that transfer bulk power or are part of a critical network path, high speed reclosing may be required. This high speed reclosing will not be checked for synchronism and must be balanced against the requirement for de-ionizing the fault path. Typically, this value would be in the 0.5 second range. If the system can not accommodate this dead time because of stability or other considerations, single pole trip and reclose should be considered, which would allow longer dead times of up to 1 second.

4.5 Single-Pole Tripping and Reclosing

Single-pole tripping and reclosing brings vital advantages over three pole operation. Reduced impact of the recloser dead time on system stability, reduced impact of reclosing on generator and turbine shafts, increased availability of generation by avoiding re-synchronization, and improved power quality are among key benefits [4].

Recently, power quality improvements and efforts to keep distributed generation on-line are encouraging the application of single pole tripping and reclosing at lower voltage levels, including attempts on distribution feeders.

In theory, single-pole tripping and reclosing could be implemented in time-coordinated schemes without the use of a pilot channel. However, the extra technical difficulties related to coordinating individual phases, the need to coordinate with area backup ground elements, and the diminishing effect of delayed fault clearance make single-pole time-delayed (non-pilot) tripping applications impractical.

Combined with an instantaneous fault clearing when using pilot aided schemes, single pole tripping greatly improves system operation by reducing both the impact of the fault itself along with the reclosing operation that follows.

4.6 Network Lines with Long Service Taps and Multi-terminal Lines

4.6.1 Tapped Lines

Load centers that are off the networked line right-of-way may be served by looping the networked line into the station (for this discussion, it is assumed line circuit breakers will not be added at the load substation) or by creating a radial tap off of the networked line. Looped loads will have a limited affect on the network line protection. Relay coordination may be adjusted to allow for the increase in line length. Tapped loads will present challenges to the non-pilot terminals based on the location from the terminal and the length of the tap.

Under normal conditions, network line terminals will supply fault current based on distance to the fault and the source impedance behind the terminal. Faults that occur on line taps appear as high impedance faults to each terminal of the networked line. A network line may have multiple tap locations of varying lengths. Each tap should be studied for relay response and end-of-tap faults.

For taps located near either end of the networked line, the local terminal should detect bolted faults with instantaneous elements or within Zone 2 reach. The remote terminal should detect the bolted fault within Zone 2 reach (Zone 3, if present) and by available delayed overcurrent elements. At a minimum, the remote terminals should detect the bolted fault within Zone 2 reach and by available overcurrent elements once the local terminal has opened (sequential tripping).

For taps spaced along the networked line, both network terminals should detect a bolted fault at the remote end of the line tap within Zone 2 reach or by overcurrent elements. Following the opening of one of the network terminals, the remaining terminal should detect the fault within Zone 2 or Zone 1 reach and by overcurrent elements (sequential tripping).

If system conditions, stability, or customer needs preclude extended fault clearing times, pilot relaying should be applied. It should be noted that pilot relaying will not protect for extremely long taps. If the fault cannot be detected by standard Zone 3 elements, alternative forms of transmission service must be considered.

4.6.2 Multi-terminal lines

Multi-terminal lines are created by adding network terminals or by adding dispersed generation at a tapped load center. Additional sources on a network line interact to cause truncated relay reach (underreach). Each network terminal must be evaluated for normal conditions and for various contingencies where sources or terminals are out of service. As each terminal is opened, the remaining terminals must be evaluated for coordination.

Clearing times for multi-terminal lines will be longer. The ability to obtain instantaneous sequential clearing is reduced. The probability of a single terminal failing to detect the initial fault is greater. Breaker failure on one terminal may not be detected by the remaining terminals. A multi-terminal line configuration will in many cases require some form of pilot protection to provide dependable and predictable tripping, including dependable tripping for a breaker failure case.

4.7 Lines with Series Transformers as part of the line and no high-side (line voltage) breaker

Figure 3 shows a typical one line diagram of a breaker and a half configured station with two transmission lines (the first line being between the HV station and the transformer station, the second being fed by breaker 2 to a remote station). In this example, a transmission transformer is part of one of the lines, the transformer being at a remote location away from the station where the line breakers are located. The line which is providing the source to the transformer is equipped with line protection. Also, the transformer is shown with multiple levels of protection, with all transformer protection, including the sudden pressure and low oil detection, initiating the trip signal to the source location. In such applications, pilot protection is applied. When the transformer protection detects a problem, transfer trip signals are transmitted to the station to open the source breakers and block reclosing when applicable.

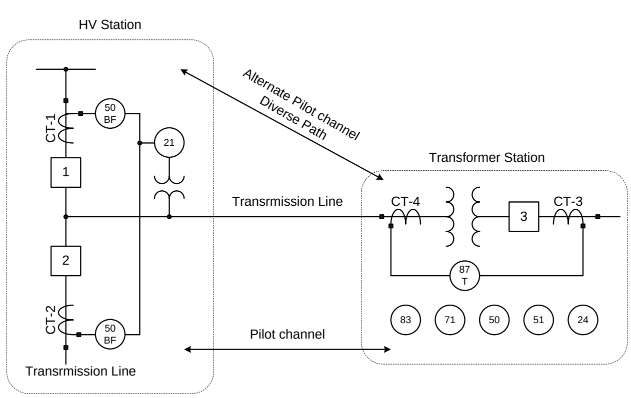

Figure 3. Transmission line with series transformer and no high-side breaker

In addition to the listed transformer protective functions, there may be additional devices that would initiate the trip signals to isolate the transformer (for example, low voltage transformer protection, or the low voltage winding breaker failure condition where low side winding is equipped with a breaker). Likewise, breaker failure protection of the source breakers (transmission line breakers) would need to isolate the transformer lower voltage windings if the low voltage bus has sources.

Users may design some level of zone protection (or areas of coverage) in order to differentiate line faults near the transformer or low voltage winding breaker failure from transformer trouble. For example, by use of different digital signals on the pilot channel(s), the user can selectively allow reclosing on the line.

Where multiple levels of communication routes from the transformation station to the source breakers are available, the transformer teleprotection scheme is generally designed to allow maintenance flexibility for the transformer protective devices as well as geographical diversity of paths to provide a more dependable protection.

4.8 High Source to Line Impedance Ratio

Under high source to line impedance ratios (SIRs), protective relays face difficulties in discriminating in-zone and out-of-zone faults. This applies to all single-ended protection techniques based exclusively on measurements from one end of the protected line.

When the line impedance is significantly lower compared with the equivalent source impedance, variability in both currents and voltages at the relay point in response to the fault location is considerably reduced.

The fault current characteristic becomes flat, with very small differences between in- and out-of-zone faults. Given variability of the system equivalent impedance, the impact of the source on the fault current level may be comparable or even higher than the impact of the fault location. This diminishes the selectivity of any overcurrent based protection.

Voltage signals at the relay location not only depend very little on the fault position, but also become very low for faults at the far end bus. The following equation uses a simple voltage divider principle to approximate the fault loop voltage at the relay for a fault at a distance, *d*, in per unit of the line length, under the a given SIR:

$$V_{RELAY} = \frac{100\% \cdot d}{SIR + d}$$

For example, under the SIR of 20, the relay measures approximately 4.76% of the nominal voltage for a fault at the far end of the line (d = 1) (100%/(20+1) = 4.76%), while for a fault at 75% of the line (d = 0.75) the relay sees 3.61% of nominal (100%*0.75/(20+0.75) = 3.61%). Observing that there is almost no difference in the fault current between the two faults, an underreaching directly tripping distance function (Zone 1) must be capable of detecting difference in the voltage of 1.15% of nominal if it is set to 75% of the line. The difference becomes even more challenging under higher SIRs and more aggressive relay settings. For example, a 10% transient accuracy under the SIR of 30 requires detecting a difference in voltage of 100%/(30+1) = 3.23% for end of line fault, and 100%*0.9/(30+0.90) = 2.91% for a fault at 90% of the line.

Accuracy of such discrimination is limited, particularly when Coupling Capacitor Voltage Transformers (CCVTs) are used as potential sources. CCVTs generate considerable transients in their secondary voltages with frequencies close to system frequency and magnitudes several times higher than the rated voltage at the relay. This means the CCVT transients could be tens of times higher than the small difference in voltage between the in-zone and out-of-zone faults, challenging selectivity of Zone 1 protection [5,6].

State of the art distance relays could provide for transient reach accuracy at the level of 5% under the SIRs of 30 at the expense of slower operation for end of zone faults under high SIRs. In many cases, Zone 1 reach needs to be reduced to retain selectivity, reducing the area of instantaneous fault clearance from Zone 1 significantly below the typical 80-90%.

In strong systems, a high SIR situation typically occurs when a relatively short line feeds a step down transformer and experiences a weak backfeed from the lower voltage side during line faults. The short reach of Zone 1 in such cases results in small resistive coverage of a mho distance function. Even when using quadrilateral characteristics, one also faces limits of resistive coverage given the impact of resistive external faults and load on the allowable setting of the right hand blinder.

With limited or entirely diminished selectivity and poor resistive coverage of current and distance functions under high SIRs, line current differential and pilot assisted schemes are the only practical solution for selective fault clearance.

The Line Protection Guide IEEE C37.113 [2] strongly suggests the application of pilot assisted schemes for short (SIR > 4) and medium (SIR > 0.5) lines. Applications to physically short lines, i.e., in the range of few miles, also call for pilot-based protection. Line impedances in such cases are very small and are known with very limited percentage accuracy. Even with very strong systems behind the relay, the SIR is typically very large for such lines causing the same steady state and transient accuracy problems already described. In a sense, such lines become "long buses" and must be protected by differential or directional comparison principles.

As an example, consider the system in Figure 4 below. Relay R at plant P2 protecting the 161kV line to plant P1 is affected by high SIR due to the relatively weak generation and 69kV network behind it. The line itself is almost 9 miles in length and 0.028 pu impedance. The SIR with all ties closed is 2.7, which would define the line electrically as medium length. However, when the 69kV line from P2 to S3 is out, or when the 161kV line from P1 to S3 is out, the SIR increases dramatically to 25.

In this case, a phase-to-ground fault on the 161kV bus at P1 resulted in a misoperation of the Zone 1 element at P2, due to overreaching of the Zone 1 distance element. Terminal voltage dropped to about 17kV or about 12V secondary (VT ratio 1400/1), but the relay event record indicated the relay saw only about 5V secondary with erratic phase angle. Zone 1 elements were disabled and an additional pilot channel installed to provide secure instantaneous tripping for 100% of the line, even for outage of the one of the pilot channels.

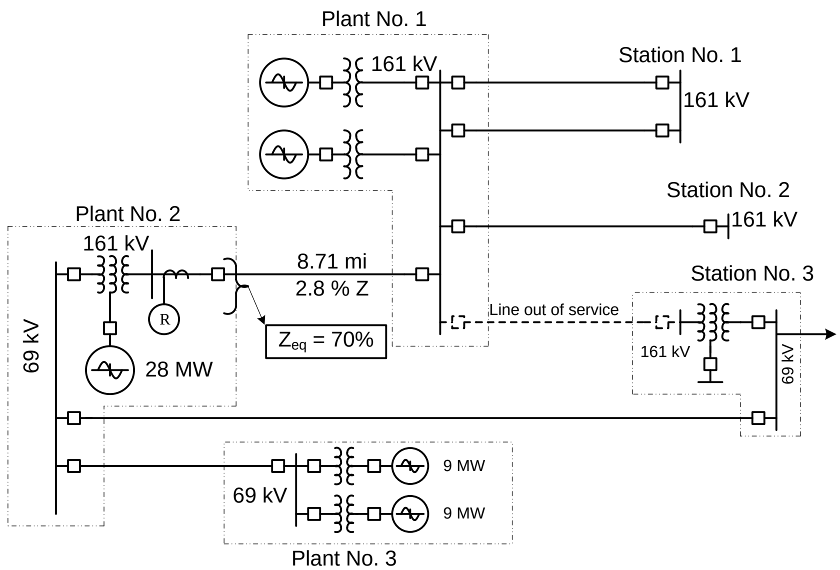

Figure 4. Sample system with high SIR at Plant No. 2 on line to Plant No. 1

4.8.1 Weakfeed problem

Under weakfeed conditions, the amount of fault current is so low that application of current or distance functions becomes problematic or impossible. This phenomenon is more severe than the high source to line impedance ratio. The latter creates problem for selectivity of directly tripping underreaching distance elements. Weakfeed, in turn, prevents overreaching functions from reliable operation even during close-in line faults.

With limited ability to detect fault conditions in the forward direction, not to mention discrimination between in-zone and out-of-zone faults, weakfeed terminals cannot provide current- or impedance-based fault protection for the line. A crude solution is to disconnect the weak terminal sequentially, based on an undervoltage condition or other version of remote end open detection, after the strong terminal clears the fault.

Pilot assisted schemes allow for reliable operation under weakfeed conditions (typically as part of a permissive overreaching transfer-trip scheme). Weakfeed logic enabled at the weak terminal allows tripping if the strong terminal sees a forward fault (permissive signal received), with voltage supervision at the weak terminal (phase undervoltage or neutral/negative-sequence overvoltage), and no reverse fault is detected (reverse distance or current directional). Such schemes typically include a “weakfeed echo” feature, where permission is simultaneously echoed back to the strong terminal to allow a trip.

As a specific example of weakfeed, consider the system in figure 5. The 48-mile line from plant P1 to station S5 has two intermediate tap stations, one with positive-sequence sources, making a three-terminal line. The protection scheme uses a transfer-trip channel from P1 to trip the low-side breaker B at S3. The transfer-trip is keyed by relays at P1 which see to S5. No communication channel exists to station S5, which has a small hydro source into the 69kV bus. The result is that for faults beyond station S4 toward S3 and P1, the relays at S5 (on breaker C) have only the contribution of the single generator at plant P4. After breaker A at P1 and breaker B at S3 have tripped, there may not be enough current for the relays on breaker C at S5 to operate.

In this particular case, a fault on the 161kV bus at station S3 draws on 0.5pu current from station S5. The bus voltage at S5 drops to 0.05pu initially, then even lower to 0.025pu after breaker A at P1 and breaker B at S3 trip.

Weakfeed, in this case, would require a pilot channel from plant P1 to station S5, which would be keyed by relays on P1 and would trip breaker C at S5 if bus voltage at S5 was low.

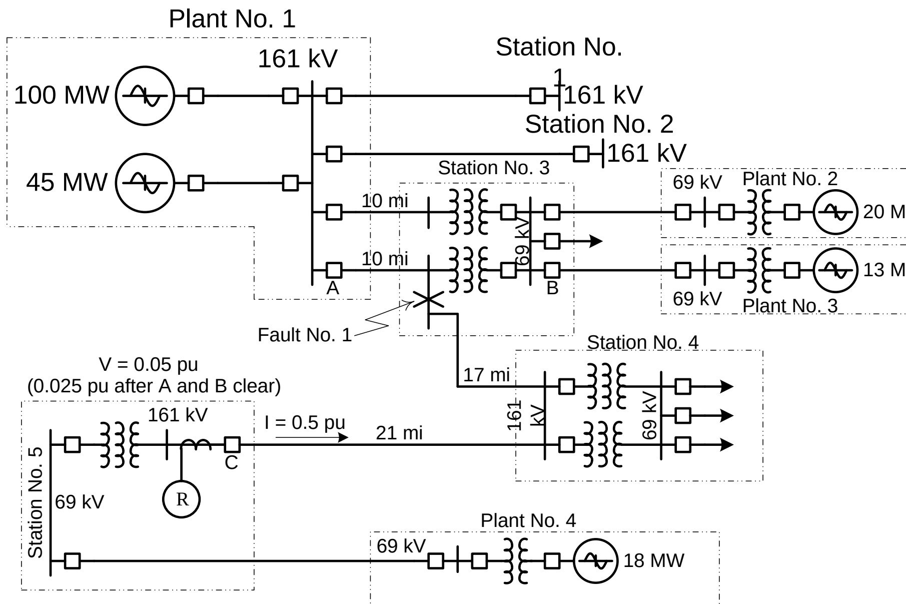

Figure 5. Weakfeed at station S5 on line to P1 via tap stations S4 and S3

4.9 Instantaneous clearance of low-current faults

Low-current ground faults occur with high fault resistance or due to an infeed (apparent impedance) effect or under a combination of the two factors. Such faults are not detectable by distance or phase overcurrent protection functions.

Quadrilateral distance characteristics provide for enhanced resistive coverage, but are still limited to faults with moderate fault resistance.

Low-current faults can be detected by differential and phase comparison relays, and via sensitive ground directional elements.

When applying differential line protection, these faults can be detected with great sensitivity, limited only by line charging currents, accuracy of synchronization (when applying microprocessor-based relays), and accuracy of current transformers. Selective detection of such faults is instantaneous without the need for time coordination.

Phase comparison relays configured to respond to a ground current quantity such as a zero- or negative-sequence current provide for sensitive and instantaneous protection as well. They are more complex to apply, however, due to the need for starting elements (fault detectors).

Sensitive ground directional elements include negative-sequence / neutral overcurrent functions, and a zero-sequence wattmetric function. In either case, the function is a sensitive directional element responding to phase unbalance that signifies a ground fault. The wattmetric method is widely used in some medium voltage networks, and is used on transmission lines as well.

Sensitivity of these ground fault methods can be further increased using the concept of an offset impedance to safely increase the polarizing voltage for forward faults [7].

Sensitive ground directional elements can be coordinated via time delay or used in an instantaneous directional comparison scheme.

In general, time coordination is a more challenging and burdensome activity, particularly when very high sensitivity is required. Several sources of errors must be factored in including errors of instrument transformers, line charging currents, natural system unbalance, accidental open pole conditions, temporary by-pass of series capacitors, etc. As a result, time coordinated ground directional elements operate with an intentional time delay but are also limited in terms of very high sensitivity.

Having a very long reach, these functions must coordinate with a potentially large numbers of relays in the system. With aggressive sensitivity targets, these relays will all have to use the same operating principle. For example, it is very risky to attempt to coordinate a wattmetric function with a neutral directional time overcurrent function or a neutral time overcurrent with negative-sequence time overcurrent. This is because small differences in the measured quantities may result in considerably different responses of these sensitive functions if they use different operating principles. As a result, de-facto standardization takes place through a utility when using sensitive time-coordinated ground fault protection. Otherwise, considerable sensitivity concessions must be made. This de-facto standardization limits procurement and relay replacement options.

When used in a directional comparison scheme, ground directional elements provide for practically instantaneous fault clearance and allow for higher sensitivity. These ground fault-detecting functions must still be coordinated to account for possible instrument transformer errors and line charging currents, but the task is typically simpler, particularly if a permissive scheme is used. Each function needs to coordinate only with the functions on the other line terminal(s) in terms of sensitivity and equivalency of their operating principles.

Having practically unlimited reach, these elements require current reversal logic when used in a communication-assisted scheme to cope with sequential tripping on parallel lines and other switching events in general. As a safety precaution, they may be intentionally delayed by some tens of milliseconds for both keying the pilot channel and generating the trip command.

Excellent sensitivity can be achieved when using blocking schemes with ground directional overcurrent elements that employ the concept of offset impedance [7]. Owing to the offset impedance, the strong terminal will detect the event as a forward fault even under a very small ground current. Not blocked, this terminal will trip and remove the potential infeed effect allowing the other terminal(s) to detect and clear the fault.

Following is an example of typical fault declaration criteria for different fault resistances:

- Two cycles for single line to ground faults with 0-50 ohms resistance. The time is based on a communication-assisted scheme with both ends detecting the fault. The 50 ohm value may be outside of the detection capabilities of impedance functions, and therefore requires ground directional elements. To detect such faults, these elements can be set relatively high and do not require intentional time delays for security.
- Four to five cycles for single line to ground faults with 50-100 ohms resistance. The time is based on a communication-assisted scheme with both ends detecting the fault, but one or both ends would be slower because of lower fault currents. These faults require ground directional elements set relatively low.
- Seven cycles for single line to ground faults with 100-200 ohms fault resistance. This operation is practically instantaneous requiring a communication-assisted scheme, but it involves intentional delays given the applied sensitivity of the ground directional functions and potentially sequential tripping due to the infeed effect. A second set of ground directional functions can be used with increased sensitivity, but with intentional time delay for security.
- Twenty cycles for single line to ground faults with resistance above 200 ohms resistance. Again, this operation is an instantaneous operation requiring a communication-assisted scheme, but it involves even longer intentional delay given the sensitivity is encroaching on

the accuracy of instrument transformers and relays, and very likely sequential tripping due to the infeed effect.

The significance of the above examples is simply that as ground resistance increases, increased fault detection times from a system point of view are tolerable. Longer tripping times might be required to detect high ground resistance to cover momentary unbalances on the system such as temporary single phase series capacitor bypass, current reversals, increased CT errors due to significant load pickup or transformer inrush, capacitive current outrush on external faults, switching events in general, etc.

The above examples are concerned with communication-assisted schemes. The intentional delay is to provide proper measurements given the targeted sensitivity and is not a means of providing selectivity. Time coordinated trip times for low current faults will be significantly longer – in the range of seconds.

4.10 Communication-Based Local Breaker Failure Protection

4.10.1 Ring or /Breaker-and-a-half Bus Breaker Failure Protection

In a ring or breaker-and-a-half bus configuration, for a fault on a line terminated in such a bus and subsequent possible failure to open of one of the two breakers powering the line, the local breaker failure protection, which clears the adjacent breaker on the neighboring bus, itself is not adequate to clear the original line fault. Additionally, fault contribution from the remote end of the line terminated in the neighboring bus on the ring or breaker-and-a-half must also be eliminated (Figure 6). One option is to rely on the remote terminal Zone 2 or Zone 3 protection of this line on the neighboring bus, which will sense the fault and trip the breaker at the remote terminal, and thus will halt the fault contribution. However, the Zone 2 typical time delay is 18-24 cycles, which will slow down halting the contribution to the fault. The Zone 3 typical time delay is 40-60 cycles, which may be unacceptable. Oft times, the remote Zone 3 may not be used and there will be no protection to eliminate the contribution to the fault.

Therefore, a direct transfer trip (DTT) may become necessary for the ring or breaker-and-a-half bus breaker failure protection, which will require a communication channel. This scheme is applicable for the ring and breaker-and-a-half buses for practically all voltage levels in the transmission system.

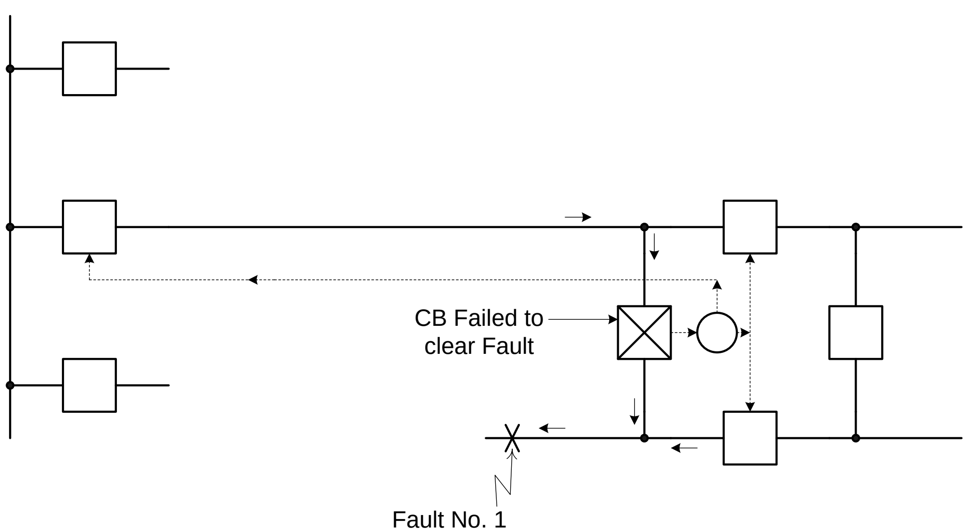

Figure 6. Ring Bus Breaker Failure

4.10.2 In-line Breaker Protection

Figure 7 shows a straight bus configuration, usually at a two-transformer distribution substation, where only a bus tie breaker is present protecting both incoming transmission lines where no separate line breakers are installed. The advantage of such a bus configuration is the reduced capital cost of the substation construction and maintenance, while the system reliability is not significantly decreased.

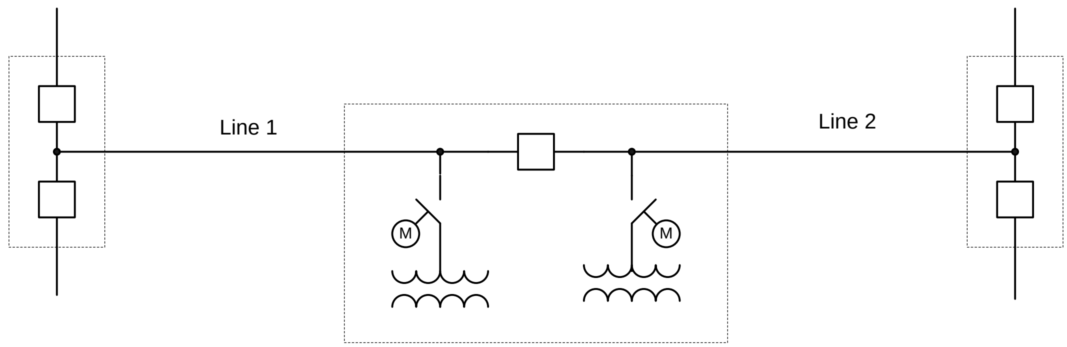

Figure 7. In-line Breaker Protection

In this bus configuration, there is no local breaker failure protection as there is only one breaker in the substation, which is the bus tie breaker. Should the tie breaker fail for a fault on one of the two incoming lines, remote terminal Zone 2 or Zone 3 protection of the other line will sense the fault and trip the breaker at the remote terminal and, thus, will clear the fault and isolate the failed tie breaker. As discussed in the previous section, remote clearing times can be slow due to necessary time coordination.

If the transformers are line connected via disconnects, transformer protection may be applied by keying direct transfer trip signals to the remote line ends. These transfer trip channels will likely be available if pilot protection was required for the line protection schemes themselves.

Therefore, a direct transfer trip (DTT) sent to the remote terminal of each incoming transmission line may become necessary for the bus tie breaker failure protection which will require a communication channel.

4.11 Power quality

All loads are affected to some extent by nearby faults. The response of the load is determined by a number of factors such as the magnitude of the voltage dip, its duration and the characteristics of the load. Some industries have extremely sensitive processes that cannot stand extended duration fault clearing. Additionally, some customers have incentive contracts that penalize the supplying utility for zero voltage or voltage sag events. Fast clearing of EHV faults may be essential to maintain power quality in an area because events on the EHV system affect the underlying transmission and distribution systems.

It should be noted that the minimum possible fault clearing time using conventional circuit breakers and protective relays is about 3 cycles (1 cycle relay time and 2 cycle breaker interrupting time). More typical clearing times are between 6 to 8 cycles with older relaying and circuit breakers, even with pilot protection. If this still causes sensitive customer problems, they will have to consider installing their own ride-through capability (minimum 10 cycles).

The Information Technology Industry Council publishes a curve defining the voltage thresholds that define the operating limits by which some sensitive electronic equipment is constrained. It is noted that for a 30-cycle voltage sag, this equipment can shut down if the voltage magnitude sags to 70% of nominal or lower (see Figure 8, source http://www.itic.org/archives/iticurv.pdf).

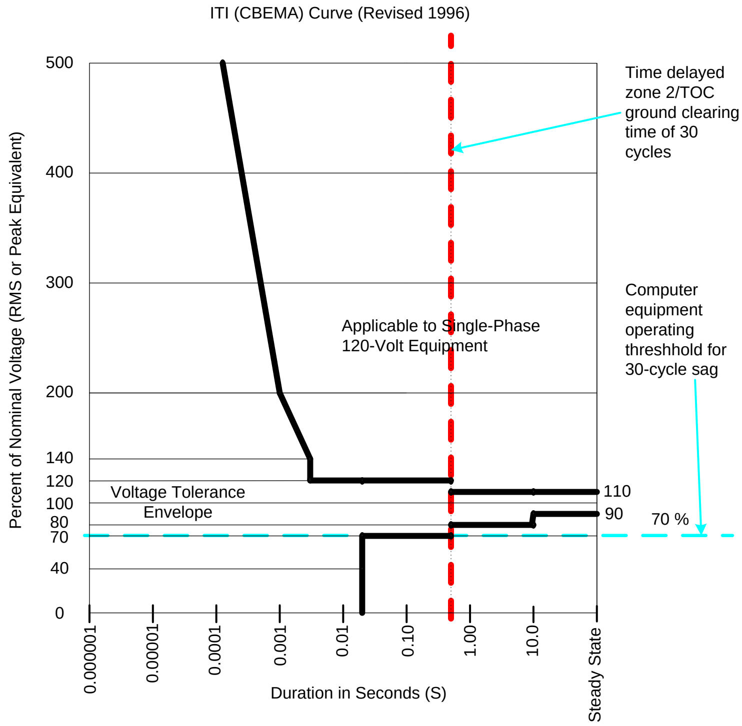

Figure 8. ITI Curve

It should be also be mentioned that customers tapped directly on the line being evaluated will see a complete blackout during fault clearing, and power quality for those customers should not affect the decision to install pilot protection. Power quality should be evaluated for customers electrically nearby, such as those served directly from the bus at the line terminals, or those tapped on adjacent lines. Thus, it is necessary for the protection engineer and system planners to become familiar with the transmission system and loads around the line being evaluated, in order to determine how slowly cleared faults on a particular line might affect loads in close proximity.

As an example, consider the switching station S1 in figure 9. When evaluating the need for pilot protection on the line from S1 to station S2, the power quality issues for the semiconductor plant do not figure in, because for faults on the line S1-S2 itself, the semiconductor plant will see a total outage (zero voltage) for at least 10-15 cycles (minimum reclosing time). The same is true for the line from S1 to station S4; the automobile assembly plant does not affect the need for pilot protection on the line S1-S4. However, when evaluating the need for pilot protection on the line from station S1 to station S3, the power quality issues for the semiconductor plant, the automobile assembly plant, and the chemical plant should be considered.

In a broader sense, any line fault in close proximity to sensitive loads that reduces the voltage at the plant connection point should be reviewed for voltage magnitude and expected duration of sag for normal clearing (including pilot/non-pilot operation). Depending on system configuration, line impedances, etc, this could be beyond stations S2, S3, and S4 in Figure 9. Short-circuit programs can be used to determine an “area of vulnerability” for sensitive customer buses, which searches for those lines which, when faulted, sag the customer bus below a certain threshold.

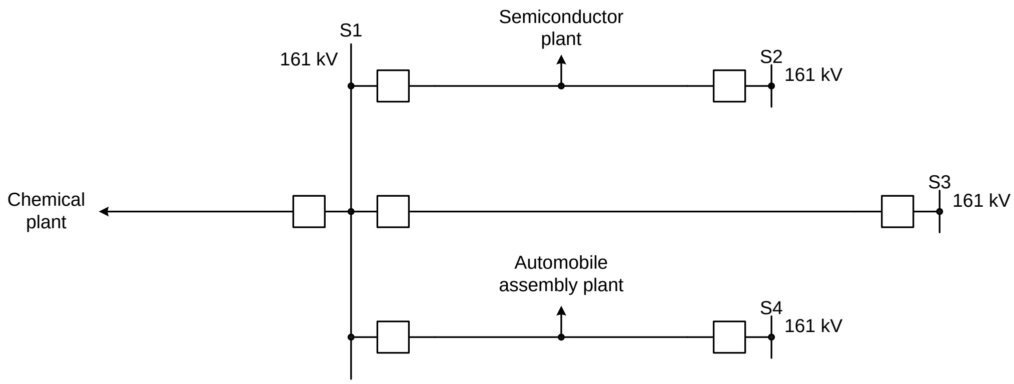

Figure 9. Evaluating transmission line protection for PQ issues

4.11.1 Avoid initiating auto-transfer schemes

To maintain continuity of supply, auto-transfer schemes are employed to transfer load from a faulted source to a healthy source. Auto-transfer schemes are often set to initiate for a drop in voltage far below nominal for a length of time greater than the normal clearing and reclosing times. Delayed clearing may initiate auto-transfer schemes that might need to be reset manually in order to return the supply to the normal configuration.

4.11.2 Avoid starting diesels for loss of offsite power at nuclear plants

Nuclear plants require a secure supply to their plant safety systems. Plant auxiliary systems have degraded voltage and loss of power protection set to around 75% of their nominal auxiliary system voltage with delays as little as 3 seconds. Operation of this protection starts the diesels to support plant voltage so that motors in the safety systems can continue to operate. Starting these diesels is reserved for extreme events such as the loss of offsite power and, therefore, should be avoided. Considering the typical delays used in this protection, a more likely concern of the nuclear plants for slow clearing faults is the drop out of sensitive plant motors which then must be restarted.

At least one utility has reported requiring pilot protection on a transmission line terminated at a hydro plant (plant P1 in Figure 10) that also serves offsite power for a nuclear plant over two short (less than 2 miles) 161kV transmission lines. The transmission line in question is 38 miles long, from plant P1 to station S1. A three-phase fault 80% down the line (F1) drops the hydro plant P1 bus voltage to 80% of nominal after the remote terminal opens. For Zone 2 time-delayed clearing of 30 cycles (0.5 seconds), it was determined this could result in false starting of the diesel generators. This is because the undervoltage relays at the nuclear plant are set to dropout at 87% voltage and 0.75 seconds, but the tolerance for the time delay could be up to 0.25 seconds.

It is interesting to note that before line breakers were installed at station S1, the 81 mile line from plant P1 to station S2 did not require pilot protection.

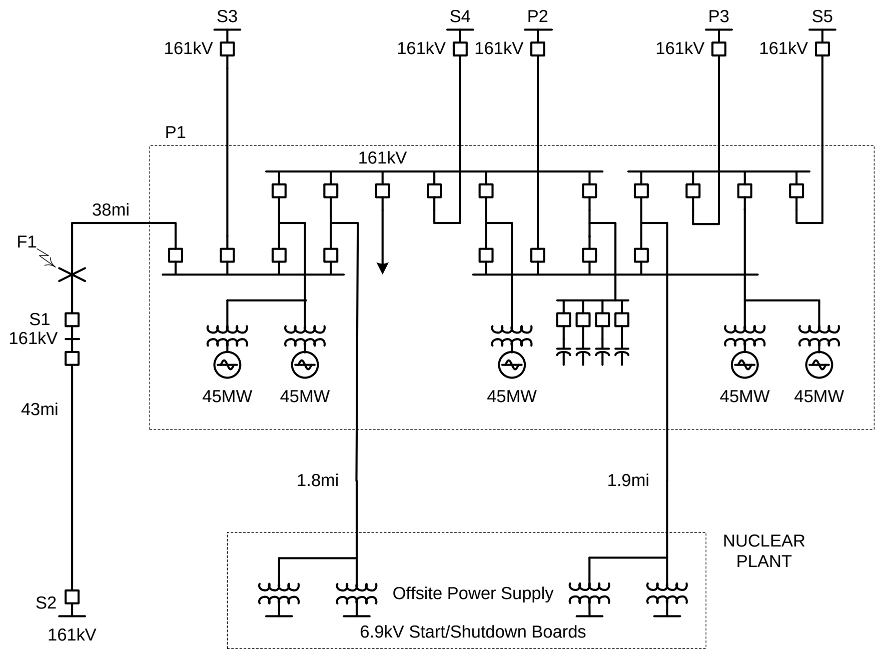

Figure 10. Hydro plant serving offsite power to nuclear plant

4.11.3 Avoid motor stalling during extended fault clearing, which could lead to voltage collapse

If voltage drops to about 80% at a motor's terminals for an extended period, the motor will stall and draw near locked rotor current. When a motor stalls, the danger is that the event will cascade to other area motors and adversely affect a wide area. Time-domain studies using dynamic load models typically will need to be performed to verify this as a problem.

Slow clearing of bus faults has led to voltage collapse in at least one instance [8] due to this phenomenon. More recently, a utility experienced slow voltage recovery (10-15 seconds) following 23-cycle clearing of a multiphase bus fault within a large load center. Had there not been several hundred MW of inadvertent load shedding, voltage collapse could have occurred.

Such fault-induced delayed voltage recovery (FIDVR) or collapse is a real risk not only for slow-cleared bus faults, but for transmission line fault clearing as well. Depending on the load mix, the potential for extended voltage sags on short lines presents a risk of motor stalling for Zone 2 time-delayed clearing, especially in those areas with known concentrations of induction motor load (e.g., in a tightly interconnected metropolitan area during summer with high air conditioning loads as described in [8]). The same "area of vulnerability" concept mentioned previously may be helpful in studying this criterion as well.

4.12 Regulatory/regional reliability council requirements

NERC Transmission System Standards defines four categories of system conditions. The relay engineer must ensure that the utility's protection system complies with the NERC Standards. For example, Category A has all facilities in service, and the protective system must allow the system to operate. Category B – loss of a single element and Category C – loss of two or more elements requires the protection system to operate correctly to isolate the faulted condition(s) and does not allow for any cascading tripping although planned tripping of load and/or generation is allowed.

In addition to the above considerations, the NERC System Protection and Control Task Force (SPCTF) has developed criteria for distance relay settings as a result of the 2003 Northeast Blackout. The SPCTF work is ongoing, and the interested reader should access the NERC website for the most up to date SPCTF materials.

5 Alternatives to Pilot Protection

5.1 Reasons pilot is unavailable

Pilot protection may not be available for a number of reasons:

- It was not originally installed.

- It becomes unavailable due to a problem in, or during maintenance on, the communication path or equipment or associated relaying equipment.

- When a line is transferred to the spare line breaker/relays. Figure 11 shows a switchyard including a spare line breaker and relays (breaker A). Where justification is sufficient, the pilot channel is transferred to the spare relays, or more commonly, the breaker currents/tripping are transferred to the normal line relays. However, in many cases where this added expense and complexity are not considered justifiable, the result is non-pilot operation. It should be noted that in such arrangements, the relays at the remote terminal will need to operate non-pilot. This may require a manual selector or cutout switch to avoid misoperation for external faults.

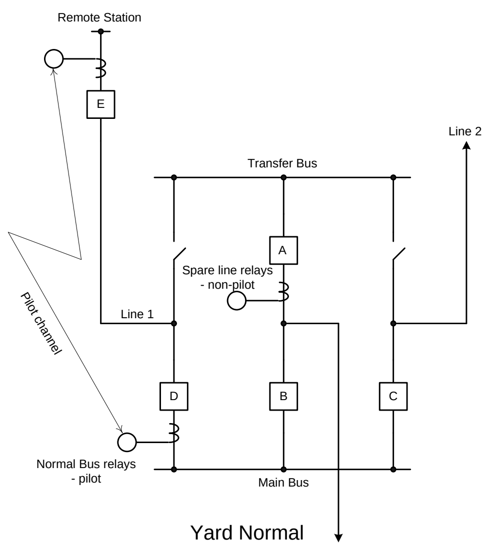

Figure 11a. Main/Transfer Bus - Pilot relays on breaker D for line 1

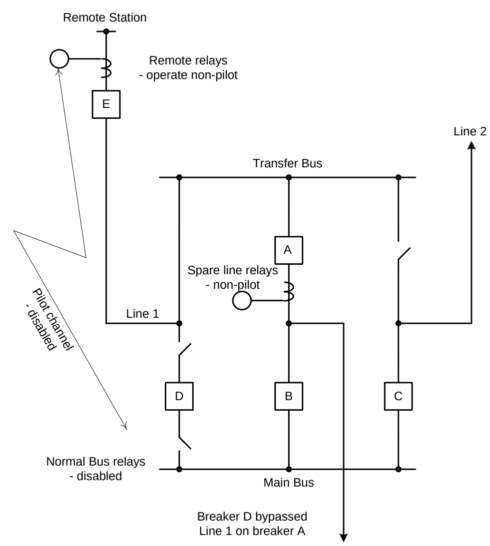

Figure 11b. Non-pilot relays on breaker A for line 1 when A spares D

- Temporary configurations - If a substation is out of service for an extended period of time (e.g., main bus outage for switch maintenance, etc), some utilities will bypass the entire station via jumpers external to the main bus or station, thereby creating a temporary transmission path. For example, consider Figure 12, with three stations and with transmission lines between stations S1 and S2 and stations S2 and S3. Pilot protection has been installed on both transmission lines. Station S2 is to be taken out of service, but the utility wishes to retain the transmission path between stations S1 and S3. In some cases, utilities wish to retain pilot protection on the temporary S1-S3 line. However, special arrangements must be made for the communication circuits if secure pilot protection is to be maintained.

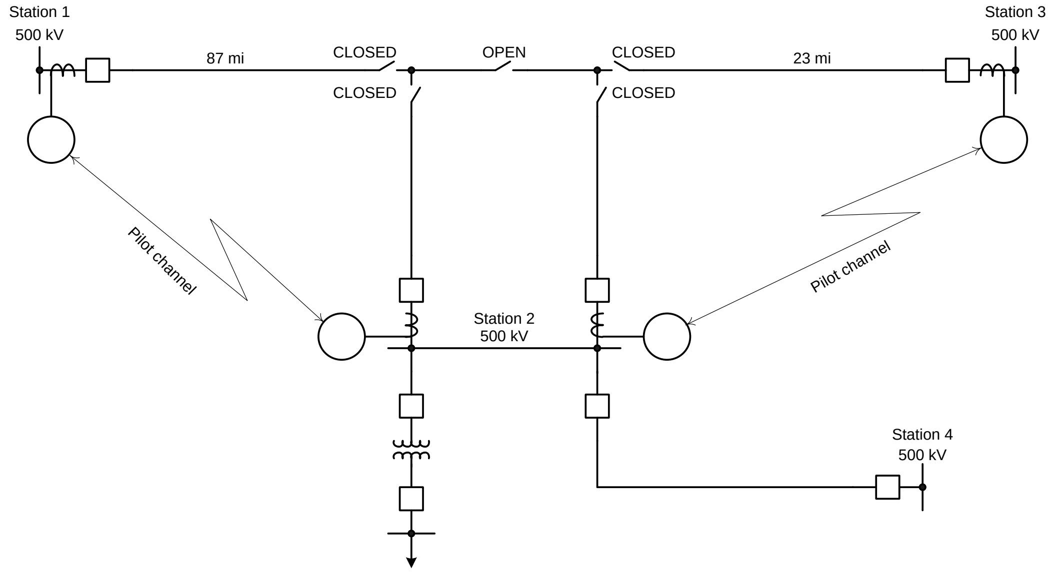

Figure 12a. Normal configuration

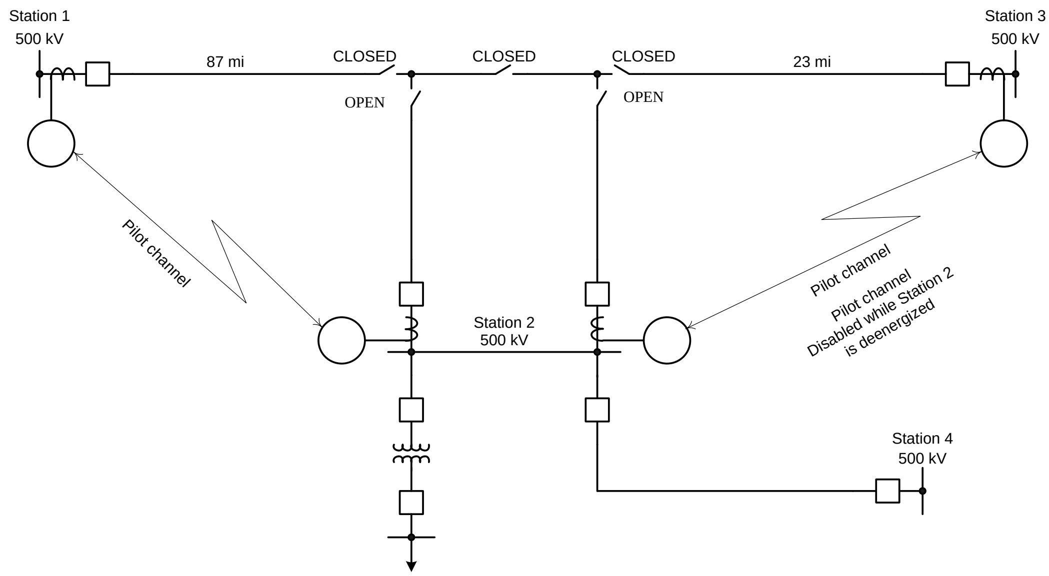

Figure 12b. Temporary bypass

- Some relay systems become completely disabled (not reverting to non-pilot stepped distance) when pilot is turned off. For this reason, some designers chose to install two redundant relay systems (with an additional electromechanical backup set) to allow the pilot channel to be switched off one set.

5.2 Options for line protection without pilot

Operating a line without pilot is a decision that should not be taken lightly, especially when the reasons for installing pilot initially were well thought out and documented. This decision should be made jointly by the transmission operators and the system protection engineers, and should take into account the reason pilot is unavailable, the length of time pilot is expected to be unavailable, the risks associated with a time-delayed trip. Every effort should be made to return pilot to service as quickly as possible.

When pilot is not available, there are several options for protecting the line.

5.2.1 Operate the line without pilot

In doing so, any risks described above are inherently accepted for the period while pilot is unavailable. For short periods (e.g., eight hours maximum during periods of fair weather), this may be acceptable.

In order to mitigate any machine angle stability risks (section 3.1) associated with time-delayed clearing, in some cases a utility may impose upper limits on real power output (MW derating) and/or minimum reactive power output (MVAR) on affected generators.

5.2.2 Switch the line out of service

The risk of instability or customer sensitivity to voltage sags for slow clearing of a fault may be more detrimental than the loss of load flow capability the line provides. In that case, an operating alternative for loss of pilot channel is to take the line out of service. This of course must be weighed against the potential risks associated with subsequent contingencies. (For example, if a plant is served by two transmission lines with pilot protection, and one line is switched out due to pilot being disabled, loss of the remaining line would interrupt the plant.)

5.2.3 Modify the relay settings/wiring to emulate pilot tripping

If the line is needed for load flow capability but instability or severe voltage sags for slow clearing of faults is a risk, then some other alternatives to provide fast clearing are possible:

- Extend the Zone 1 reach to at least 100% of the line.
- Shorten the Zone 2 timer to zero or near zero to provide faster clearing for Zone 2 faults.
- Jumper the PT (permissive trip) input for a POTT scheme to enable a pilot trip even though the channel is unavailable or degraded.

Caution should be used when utilizing these solutions, as they all have vulnerability to lines incorrectly tripping for faults external to the line.

5.2.4 Use local pseudo-pilot schemes

There are several schemes available without the use of a communication channel as alternatives to pilot schemes. These schemes have limitations, but are accepted as a fall back when the channel is out of service or not installed.

5.2.4.1 Zone 1 Extension Scheme

In this scheme, the Zone 1 has two settings, one with the normal Zone 1 reach (for example 80% of the protected line) and the other with the extended Zone 1 reach, overreaching the protected line (for example 120% of the line). The Zone 1 reach is normally controlled by extended Zone 1 setting and all line faults are cleared instantaneously at both ends. As there is overtripping for external faults, it is mandatory that the autoreclose function is used with this scheme. After the trip, when autoreclose is initiated, the extended Zone 1 reach is disabled and the relay operates with the normal Zone 1 reach. After the reclose, only the relay on the faulted line will operate if the fault is permanent.

The main disadvantage of the scheme is that there is unnecessary tripping of the breaker external to the faulted section, increasing the amount of breaker maintenance needed and needless transient loss of supply.

5.2.4.2 Loss of Load Scheme

The loss of load scheme works on the principle that the clearing of a line-end fault by Zone 1 of the remote relay causes the unfaulted phase currents to drop to zero. The scheme is enabled by the presence of prefault load, and Zone 2 operation with the loss of load on one or two phases initiates a high speed trip.

The main disadvantages of the scheme are that it does not work for three-phase faults, prefault load must be present, and load taps should be disallowed or minimized.

5.2.4.3 Sequential tripping

For single-phase-to-ground line-end faults, in many cases the zero-sequence current contribution from the local terminal may significantly increase after the remote terminal clears. If residual ground overcurrent elements are used (not ground distance elements), this may result in sequential "instantaneous" clearing by the local terminal after the remote terminal clears.

Note that this is not true for multiphase faults where phase distance elements are used: Zone 1 direct trip elements can not and should not be expected to operate on line-end faults after the remote terminal clears.

While it is true that the majority of faults are single-phase-to-ground, it may also be true that the primary reasons for requiring pilot protection were primarily associated with the effects of multiphase faults.

5.2.5 On weakfeed lines, switch in backup DTT scheme if weakfeed unavailable

Weakfeed logic may also be disabled if an associated pilot scheme (POTT, DCB, etc) is disabled. In that case, an alternative is to have the strong terminal send direct trip to the weak terminal on the detection of a forward fault (for example, by using a DTT signal used for breaker failure at the strong terminal). Note this may result in overtripping the line for faults beyond the weak terminal.

5.3 Impact of channel unavailability on voting schemes

An example voting scheme uses two distance relays with separate pilot channels and other backup zones of protection. Trip outputs from both distance relays are required. The third relay is a current differential relay, and the backup distance elements are not used.

Channel failures can affect this voting scheme. If the channel fails on any of the distance relays, the voting scheme stays intact. In this case, other zones of protection are considered adequate. If the channel fails on the current differential relay, the voting scheme reverts to a single distance relay trip.

5.4 Line current differential relays and their built-in or external pilot-aided distance backup

Line current differential protection has a big advantage of being independent from voltage in the power system and, therefore, is often utilized for protecting extra-high and high voltage lines if a suitable digital communication channel is available. This protection is also a great alternative to traditional distance protection, as it presents a different protection algorithm. In a line protection package, applying the line current differential protection together with the distance protection guaranties a full protective coverage of practically all faults in the protected transmission line.

This protection, however, is communication channel dependent as it requires a digital communication channel for its application. If a digital communication channel is unavailable, a similar phase comparison protection may be considered, which can be utilized with an analog communication channel while preserving the advantage of a current-only type of transmission line protection.

The distance protection, which typically acts as a backup to the line current differential, can be provided in the same multifunctional digital relay with the current differential (internal backup) or located in a separate relay (external backup).

If the distance protection is part of the same relay with the line current differential and is pilot-aided, they can also use the same communication channel. A drawback of implementing the primary and backup protection functions in the same relay is common relay hardware failures, which may disable both functions.

If the distance protection is located in a separate relay and is pilot-aided, it can have its own communication channel if it is necessary for complete redundancy or still share the same communication channel with the line current differential protection. An obvious advantage of this design is eliminating the common hardware failures. A drawback of implementing the primary and backup protection functions in the separate relays is additional cost of the hardware and the second communication channel when it is required.

6 Considerations to Determine Number of Pilot Systems Required

The protection performance requirements for the line will dictate the number of pilot schemes required. Where time delayed clearing meets the performance requirements, no pilot channels are required.

6.1 Number of systems required

Where high speed clearing is desired for faults anywhere on the line, but time delayed tripping still is acceptable under contingency failures, a single pilot scheme with a non-pilot second system is normally used.

Where high speed clearing is required for faults anywhere on the line and time delayed tripping is not acceptable, multiple pilot schemes are required. The need for two or three pilot protective systems will be determined by protection system owners based on their level of confidence in the systems employed and the number of contingency failures taken into account.

6.2 Different voltage levels

Protection system performance requirements can differ greatly and will dictate at what voltage level pilot channels are used. While many lines from 69kV to 161kV have a pilot system, many do not.

From 230kV to 345kV, there is normally at least one pilot scheme and often, depending on system configuration, there are two and also direct transfer tripping for breaker or tapped transformer failure.

Above 345kV, it is typical to apply at least two pilot schemes and direct transfer trip for equipment failure.

6.3 Regulatory/regional reliability council requirements

The reliability councils sometimes dictate the protection system performance requirements and thereby the number, and sometimes type, of pilot systems and channels required.

6.4 Balance of dependability vs. security

The system topography, sensitivity of load, type of equipment being protected and availability of pilot channels all influence the protection system being applied. The dependability and security of pilot systems are often a function of the pilot channel employed and the logic in the protection scheme.

Where there is an overwhelming need for security against tripping for faults external to the protected line, permissive and differential schemes are preferred. Permissive schemes are secure in as much as they require a permissive signal be received from the other terminal(s) prior to tripping for a detected fault. They are also somewhat less dependable for tripping for an internal fault because they must receive permission from the remote terminal(s) in order to trip high speed. Differential pilot protection is secure. Loss of the pilot channel generally disables protection so this scheme must either be used in conjunction with some other pilot system or have redundant communication paths. It should be noted that some differential schemes enable a non-directional instantaneous overcurrent element on loss of channel. Such schemes are obviously insecure unless that feature is disabled.

Directional comparison blocking pilot schemes are dependable inasmuch as the lack of a blocking signal allows high speed clearing. They are also less secure for the same reason – the failure of the pilot channel allows tripping for an external fault.

There are many variations of the basic three schemes above that are intended to compensate for the weakness of the scheme. In each case one must evaluate the scheme in terms of its strengths and weaknesses, in terms of complexity, and how it affects the dependability and security of the protection scheme.

6.5 Economics

Many protective schemes have been adapted to work successfully with any of the following channels. The type of channel used is more often a function of what has or has not worked well in the past for the user.

Leased analog phone circuits (for audio tone relaying or hard wire current differential) - Advantage is very low initial cost for audio tone permissive or direct transfer trip schemes; however, they have continuing monthly charges. In general, reliability and dependability suffer due to phone company maintenance of these paths. Analog pilot wire differential circuits are typically limited to distances on the order of a mile, but have been successfully applied up to 10 miles or longer.

Leased digital phone circuits are similar to analog.

Power line carrier (PLC) (permissive, blocking and direct transfer tripping schemes) - The design and maintenance of the pilot channel is under the control of the transmission owner. PLC can be applied on lines over a hundred miles. Initial cost of a blocking system is significant, on the order of $100-150K per terminal, but maintenance costs are minimal which may make it overall more economical compared to other choices. In many cases, two or more pilot schemes can be used over the same transmission line.

Fiber optic (FO) channel - A very flexible and desirable communications channel that can be used for many digital protection schemes, including blocking, permissive, direct transfer trip and differential. Costs per mile for new construction fiber optic ground wire ranges from $20-30K which may make it expensive for longer lines compared to PLC, but fiber provides greater flexibility and immunity to noise interference. There are costs associated with maintaining the fiber interface equipment and the functional life of the fiber has not yet been proven, so the true cost of a long term fiber system is not clear. Shared bandwidth may improve the economics. When the fiber is included in the shield wire (optical ground wire or OGPW), consideration must be given to the mechanical design of the OGPW to minimize the likelihood of physical damage or even breakage during storms as well as to the ground fault current rating of the OPGW to minimize the likelihood of damage to the optical fibers during ground faults.

Microwave – both analog and digital – also have high cost but can be economical depending on the length of the line, the terrain, and shared bandwidth. Schemes have been developed to allow under-reaching relay timers to “speed-up” should the microwave channel be lost.

For modern digital microwave networks, there are more protection opportunities to provide pilot protection because of (1) lower costs when compared with older analog systems that used audio tones, and (2) more opportunities with relay-to-relay communications which can easily accommodate a number of ‘virtual channels’ at little incremental cost once the initial telecom infrastructure is put in place.

Incremental Cost – If existing infrastructure is in place for other line protection, SCADA, revenue metering, etc., the incremental cost to provide pilot protection will be a consideration as to the scheme chosen. For example, the addition of a DTT function may be a matter of purchasing cards and plugging them in to the existing shelves and adding appropriate wiring.

Additionally, a bi-directional direct transfer trip channel may be used to enhance the pilot protection of a line when only a single direction channel would normally be required. This added level of protection could be provided at minimal incremental cost if the communication system interface equipment offers a bi-directional channel by default.

Spread Spectrum Radio - Point to point spread spectrum radio can be used to provide pilot functionality over short distances. In most cases these are unlicensed and fairly simple to implement. However, there are some limits to the applications of these systems that must be understood in order to achieve the required reliability for a protection channel. A good reference is “Using Spread Spectrum Radio Communications for System Protection Relaying Applications” available at www.pes-psrc.org.

6.6 Monitoring channel status - analog and digital channels, permissive versus blocking schemes

Channel integrity is critical in any pilot scheme and requires that it be monitored by some means.

Any permissive or direct transfer trip channel that shifts from ‘guard’ to ‘trip’ provides an excellent method of monitoring channel health. This can be analog or digital signals depending on the channel selection.

A directional comparison blocking scheme, which uses an ‘on-off’ carrier, normally is not sending a signal. This application generally uses a checkback scheme to verify the channel health on a regular basis, typically every 8 or 12 hours. The terminals communicate with each other on a scheduled basis and alarm should the checkback fail. This checkback helps ensure that the scheme will work properly when called upon.

6.7 Voting scheme applications and requirements

Where utilized, there are three commonly used versions of voting schemes:

- One-out-of-two (or three) (high dependability)
- Two-out-of-two (high security)
- Two-out-of-three (high reliability, high security)

The vast majority of high voltage transmission lines are protected where two or more protective systems are applied but only one scheme is required to operate to trip the line.

In critical applications where a possible false trip is unacceptable, voting schemes are applied that require multiple protective systems to provide a trip output in order to actually trip. Where this is done, it is normally configured so that 'two-out-of-three' systems are required in order to trip. These types of schemes can be very costly as independent communications channels are normally applied.

6.8 Applying pilot schemes via relays with integrated communications interfaces (advanced protection applications via spare bits or channel capability)

Many of the more modern relays that use fiber optic communications have additional channel features built in that can be applied to enhance protection performance. For example, one digital line differential has the ability to also send direct transfer trip. Another relay has additional data bits that can be used for direct transfer trip.

The advantage of these systems is that the logic is built-in which eliminates time delays associated with interfacing communication devices with the protective relays. The disadvantage is that a failure could take out two of the overall protective schemes, which needs to be considered when determining overall protection system dependability.

6.9 Diversity in transmission line protection principles and communication channels

When ensuring that the EHV protective systems meet the desired performance criteria, one must always consider using independent communications channels so that a single channel failure will not undermine the required performance. This is especially true where substation and communication equipment may be particularly susceptible to damage caused by natural disasters [9].

7 Conclusions

Machine rotor angle stability is only one issue in a list of considerations that may justify the need for pilot protection on a transmission line. There are at least a dozen other technical reasons why high-speed clearing down the entire length of a transmission line may be required. Each of these issues should be studied when determining the need for pilot protection. These considerations may be added to other uses for communication paths (e.g., need for substation SCADA) that may provide sufficient justification to permit pilot protection to be implemented.

Once the need for pilot protection has been established, some additional general requirements must be determined, including the number of pilot systems required, how to operate the line if the pilot protection becomes unavailable, and how breaker and relay maintenance affects the pilot protection at each terminal. This report addresses these issues, without delving into the specific design decisions (i.e., which pilot scheme to use or details of communication channel/equipment design).

This type of thorough analysis of the technical justification and operational requirements for pilot protection should be integrated with the economic implications of those requirements in a comprehensive review of the transmission line protection, for both new transmission lines and when protection is replaced/upgraded on existing lines.

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