

# Practical Considerations for Single-Pole-Trip Line-Protection Schemes

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# PRACTICAL CONSIDERATIONS FOR SINGLE-POLE-TRIP LINE-PROTECTION SCHEMES

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## ABSTRACT

This paper discusses some practical aspects of implementing single-pole tripping schemes in transmission-line protection. Implementation and techniques will vary in the design of protective relaying systems that implement single-pole trip (SPT); as well as in the philosophy of the users applying these devices; however, the intent is to discuss issues that need to be considered for SPT systems.

We present a quick review of the benefits and implementation of SPT, emphasizing the benefits for power system stability with a relatively minor incremental cost compared to three-pole trip (3PT) systems for EHV and many HV transmission systems. We also discuss specific aspects of implementing single-pole-tripping in line-protective relaying schemes. In addition, we discuss using a faulted-phase selection algorithm, some reclosing scheme philosophy, and the greater flexibility that improved communication channels give to SPT systems. We analyze the open pole period of an SPT system to gain some insight into the behavior of the measured quantities and protective relaying elements.

## INTRODUCTION

Single-pole tripping (SPT) systems are being used worldwide to enhance the stability, power transfer capabilities, reliability, and availability of a transmission system during and after a ground fault [1][2]. The basic idea is to take advantage of the higher probability of occurrence of single-line-to-ground faults, SLGF, (AG, BG or CG) with respect to the other seven fault types, designing the system to correctly differentiate between SLGF and the rest of the occurrences, for the purpose of tripping a single pole.

The benefit of having a single pole of the transmission line breakers open is that the two ends of the transmission line remain metallically connected by the other two phases, allowing power transfer and reducing the possibility that the two ends will lose synchronism.

## BENEFITS OF SPT

When a single-line-to-ground fault occurs, the protective system should detect the ground fault and identify the faulted phase, tripping a single pole of the breaker to clear the primary arc current. The open-pole period should be long enough to ensure that the secondary arc current (fault current fed by the energy from the other two phases) is extinguished. The design of the transmission line should consider whether additional shunt compensation reactors are needed to extinguish the secondary fault current after the single-phase poles are open [2]. Once the secondary arc current has been extinguished, the reclosing scheme will take care of bringing the breaker back to normal.

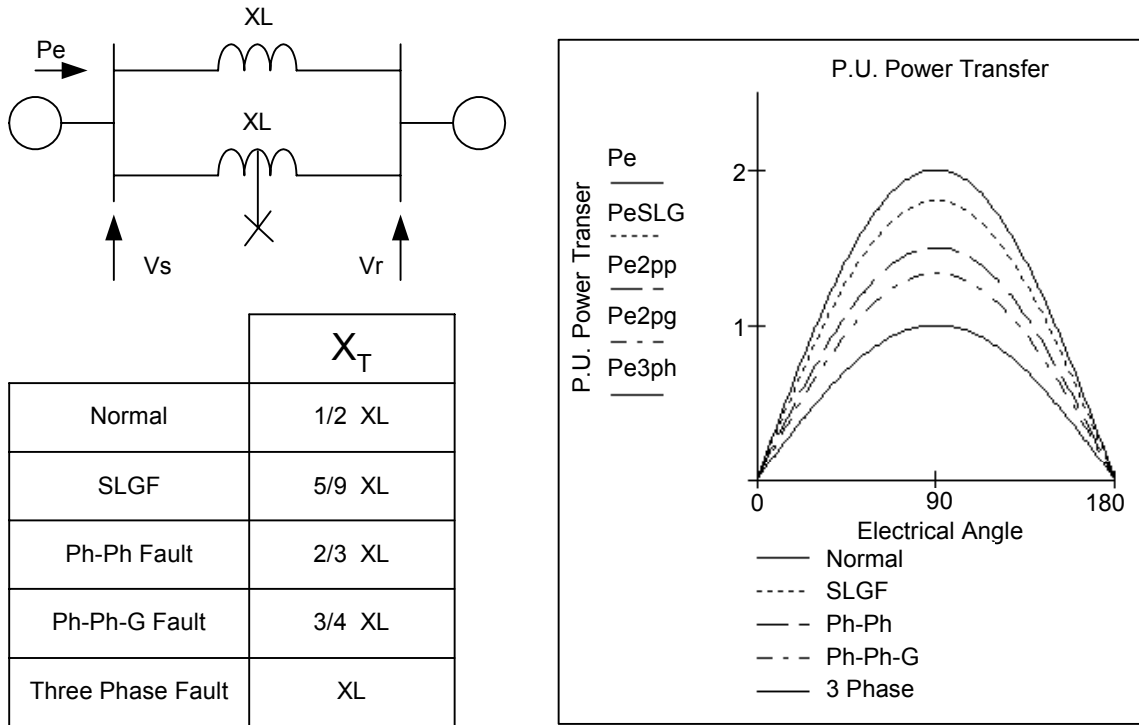
The classical use of the power transfer capability equation demonstrates the benefits obtained when a single-pole-trip system is applied to the protection of a transmission line [3][4]. The equation describes the maximum electrical power that can flow across a transmission-line impedance:

$$P_e = \frac{|V_s||V_r|}{X_T} \sin(\gamma) \quad (1)$$

Where:  $P_e$  is the real electric power transferred in Watts  
 $V_s, V_r$  are the sending and receiving equivalent source voltages.  
 $\gamma$  is the angle between the two source voltages

In a steady-state power system, the energy conversion is at equilibrium. All the mechanical power is converted into electrical power ( $P_m = P_e$ ), if losses are not considered. The power flow across the line impedances of a power system should ensure that the mechanical power is transmitted to the loads. Any lack of transmission capacity implies that the equilibrium is lost and there is more mechanical power than the lines are able to transmit electrically.

The transfer reactance ( $X_T$ ) between the two voltages ( $V_s, V_r$ ) in Equation 1 is the key for evaluating the power transfer capability of a system configuration. The system in Figure 1, for example, illustrates a simplified arrangement of two parallel lines. For the sake of simplicity, the assumptions are that the source impedances are negligible, the lines are reactances, and the zero-sequence impedances of the lines are three times the positive-sequence impedances ( $X_{L0} = 3X_L$ ).



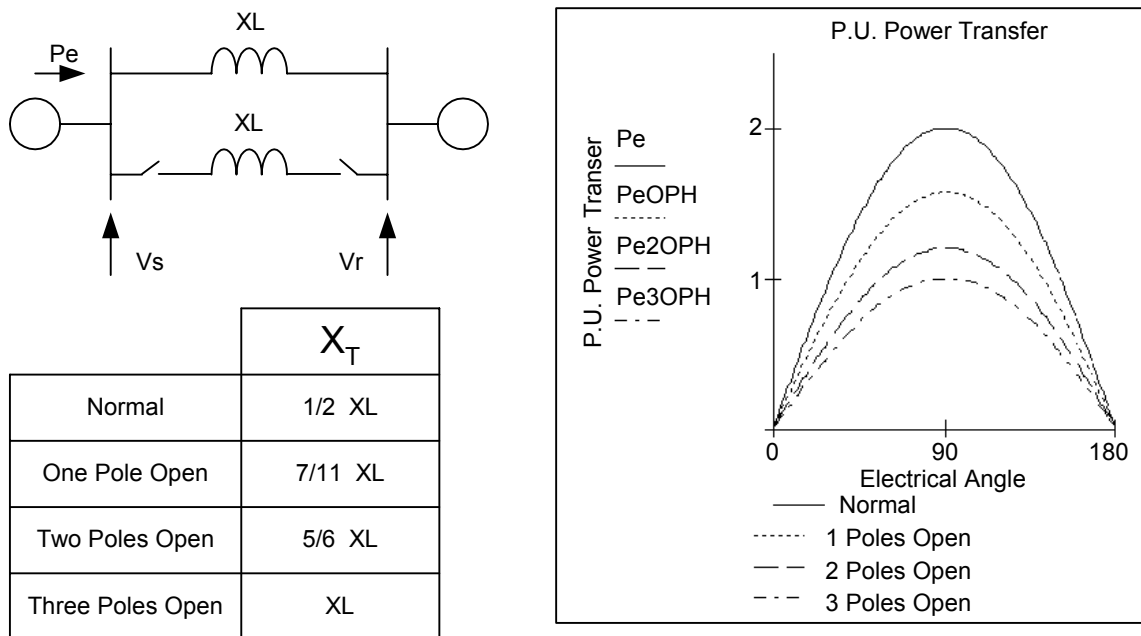
**Figure 1** Power Transfer Capability of a System During Power System Faults in the Middle of the Line

Figure 1 illustrates the results of calculating  $X_T$ , the equivalent transfer reactance between the two sources, for different types of faults in the middle of one of the parallel lines. During normal power flow, the equivalent transfer reactance is  $X_T = 1/2 X_L$ , the parallel combination of the two

line reactances. If a fault occurs in the middle of one of the transmission lines, as shown in the figure, the equivalent transfer reactance is calculated using electric power system analysis techniques and the theory of symmetrical components [5][3].

The severity of the power system fault can be evaluated. The value of  $X_T$  illustrates how much electrical power can be transferred across the system. The SLGF, which fortunately is the most frequent fault, is in general the least severe for the power system. During normal operation of the simplified power system shown in Figure 1, 2 p.u. can be transferred across the transmission system. During a SLGF the system can transfer 9/5 p. u. As expected, for a three-phase fault the system can only transfer 1 p.u., half of the normal operation power, and it is this fault that greatly affects the stability of the power system. A three-phase fault severely affects the ability of a power system to transfer power.

Using the same power system, we calculate the power transfer capability during the operation with open poles in one of the transmission lines. We use the same circuit analysis and symmetrical component techniques to find the equivalent transfer reactance ( $X_T$ ) of the system. Figure 2 illustrates that having a single pole open allows the maximum power transfer.



**Figure 2** Power Transfer Capability of a System During Open-Pole Periods

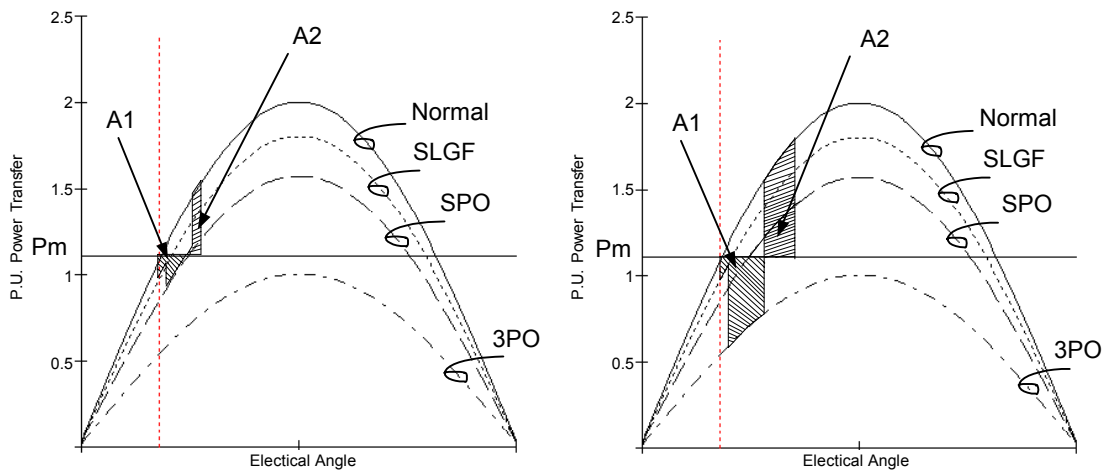
The simplified example provides arguments for doing single-pole tripping in a power system. A SLGF is the least damaging fault to the power system and the most common. Moreover, a single open pole, as would be expected, allows the power transfer over the two remaining phases.

Power systems are subject to faults; single-pole tripping and reclosing can help reduce their impact on the power system. During normal operation of the power system, the mechanical power and the electrical power transmitted are equal, neglecting losses for simplicity. Equilibrium is disturbed when a fault occurs and there are no means to transfer all the mechanical power delivered to the generators. As a result, the generators accelerate and the power transfer angle ( $\gamma$ ) increases.

If this  $\gamma$  increase is not limited, the power system goes into instability, because the generators will start slipping poles. A ground fault disrupts the equilibrium of the power transfer and  $\gamma$  changes.

The rate of change is less than that of a multiphase fault, as discussed in earlier paragraphs. An open-pole condition, by allowing power transfer through the two healthy phases, allows the change in  $\gamma$ , and the rate of change is less than the complete opening of the three poles.

The classic equal area criterion is a relatively simple concept that can be used to describe the benefits of SPT systems for power system stability. This criterion uses Equation 1, which recognizes an accelerating energy caused by more mechanical power than electrical power being transferred. This is represented by the area where  $P_m > P_e$ , mechanical power greater than the electrical power transferred. On the other hand, the decelerating energy is represented by the area where  $P_e > P_m$ . For simplicity, it is assumed that the mechanical power ( $P_m$ ) remains constant. When the power-transfer capability of the power system changes, the existing equilibrium is broken. The equal area criterion says that the stability of the system is guaranteed if the accelerating area is less than or equal to the de-accelerating area.



**Figure 3** Equal Area Criteria for SPT (left) and 3PT (right)

In Figure 3 the equal area criterion is used on the simple power system discussed, to illustrate the single-pole trip-and-reclose sequence and the three-pole trip-and-reclose sequence for a ground fault.

The figure on the left side shows the SPT sequence. The accelerating area, A1, is small and most likely the system may even reach a steady state without reaching instability. The respective de-accelerating area, A2, is also small. A slow angle drift has been assumed, since the accelerating power ( $P_m - P_e$ ) is small. The graph shows the change in  $\gamma$  for the ground fault and the single-pole open. A1 represents these two states. A2 represents the de-accelerating area, denoting the return to normality.

The figure on the right hand side represents a 3PT sequence. When opening the three poles, the system loses a large percentage of its transmission capability, making the accelerating area, represented by A1, large. A large accelerating area denotes a faster rate of change in  $\gamma$ . If the three poles are left open, for this particular system, there is not even a chance for a de-accelerating area; therefore, the system will become unstable. A reclose of the breaker and the return to normal operating conditions provide the system with the de-accelerating energy, A2, which is also larger than in the SPT sequence.

Figure 3 shows that, for the same fault, a power system using three-pole-trip relaying presents a larger accelerating area (A1) than for system implementing single-pole tripping. It is therefore

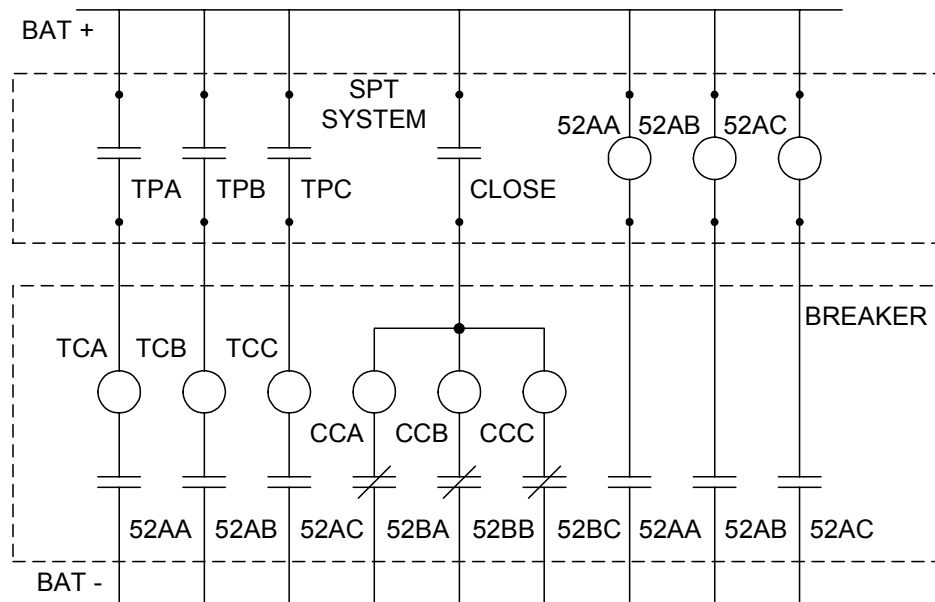
necessary to have a larger de-accelerating area (A2) compared to the same fault and SPT. SPT systems impact the equilibrium of the power system less than 3PT systems.

The example just discussed illustrates the benefit of SPT systems for power system stability [6].

## IMPLEMENTING SPT SCHEMES

SPT protective relaying systems have been implemented successfully for many years. Modern numerical protective relays provide the necessary logic for protecting the transmission line with advanced fault-detection algorithms and SPT logic for determining correctly the faulted phase and fault type.

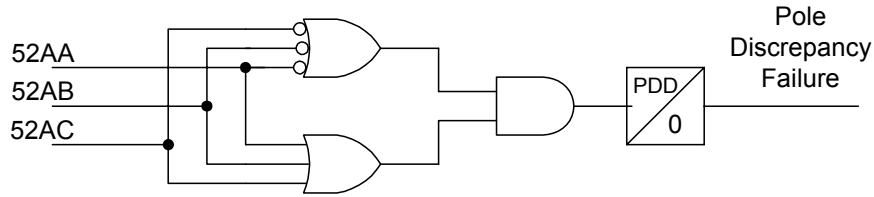
The main component of a single-pole-trip relaying scheme is, of course, the power system breaker. The power system breaker should be designed to support the tripping of individual phases. In reality, EHV circuit breakers can all support the tripping of individual phases because of the large physical separation of breaker poles that require individual contact operating mechanisms. HV breakers, on the other hand, may need to be designed to accommodate SPT.



**Figure 4** Implementing an SPT system

Figure 4 illustrates the required control mechanism of an SPT protective system and an SPT-capable breaker. The outputs for tripping single breaker poles (TPA, TPB, TPC) are controlling the individual phase trip coils (TCA, TCB, TCC). The need for a reclosing scheme is shown with a close contact controlling all the close coils. There is no need to provide individual close outputs because the energization of the close coils depends on the 52b contact of the breaker. The relay system will probably require the position of the three breaker poles (52AA, 52AB, 52AC).

A single-pole-trip breaker should include a breaker-failure-scheme denominated pole discrepancy logic. This logic is a simple combination logic that ensures that all the breaker poles are in the same position during normal operation. To account for the expected open-pole period, the logic should include a timer set longer than the maximum normal open-pole condition, including breaker closing time and security margin.



**Figure 5** Pole-Discrepancy Logic

Figure 5 illustrates typical pole-discrepancy logic. It could be done with combination logic using the programmable abilities of modern relays, or using 52A and 52B contacts directly from the breaker. Other implementation may be looking at the phase currents to implement the same. The location of this logic may also be included in the control electronics of the single-pole trip breaker. Whether the logic is implemented in the single-pole trip breaker, the protective relay or other control equipment, it is very important that it exists. It denotes a failure of the breaker; tripping the other two poles is the remedial action. Care should be taken in coordinating the timer, PDD, with the open-pole period, as we stressed earlier.

SPT systems are the standard in a large number of utilities throughout the world. They are implemented in HV and EHV lines without further considerations. Some utilities, however, have considered the incremental cost of implementing a SPT protective scheme compared to a 3PT protective scheme. A utility in the Northwest US made the following comments on this subject:

- In modern numerical transmission line protective relays, SPT logic is already included. This is a big advantage compared to electromechanical or solid-state relays, where the hardware needed to be different because of the more complex tripping logic. The incremental cost of using SPT in a 3PT relay is minimum, if not negligible. Perhaps the biggest incremental cost is in the wiring to the protective relay, since SPT systems require more I/O than 3PT systems.
- For 220 kV and lower power systems, the new installations will require more expensive power breakers, because independently operated breaker poles are more expensive than the simpler single mechanism of the gang-operated breakers. In older installations, it may be possible to upgrade existing breakers to have SPT capabilities.
- The secondary arc extinction during the open-pole period may require a bank of four reactors, three for the phases and one for the neutral. This is more common in long transmission lines. Power system studies with the Electro-Magnetic Transients Program (EMTP) should be conducted simulating the open-pole condition.

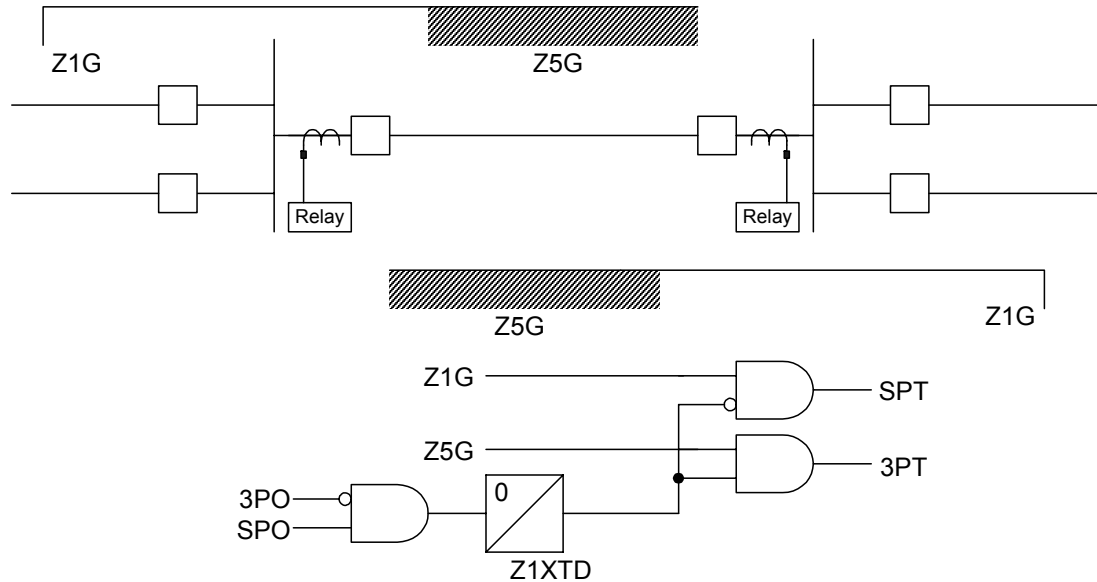
## PROTECTIVE RELAY SCHEMES FOR SPT

The line-protective relaying schemes used for SPT systems are the same as the ones used in 3PT systems. However, being able to select the proper pole to trip and the required reclosing sequence allows for additional customization. Using the fault-detection techniques for transmission line protection, we can classify SPT schemes as nonpilot-distance, directional-comparison, and current-only systems [7][8].

### Nonpilot Distance Protection

The words have been carefully chosen to avoid denoting this protection scheme as ‘stepped distance’ protection. The correct denomination for this SPT scheme is “Zone 1 Extension.”

For efficient and reliable protective relaying of transmission lines, line-protective schemes should employ a communications channel that allows protective relaying coverage of the whole line. When the communications channel is not available, Zone 1 extension is an option for SPT schemes. The implications of its use need to be evaluated, because a concept of this scheme is to disconnect more than is necessary.



**Figure 6** Nonpilot SPT Scheme

This scheme takes advantage of the highest probability of occurrence of phase-to-ground faults in a transmission line. The protective relaying scheme implements a traditional stepped-distance protection for phase faults. For single-line-to-ground faults, the protective relaying scheme uses an overreaching arrangement to trip the proper single-pole trip and reclose.

Figure 6 is a concise illustration of this scheme. The idea is to have Zone 1 ground (Z1G) overreaching the length of the line, typically 125 percent. If an internal phase-to-ground fault occurs; the relaying system will trip the proper pole at both terminals. Also, for the ground distance units (Z1G) of the adjacent terminals, the overreaching zone will also trip the same phase.

If an external phase-to-ground fault occurs within the Zone 1 reach, one of the terminals will trip the faulted-phase pole; as will the relays located in the adjacent line. The scheme tolerates the tripping of the faulted phase for an external fault because the system remains electrically connected with less probability of a loss of synchronism, allowing fast reclosing. Moreover, as mentioned in the discussion above, power flows in the remaining two phases.

After reclosing of the faulted phase, the ground distance reach is changed to the normal 80-90 percent of the transmission line. As with most transmission line SPT schemes, if the single-pole recloses into a fault, the protective relaying scheme opens the three poles and does not automatically reclose.

The advantage of this nonpilot scheme is the quick identification and opening of the faulted phase, while preserving the system electrical synchronization while the pole is open. The unfortunate consequence of the overreaching Zone 1 elements is the tripping of more breakers than necessary. However, the system integrity is conserved.



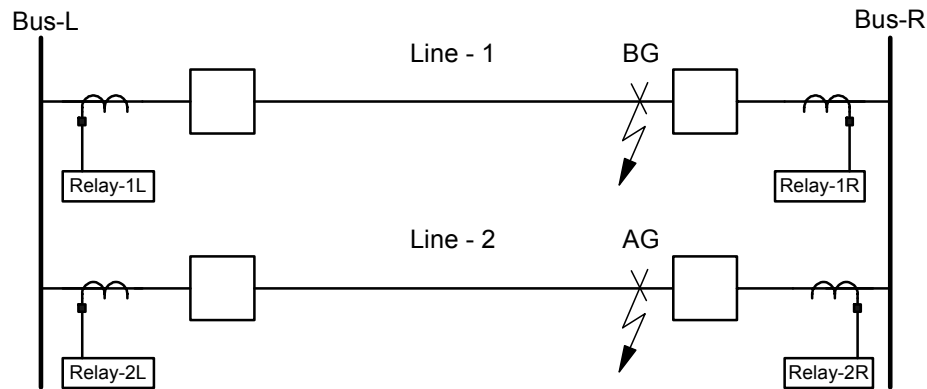
Figure 6 illustrates a simple implementation of Zone 1 extension using two zones of ground fault protection. Some other implementations are designed to change the Zone 1 reach directly. The idea, however, is the same.

## Directional Comparison

Pilot schemes that use a communications channel to send permission to trip or to block tripping based on the direction of the fault are called directional comparison pilot schemes. The fault direction is usually determined using distance (impedance measurement) units and/or directional overcurrent units; however, other methods have been also used for this purpose. The pilot protection logic is generally based on Direct Underreaching Transfer Trip (DUTT), Permissive Underreaching Transfer Trip (PUTT), Permissive Overreaching Transfer Trip (POTT), the Blocking Scheme, or variation of these. These schemes are the same as those used for 3PT systems, with some variations to accommodate phase selection for single-line-to-ground faults.

The great advantage of directional comparison pilot systems is that the channel requirements are low. The transmission of a logical 1 or a logical 0, for either the permissive or the blocking signal, is the only requirement and the bandwidth required is very low. Directional comparison systems are very popular for line-protection systems and their performance is well known. The difference between a directional comparison scheme for an STP system and a directional comparison scheme for a 3PT system, which is more traditional, is the phase-selection requirement.

Directional comparison systems rely on the local decision for phase selection. Phase selection under certain conditions is difficult and is an important practical consideration when applying SPT directional comparison systems.



**Figure 7** Cross-Country Fault and Different Faulted Phases on Each Parallel Line

Figure 7 illustrates a cross-country fault in a two-parallel-line arrangement. Notice that the faulted phases are different in each of the transmission lines. A quick inspection of the figure yields the following table, which shows the local fault-type determination of the relay systems:

**Table 1** Local Faulted-Phase Selection

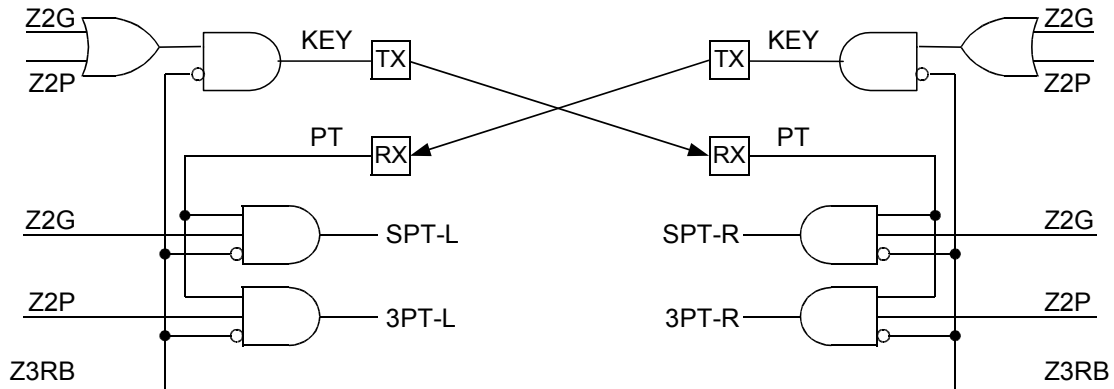
Relay	Local Fault Type Identification
1R	BG
2R	AG
1L	ABG
2L	ABG

Table 1 shows clearly that there is a problem in the fault-type identification of this cross-country fault. Ideally, the local faulted phase selection should agree between the two terminals of transmission line relaying scheme.

The issue with the above scenario is that high-performance SPT systems should only disconnect the faulted phases. Unfortunately, the local phase-selection decision is not clear for the 1L and 2L relays. For POTT systems, the situation can be resolved as more communications channels are used. This is described in the following paragraphs.

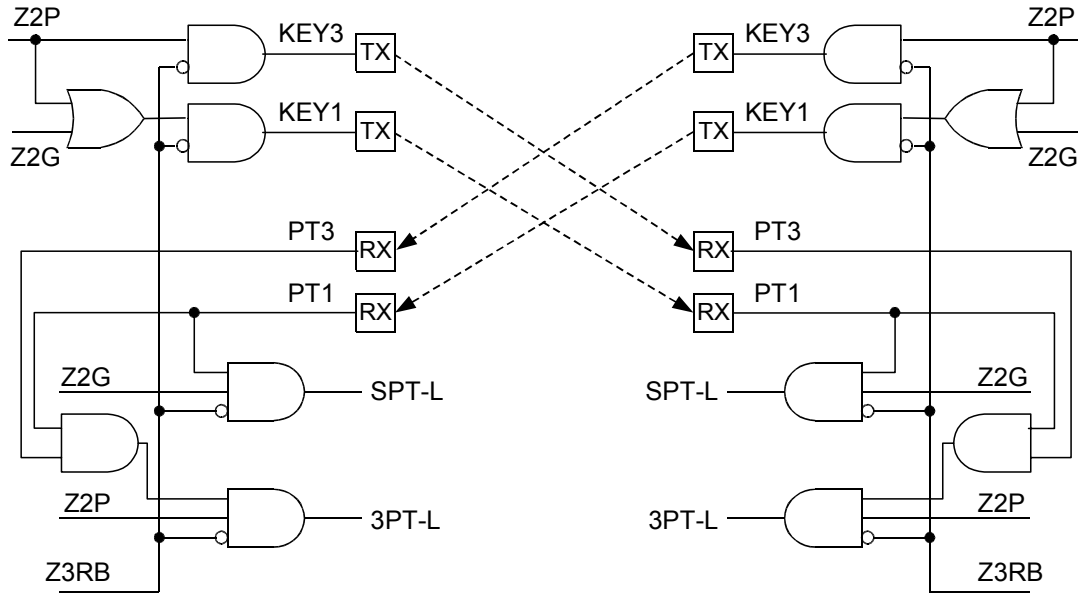
**POTT**

In a traditional POTT scheme, a permissive signal is sent by an overreaching zone. An overreaching zone (Zone 2, for example) is used to transmit the permissive signal.



**Figure 8** POTT Simplified Schematic Diagram

Figure 8 illustrates a traditional POTT scheme. With a single channel available, either Z2G or Z2P transmits the permissive signal to the other end. For our application problem in Figure 7, we can conclude that, unfortunately, the traditional POTT scheme of Figure 8 will trip the three poles of the L-Bus breakers. The R-Bus breakers will properly select the faulted phases and trip the proper poles. When the traditional POTT scheme is applied on a parallel line arrangement (Figure 7), there is an implicit acceptance that the cross-country fault may happen and the SPT scheme will disconnect more phases than really required.



**Figure 9** POTT2 Simplified Schematic Diagram

If the parallel lines in question are the interconnection between two power systems, a false three-pole trip of the two parallel lines will disconnect the two systems and synchronism between the two will be lost. In this situation and in others, the unnecessary tripping of the three poles of the two lines is unacceptable. The logic for distinguishing a single-line-to-ground fault from a multiphase fault requires a more sophisticated channel and logic. The channel may be a relay-to-relay communications channel [9] that allows the transfer of at least two bits.

In the POTT 2 scheme, two permissive signals are generated, as shown in Figure 9. A general fault permissive signal (KEY1) is generated by the operation of both phase and ground units. The phase units in this signal must be allowed to send the permissive signal for evolving faults. The multiphase permissive signal (KEY3) is generated by the operation of only the phase units. On the other side of the communications channel, the respective received permissive signals are denoted by PT1 and PT3. A single-pole trip is allowed if PT1 and the local ground units are active.

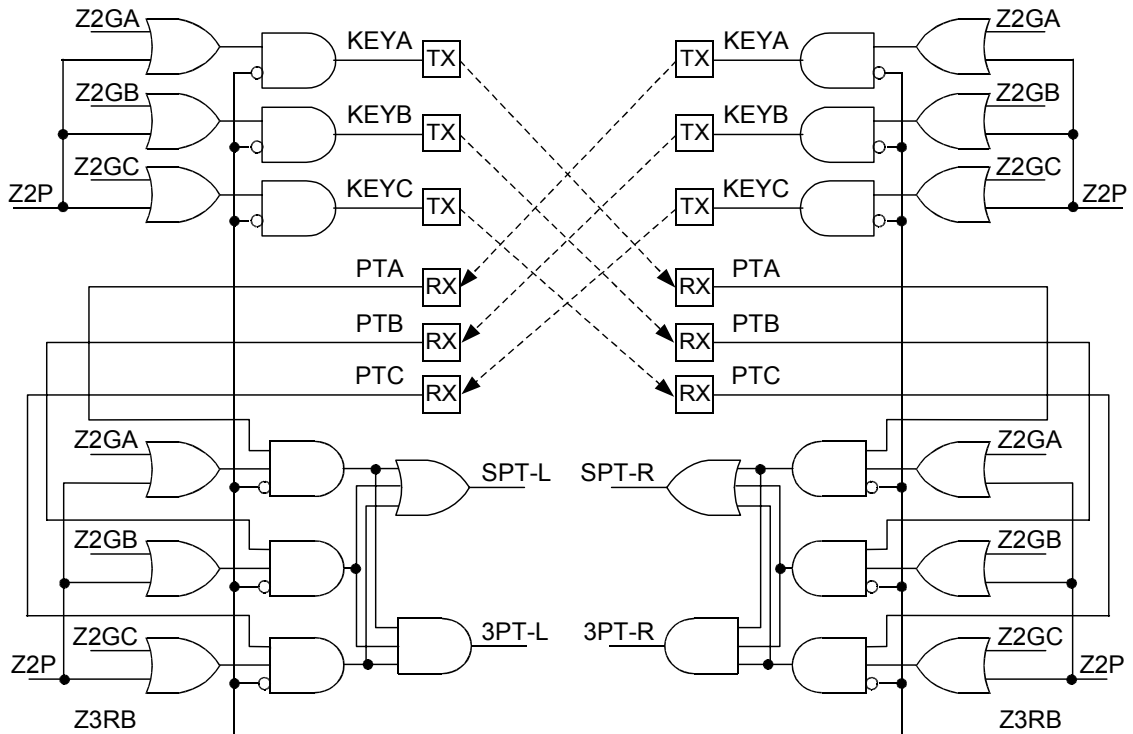
We can better visualize the operation of the POTT 2 logic by using Table 2, which illustrates the sending and receiving signals, as well as the resulting trip. Notice that the tripping is sequential since the L side will wait for the correct clearing of the phases of the relays on the R side.

**Table 2** POTT 2 Operation

Relay	Local Fault Type Identification	Type of Key Sent	Type of Permissive Received	Z2P or Z2G	Type Trip	Comments
1R	BG	KEY1	TP1, TP3	Z2G	SPT	
2R	AG	KEY1	TP1, TP3	Z2G	SPT	
1L	ABG	KEY1, KEY3	TP1	Z2P	X	Will SPT the B phase, once the 2R breaker opens the A phase
2L	ABG	KEY1, KEY3	TP1	Z2P	X	Will SPT the A phase, once the 1R breaker opens the B phase

The POTT 2 scheme increases the ability of a permissive overreaching transfer trip SPT system to correctly identify the faulted phases during a cross-country fault in parallel lines. The requirement is an additional channel.

In some situations, where the increment of an additional channel is not significant, using relay-to-relay communications, for example [9], where eight data bits are mirrored from one side to the other, allows three channels to do segregated POTT schemes on a per-phase basis. In a POTT 3 scheme the permissive signal is generated, sent, and received on a per-phase basis. This technique provides inherent phase selection.



**Figure 10** POTT 3 Simplified Schematic Diagram

Figure 10 shows the POTT 3 scheme logic. The transmission of the permissive signals is generated by individual operation of the specific phase overreaching ground units (Z2GA, Z2GB

or Z2GC) or phase units, as shown in Figure 10. On the receiving end, the respective permissive signals (PTA, PTB or PTC) are qualified with the local Z2 units.

**Table 3** POTT 3 Operation

Relay	Local Fault Type Identification	Type of Key Sent	Type of Permissive Received	Z2P or Z2G	Type Trip	Comments
1R	BG	KEYB	TPA, TPB, TPC	Z2GB	SPT	
2R	AG	KEYA	TPA, TPB, TPC	Z2GA	SPT	
1L	ABG	KEYA, KEYB, KEYC	TPB	Z2P	SPT	
2L	ABG	KEYA, KEYB, KEYC	TPA	Z2P	SPT	

Table 3 shows the generated and received signals in all the terminals. The fault detection results in a single-pole trip in the four terminals simultaneously. The advantage of this scheme is that there is no sequential trip; tripping of the terminals is simultaneous. Besides the increased performance in POTT 3 compared to the other two schemes, there are other advantages from the inherent phase selection of the scheme.

### **Blocking Scheme**

The directional comparison-blocking (DCB) scheme is a slower scheme compared to POTT because it is required to coordinate with the worst channel delay, plus a safety margin. Operation of the SPT DCB scheme compared to traditional 3PT DCB is the same. The phase-selection logic is the only fundamental difference.

The problem described in Figure 7 is also applicable to DCB and when being applied to a parallel line arrangement, the shortcomings should be acknowledged. A solution incrementing the number of channels, as explained for POTT, is not possible, because the R-side relays cannot send a block on a per-phase basis.

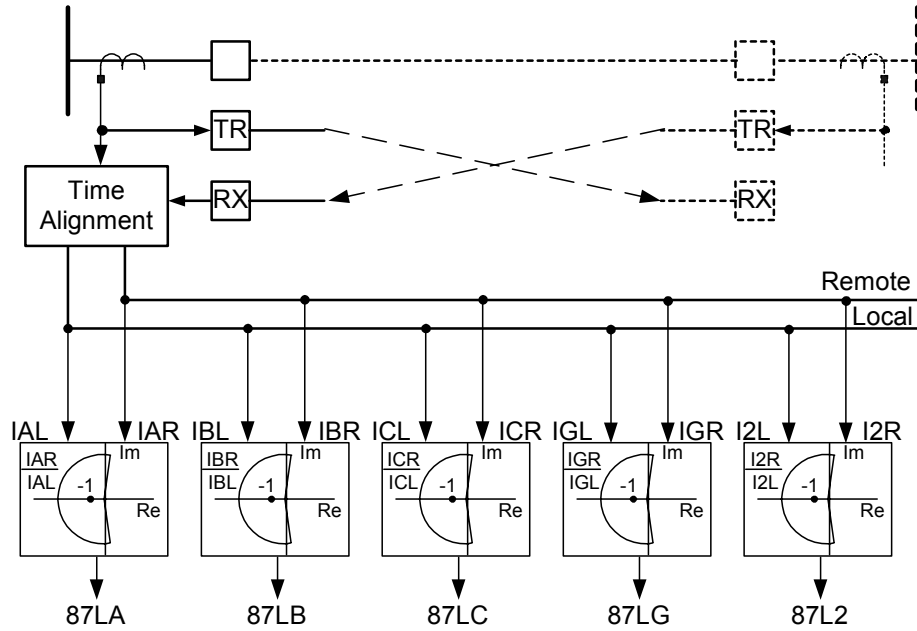
### **Current-Only Schemes**

When an adequate bandwidth is available for transferring current magnitude and/or phase information from one terminal to the other, current-only systems are an appealing solution for implementing single-pole-trip systems. Current-only systems exchange information about the currents in each terminal of a transmission line through the channel. Current-only systems have the advantage of avoiding protection problems introduced by the use of voltage signals. These problems include CCVT transient issues, power swings, series-capacitor compensation, and cross-country faults.

Current-only schemes need to have independent comparisons of the currents in each phase to benefit from the inherent phase selection of the scheme. Systems that combine the information of the three phases into a composite quantity do not provide inherent phase selection. Traditional percentage differential, phase comparison, and alpha-plane are current-only systems that compare

the information of each phase (A, B, and C) from each terminal and are perfect for single-pole tripping [10].

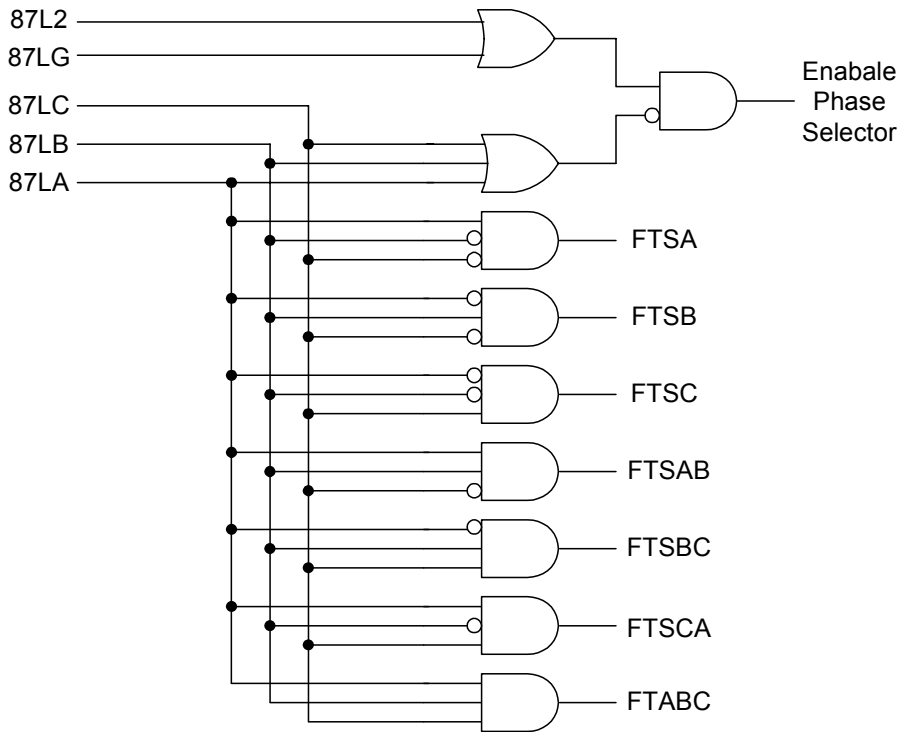
The seldom-used Selective-Pole-Tripping scheme, where only the involved phases are tripped for any fault (only phases B and C are tripped for a BC fault, for example), benefits greatly from the phase-selection simplicity in current-only systems. In fact, current-only systems seem to be the only modern alternative for selective-pole tripping.



**Figure 11** Modern Alpha-Plane Current-Only System

Consider, for example, a modern alpha-plane line differential system, as shown in Figure 11. The information exchange about the terminal currents is done through a communications channel. In each terminal, the local and remote currents are aligned, compensating for the channel time delay.

Each phase current is compared with the alpha-plane technique, yielding the trip decision, denoted by the signals 87LA, 87LB, and 87LC. For greater sensitivity, modern alpha-plane line differential relays incorporate the comparison of the zero-sequence and negative-sequence currents, whose outputs are denoted by 87LG and 87L2, respectively.



**Figure 12** Inherent Phase Selection in a Current-Only Line-Protection Scheme

Selecting the proper pole to trip in a single-pole-trip scheme or in a selective-pole-trip scheme is a very simple matter in current-only line-protective systems. Figure 12 illustrates that a simple combination logic allows the selection of the proper pole to trip, even for selective-pole tripping. The figure also illustrates, implicitly, that evolving and cross-country faults, which may be troublesome for directional comparison systems, can easily be identified with the inherent phase selection in current-only systems.

The phase unit sensitivity depends on requirements such as preventing a misoperation for an open or shorted CT at one end of the line. High-resistance ground faults will be detected by the zero-sequence (87LG) or the negative-sequence (87L2) elements. These elements cannot select the faulted phase by themselves and an additional algorithm for phase selection is needed, as shown in Figure 12. Phase selection will be discussed in the next section.

### ***Backup Considerations***

Current-only SPT systems rely heavily on the communications channel since the information for the protective algorithm is also coming from the remote terminal. The current-only system is the primary relaying system.

However, that channel may fail. Modern alpha-plane current differential relaying systems include a sophisticated distance backup. Application of the distance backup will depend on the protection philosophy of the user.

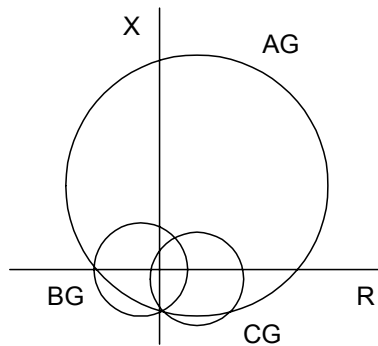
When the channel is healthy, a Zone 2 distance backup provides remote backup to the adjacent transmission lines. Backup of the adjacent transmission lines is not possible with current-only systems. A Zone 2 distance phase and ground scheme is also a backup scheme to the protected transmission line.

When the channel is not healthy, the discussion centers on use of an independent Zone 1, actually on allowing the independent Zone 1 to be SPT or 3PT.

- If the alpha-plane current differential relay is the only component of the protective relaying scheme that trips SPT, then, when the channel is not healthy, the Zone 1 trip should be 3PT.
- If the alpha-plane current differential relay is part of an SPT system, where there is redundancy in the hardware and/or protective relaying philosophies (i.e. working in conjunction with a Directional Comparison System), then, when the channel is not healthy, the Zone-1 trip should be SPT.

## The Phase-Selection Problem

The discussion about current-only systems has demonstrated their inherent ability to select the proper phases for single-pole tripping. These systems, however, also require a more sophisticated method to identify the faulted phase during a single-phase-to-ground fault with high fault resistance. Directional comparison systems depend greatly on phase-selection algorithms to determine the faulted phase.

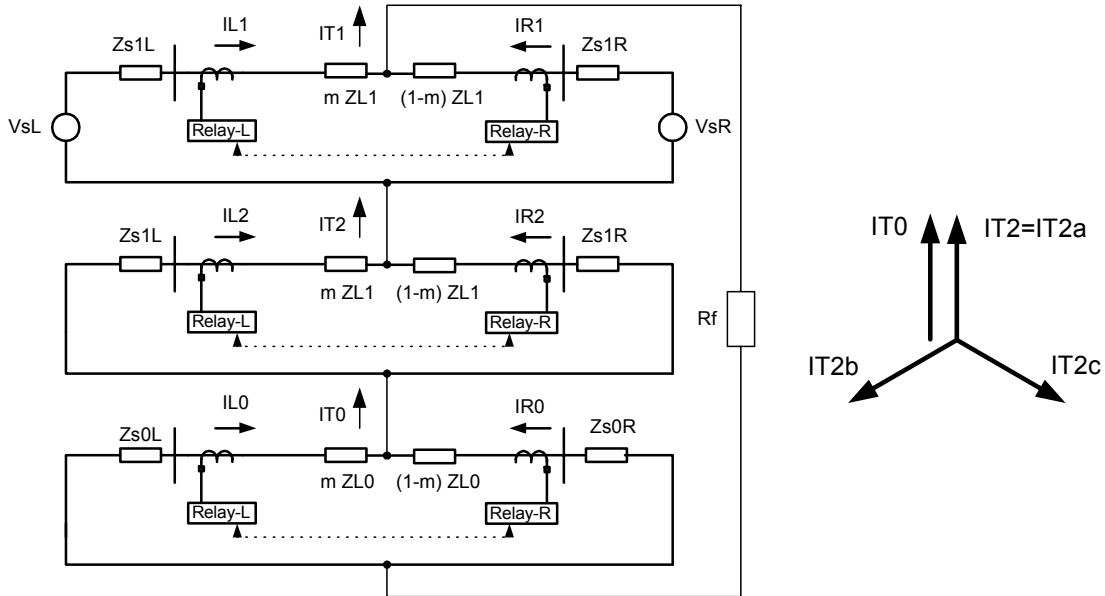


**Figure 13** Ground Distance Units' Response to an AG Fault

Phase selection is not such a simple process as one would think [10][11][13]. The ability of a relaying system to select the faulted phase can not rely on simple measurements like overcurrent, undervoltage, or the operation of the different ground impedance loops. Figure 13 illustrates the response of the different ground impedance loops for an AG fault. The main AG loop will have the expected response; yet, the other two phases will have a response that depends on source impedance and ground relay settings. In fact, it is the zero-sequence current and the  $K0$  (compensation factor) in the apparent impedance measurement equation (ie.  $Z = VB / (IB + K0 I0)$ ) that creates the responses shown in Figure 13.

Phase-selection algorithms have been a source of inspiration for many technical papers; theoretical algorithms with traveling waves and/or sophisticated neural network algorithms have been proposed. Modern commercial relays use different techniques and algorithms. One that is traditionally used in directional comparison protective systems is the angle check between the zero-sequence and negative-sequence currents.





**Figure 14** Phase-Selection Algorithm With I2 and I0

Modern alpha-plane line differential relays implement a phase-selection algorithm that is used when the inherent phase-selection process is not possible (the phase units do not detect the fault). The algorithm takes advantage of the ability of the relay to receive current information from the other terminal. This way, the total zero-sequence current ( $IT0 = IL0 + IR0$ ) and total negative-sequence current ( $IT2 = IL2 + IR2$ ) are compared and their angles checked for coincidence, as illustrated in Figure 14. Use of the total fault current components ( $IT2$  and  $IT0$ ) allows accurate phase selection regardless of source impedances in the negative- or zero-sequence networks ( $Zs0R$  could be infinite, for example) and distribution factors. Moreover, this benefit is also applicable to three-terminal line-current differential.

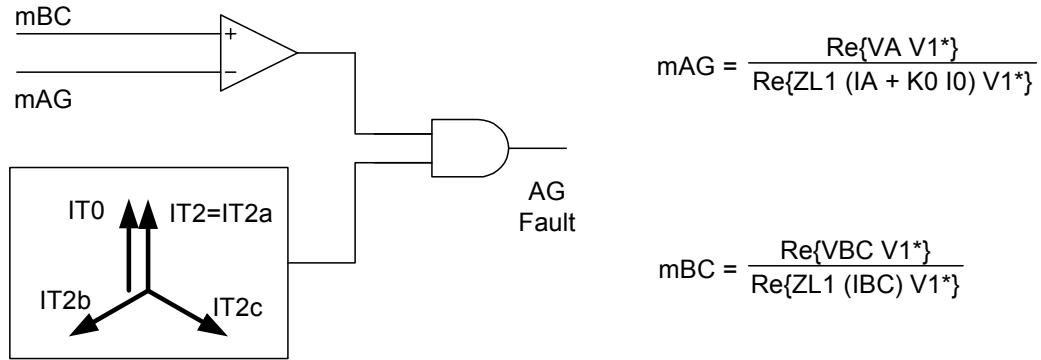
Directional comparison schemes rely on local currents to do phase selection. For example, in Figure 14, the relay in the L side would use the angle coincidence between  $IL2$  and  $IL0$ . The applicability of this local criterion has been proven satisfactory over the years in transmission systems where the source and line impedances are fortunately sufficiently homogeneous for local phase selection.

One of the absolute design requirements when using the angle check between  $I2$  and  $I0$  for phase selection is to distinguish between phase-to-ground faults and phase-to-phase-to-ground faults that have an equivalent signature of the  $I2$  and  $I0$  angles. For example, the AG fault has a similar distribution of  $I2$  and  $I0$  (angle wise) than the BCG fault.

In the alpha-plane line differential scheme, due to the inherent phase selection (Figure 12) of the differential algorithm, discriminating between an AG and a BC fault is not an issue. Phase-to-phase-to-ground faults have enough fault magnitude to allow the inherent phase selection to operate first.

Directional comparison schemes need an additional criteria to differentiate between phase-to-ground and phase-to-phase-to-ground faults. Traditionally the additional criteria involved the comparison of the phase-to-phase voltages ( $VBC$ ) to differentiate between an AG and a BC fault, for example. Another clever solution, since directional comparison systems use distance units, is

to make use of the per-unit measurement to the fault (m) produced by the AG and BC distance units.

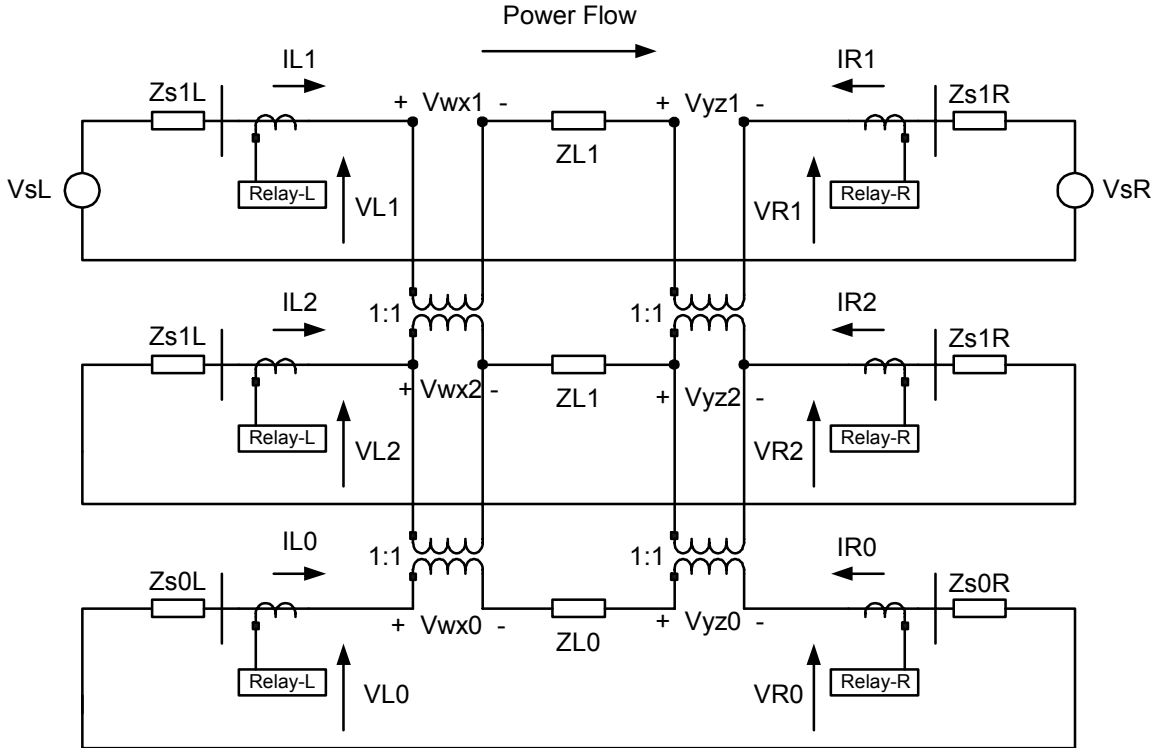


**Figure 15** (AG) Phase-to-Ground Fault Identification

Figure 15 illustrates the supervision needed to ensure correct discrimination for an AG fault by comparing the per-unit measurement (m) of the AG and BC impedance loops (mAG and mBC). For an AG fault, the calculation of mAG yields a smaller number than the mBC calculation. Modern distance relays for line protection complement the phase selection with the technique shown in Figure 15.

## RELAY INPUTS DURING AN OPEN-POLE CONDITION

The fault-detection methods and phase-selection relaying algorithms discussed above are important for fault detection. Once the protective relaying system has issued the trip for a single phase of the breakers of a transmission line, an open-pole condition is created.



**Figure 16** Phase A Pole-Open Symmetrical Components Representation

Neglecting capacitive and mutual effects between conductors, Figure 16 shows the symmetrical components representation of an open-pole condition for a transmission line (A phase “A” open condition) [3][5][12]. The ideal transformers (1:1) are tools used to ensure that the open-phase voltages are the same in the three sequences (i.e.  $V_{wx1} = V_{wx2} = V_{wx0} = 1/3 V_{wxA} = 1/3$  Phase A open-phase voltage) and that the IA current components add up to zero ( $I_{L1} + I_{L2} + I_{L0} = 0 = I_A$ ). Figure 16 shows a simultaneous series fault, when the single-phase A poles of the breakers are open in both ends of the line.

Load flow will determine the value of the components of the open-phase voltages in both locations where the pole is open. In Figure 16, the open-pole voltages are denoted by  $V_{wx}$  and  $V_{yz}$ . The diagram of Figure 16 illustrates that the larger the load flow, the greater the  $V_{wx}$  and  $V_{yz}$  components yielding larger values of  $I_2$  and  $I_0$ . As we would expect, on the other hand, with no load flow,  $V_{wx}$  and  $V_{yz}$  are zero and neither  $I_2$  nor  $I_0$  components are induced.

### Directional Units During an Open-Pole Condition

Figure 16 provides the tools needed for analysis of ground directional units. Ground directional units operate by either using negative- or zero-sequence components. We will use a negative-sequence ground directional unit for illustration. However, the discussion below also applies to the zero-sequence polarized ground directional unit.

The negative-sequence polarized ground directional unit determines the direction to the fault by calculating the  $z_2 = V_2/I_2$  impedance [14]. For a forward fault, the impedance is negative because it corresponds to the negative of the source impedance ( $-Z_{s1}$ ). For a reverse fault, the impedance is positive, because it corresponds to the positive sum of the line impedance and the rest of the system ( $z_2 = +(Z_{L1} + Z_{R1})$ ). A similar reasoning applies to the zero-sequence polarized ground directional unit.



For the R relay:

$$z_{2R} = \frac{VR_2}{IR_2} = \frac{VR_2}{-I_2f \frac{(Z_{s1L} + Z_{s1R})}{ZL1}} = \left( \frac{VR_2}{-I_2f} \right) \frac{ZL1}{Z_{s1L} + Z_{s1R}} = + \frac{Z_{s1R} ZL1}{Z_{s1L} + Z_{s1R}} \quad (4)$$

The results above indicate that the ground directional unit on both sides of the line will determine that the fault is in the reverse direction. For pilot relaying schemes, it is important to ensure that both terminals, under an open-pole condition of an adjacent line, do not indicate a forward fault at the same time. This would be taken as an internal fault by the pilot protection scheme.

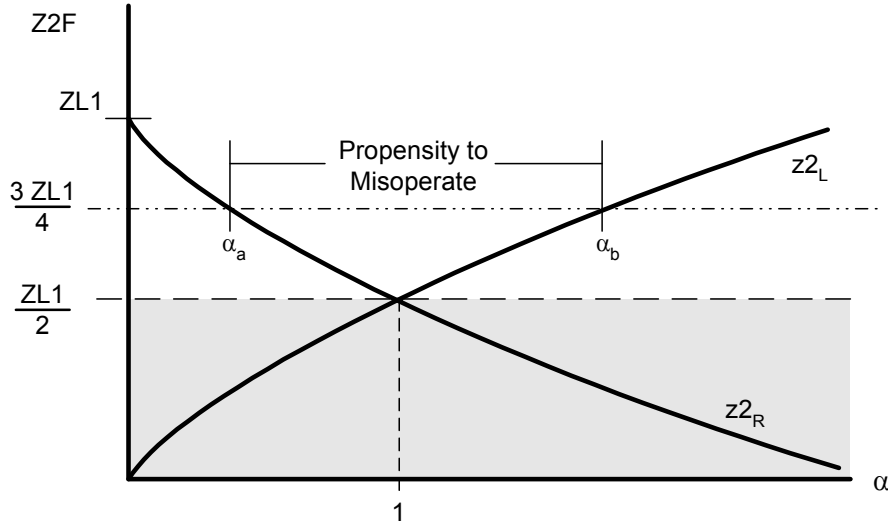
To explain the  $z_{2L}$  and  $z_{2R}$  measurements, we modified Equations 3 and 4 in the following way:

$$z_{2L} = + \frac{Z_{s1L} ZL1}{Z_{s1L} + Z_{s1R}} = k \cdot ZL1 \quad \text{Where:} \quad k = \frac{\alpha}{1+\alpha}, \quad \alpha = \frac{Z_{s1L}}{Z_{s1R}} \quad (5)$$

And

$$z_{2R} = + \frac{Z_{s1R} ZL1}{Z_{s1L} + Z_{s1R}} = (1-k) \cdot ZL1 \quad (6)$$

The directional unit measurements are dependent on the value of  $\alpha$ , which can vary from 0 to infinity. If  $\alpha=0$ , then  $k=0$  and  $z_{2L} = 0$  and  $z_{2R} = ZL1$ . The reverse,  $z_{2L} = ZL1$  and  $z_{2R} = 0$  is true when  $\alpha$  is a large number.



**Figure 19** Variation of  $z_{2L}$  and  $z_{2R}$  With Respect to  $\alpha$

Figure 19 illustrates the variation of the measurement of  $z_2 = V_2/I_2$ , for both directional units, with respect to  $\alpha$ . Since  $z_2$  will be a positive number, the requirement is that the ground directional units do not indicate a forward direction at the same time. This condition is met when both measurements are never below the threshold, or:

$$Z2F_L \leq \frac{ZL1}{2} \quad \text{and} \quad Z2F_R \leq \frac{ZL1}{2} \quad (7)$$

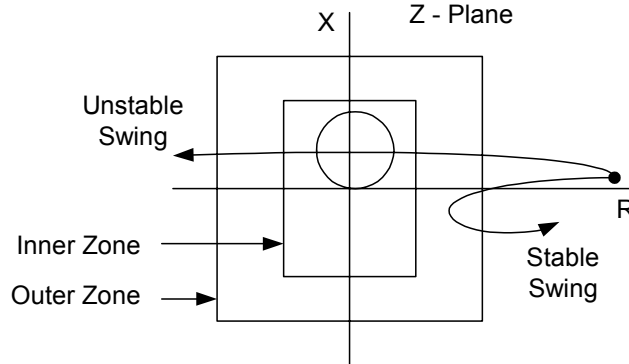
As Figure 19 shows, if any of the threshold is greater than  $ZL1/2$ , with a threshold equal to  $\frac{3}{4} ZL1$ , for example, there is a chance the pilot scheme will misoperate, within the values of  $\alpha_a$  and  $\alpha_b$ .

When the thresholds are defined as in Equation 7, there is no possibility of both terminals determining a forward fault at the same time.

## Power Swings During an Open-Pole Condition

Single-pole-trip line relaying systems add to the stability of a power system. The power transfer capability of a transmission line is not reduced to zero, which allows power transfer through the other two phases. However, it is still possible that the system could experience power swings during an open-pole period [15] [16].

Current-only systems are not affected by power swings and an open-pole condition does not affect their safe operation. Distance-based directional comparison relays are influenced by power swings observed by the change of impedance on the impedance plane. The impedance trajectory measured during an open-pole period, if not considered properly, could lead these schemes to misoperate.



**Figure 20** Traditional Out-of-Step Inner and Outer Zone Scheme

In directional comparison systems, unstable power swings should be detected by logic in the line protection system called Out-of-Step logic. Traditional Out-of-Step detection schemes, as shown in Figure 20, compare the time it takes for the impedance measured by the relay to enter the outer zone and reach the inner zone.

When all three poles are closed, any power swing in the power system is a three-phase phenomenon. The three phases have the same impedance trajectory. The out-of-step detection logic typically uses the positive-sequence impedance ( $Z1$ ) measured at the relay location. When the three poles of the terminal breaker are closed, this impedance is correctly measured using the following equations, for example:

$$Z1 = \frac{V1}{I1} = \frac{Vab}{Iab} = \frac{Va}{Ia} \quad (8)$$

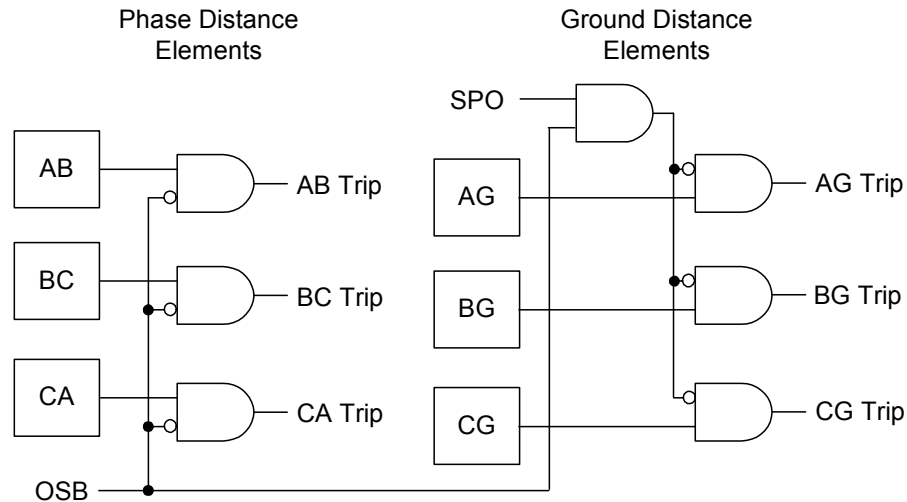
The above equation indicates that the positive sequence trajectory can be measured by phase-to-phase quantities or phase quantities when the three poles of the breaker are closed.

When one pole of the breaker is open (phase A for example), then the only correct measurement for an Out-of-Step logic is the positive-sequence impedance given by:

$$Z_1 = \frac{V_1}{I_1} \quad (9)$$

Phase-to-phase or phase quantities are not reliable quantities for doing out-of-step logic when one of the poles is open. Single-pole-trip relaying systems that provide out-of-step protection during pole-open conditions require the measurement of the positive-sequence impedance. When calculating the positive-sequence impedance,  $Z_1$ , during an open-pole condition, it is important to neglect the open-phase voltage. When the voltages are measured in the line side, the open-phase voltage is corrupted from the coupling of the two healthy phases and the natural resonant frequency of the open phase. When the voltages are measured in the bus side, the open-phase voltage makes the  $V_1$  calculation bigger and detecting the swing can get complicated.

The out-of-step logic shown in Figure 20 is used to prevent the distance units from operating for power swings that appear to the distance units as faults. This is referred to as out-of-step blocking (OSB) of the different distance zones of protection.



**Figure 21** Conceptual Implementation of Out-of-Step Block Logic in Distance Elements

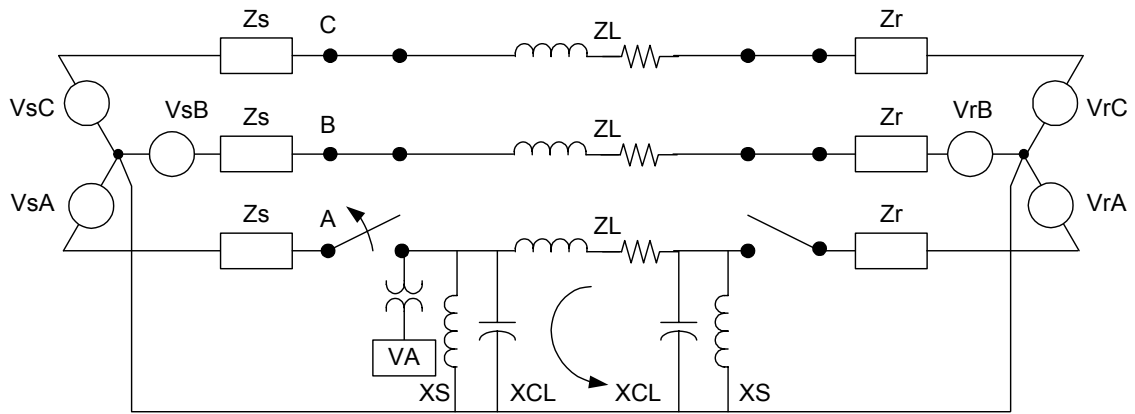
In a SPT directional comparison system, the distance units need to be supervised by the block from the out-of-step logic (OSB). Figure 21 is a conceptual illustration of the need to block the ground distance units when the breaker has a single pole open (SPO). Figure 21 only illustrates the fundamentals; the actual implementation should involve all the elements from the different zones of protection.

Blocking distance elements with out-of-step logic prevents disconnecting power lines for power swings. When the three poles of the breaker are closed, phase-distance units are blocked, allowing ground distance units to operate freely. When one pole is open, ground distance units are also blocked from power swings.

## Resonant Components During an Open-Pole Condition

The energy stored in the capacitance and reactance components in a long transmission line needs to be dissipated in the resistive component when the line conductor is de-energized [16]. The

diagram in Figure 22 illustrates this issue. When the phase-A pole opens, the energy stored in the line capacitance,  $X_{CL}$ , line reactance, and any shunt reactance,  $X_s$ , will create a resonant circuit. In some cases the natural frequency of the circuit may be close to the fundamental.



**Figure 22** Resonance After an Open-Pole Condition

The measured voltage from the phase with an open pole is incorrect when the measurement is taken from line-side VTs. As Figure 22 shows, it should not be used. This figure shows that  $V_A$  is not a reliable quantity because the measurement only reflects the discharge of the resonant circuit. Moreover, both the voltage (magnitude and phase) information and the frequency estimation are not correct for protective relaying. The measurement should not be affected by the resonant circuit.

It is therefore mandatory for the protective relaying scheme to disregard the measurement of the open-phase voltage. This ensures that no polarizing voltage, frequency estimation, or measurement decision will be affected.

## RECLOSING AND SPT

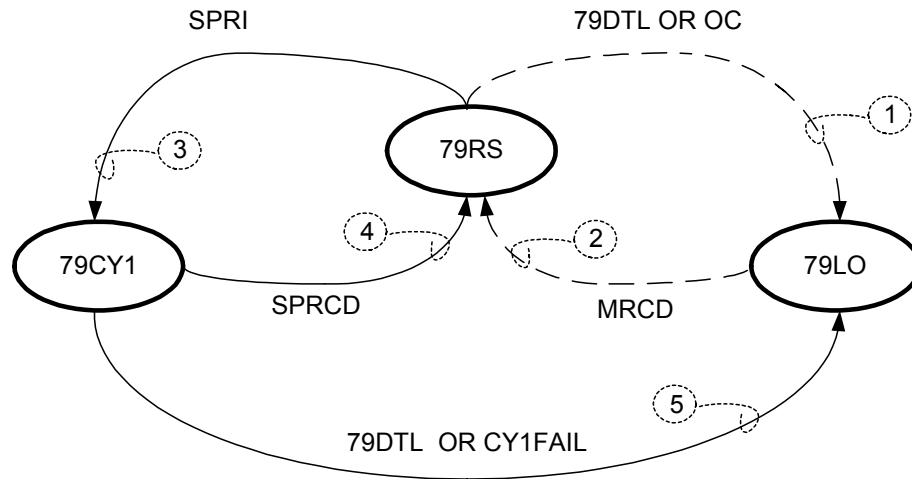
To be functional, single-pole-trip systems need reclosing schemes. A recloser can be described as a state machine in which states are transitioned depending upon set conditions. The following states, of the state machine, define the operation of the recloser:

- 79RS: Normal Reset state of the recloser. The recloser is waiting for the cycle to start.
- 79LO: Lock Out state of the recloser. A reclosing cycle will never start.
- 79CY1: The recloser is in the single-pole cycle. The pole of the breaker is open and the recloser is timing the single-pole dead time. The cycle also includes issuing the close command and the reset (or reclaim) time to exit the cycle.
- 79CY3: The recloser is in the three-phase cycle. The three poles of the breaker are open and the recloser is timing the three-pole dead time. This cycle also includes issuing the close command and the reset (or reclaim) time to exit the cycle.

It is the practice to only allow SPT operations for high-speed trips, which are Zone 1 trips and pilot (communications-assisted) trips. Time-delayed trips, which involve Zone 2, Zone 3, or inverse time-overcurrent (51N), are 3PTs. Some protective relaying philosophies allow single-pole tripping for Zone 2 and 51N. Also, some utilities are considering using traditional 3PT elements, like 51N, to provide SPT capabilities. The argument behind this is that modern numerical relays can provide the functionality for single-line-to-ground faults without fault



resistance and the same logic should be useful for providing SPT for faults with significant fault resistance.



**Figure 23** Simplified Single-Pole Reclosing

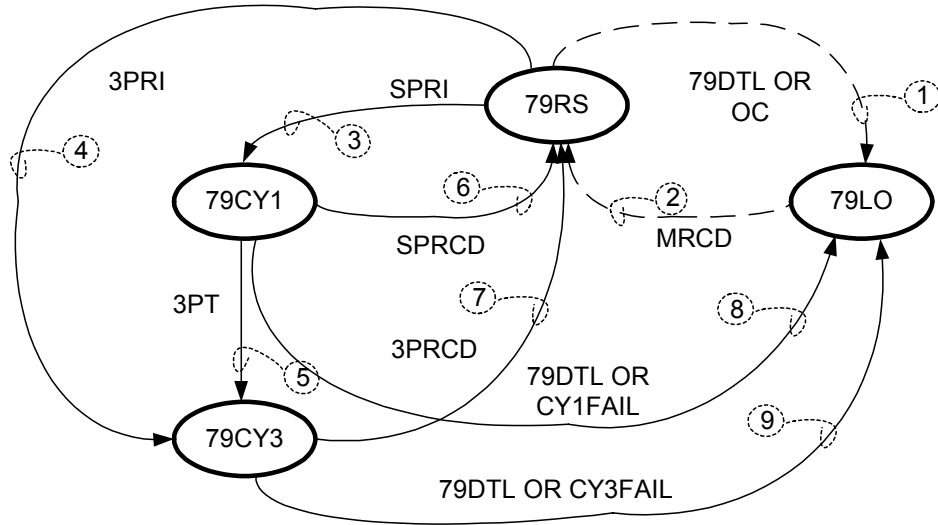
Figure 23 is a simplified state diagram for a single-pole-reclosing scheme. The protective relaying system will only issue a close command for a SPT (no 3PT reclosing will be issued). The figure shows the states as well as the transition paths, with conditions. Figure 23 shows the following transition paths:

1. The reset state (79RS) indicates the availability of the reclosing cycle waiting for the initiation. Normally, the reclosing relay will transit between the reset state (79RS) and the lockout state (79LO) when the breaker is opened and closed manually. This path represents the manual opening of the breaker (open command, OC). Moreover, if a drive-to-lockout condition exists, the state is forced to 79LO. A 3PT, for example, is sufficient to send the reclosing relay into lock-out (79LO = 3PT).
2. When the breaker is closed manually and the time-out of the manual-close reset time (MRCD) expires, the reclosing relay transits from the 79LO state to the 79RS state.
3. The transition signal Single Pole Reclose Initiate (SPRI) determines the start of the single-pole reclosing cycle (79CY1). This signal is generally assigned to the SPT of the protective system (SPRI = SPT).

Once the breaker contacts of a single pole have opened, the single-pole reclosing cycle starts timing.

4. A successful single-pole cycle (that is, the issue of the trip command and the subsequent automatic reclose of the breaker) will start a single-pole reclose reset timer (SPRCD) and when it expires, the recloser will change the state to 79RS.
5. During the single-pole-open dead time, any additional trip should be 3PT and the recloser driven to the lockout state. Moreover, internal logic in the reclosing relay should send the recloser state to lockout when the normal 79CY1 fails (CY1FAIL), which may occur if the breaker poles open in the middle of the open-pole interval or if the breaker did not close the pole when the close command was sent.

A single-pole reclose cycle will generally send the close command without supervision; in contrast to a three-pole reclose cycle where there will probably be a condition, such as synchronism check or dead bus live line, supervising the close command issue. Some proposed methods for adaptive single-pole reclosing supervise the closing of the open pole of the breaker by estimating the secondary fault current, which will be discussed in the next section of this paper.



**Figure 24** Simplified Single-Pole and Three-Pole Reclosing

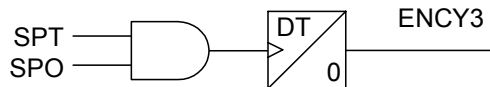
A more complete scheme for transmission line reclosing involves the cycle for three-phase reclosing, as shown in Figure 24. The complexity of the scheme has increased as the possibilities for customization have increased.

1. Whether an open command (OC) or any other condition that sends the recloser to lock-out state defines the path shown.
2. Once the breaker has been closed manually and the corresponding manual-close reset time (MRCD) has expired, the recloser moves to the ready state (79RS).
3. This path is taken to reach the single-pole reclose state (79CY1) and initiate the single-pole reclose cycle. A single-pole trip will initiate the transition (SPRI := SPT)
4. This is the path to reach the three-pole reclose state (79CY3) and initiate the three-pole reclose cycle. Time-delayed trips, such as Zone 2 or Zone 3 trips, which by definition are three-pole trips, should not be allowed to initiate the three-pole reclosing cycle. After all, these are backup trips, the probability that the fault is permanent is higher, and the power system has been shaken long enough. A typical three-pole reclose initiation is the three-pole trip (3PRI := 3PT); but, the recloser is forced to the lock-out state via the 79DTL (79DTL := ..... OR Z2T OR Z3T OR ...., for example).
5. The transition from the single-pole reclose state (79CY1) to the three-pole reclose state (79CY3) is a point of customization for different practices and philosophies.

One of the scenarios is the single-pole open interval timeout, and the unsuccessful reclosing of the faulted pole. Under this scenario, the protective relaying scheme will trip the three poles after the reclosing attempt, and the three pole reclosing cycle (79CY3) is allowed.

A second scenario is an open pole and a fault on at least one of the energized phases that makes the protective relaying scheme trip all the poles (3PT).

- The transition may not be allowed, indicating that an evolving fault is a sign of a more damaging condition to the power system (a falling tower, for example). The relaying system should therefore send the recloser to Lockout (79DTL :=... OR (79CY1 AND 3PT AND TOP) OR... for example) where the signal TOP denotes a trip during an open pole.
- The transition is always allowed, indicating that an evolving fault is acceptable to the power system and three-pole reclosing is permitted. In this case, there is no need to drive the recloser into lockout.
- The transition is permitted with a discrimination condition. This condition is generally a time window of length DT, as shown in Figure 25. Once there has been a single-pole trip and there is an open-pole condition, the window starts counting. If a three-pole trip is issued within the DT window, the three-pole reclosing cycle is allowed; otherwise, the recloser is sent to the lockout state (79DTL: = ... OR (79CY1 AND TRIP AND ENCY3), for example).



**Figure 25** Typical Discriminating Condition for the Transition From 79CY1 to 79CY3

6. This path denotes a successful single-pole reclose cycle. It implies that the single-pole open interval has timed out, the breaker has successfully closed the open pole, and the single-pole reclosing reset time (SPRCD) has timed out.
7. This path denotes a successful three-pole reclose cycle. It implies that the three-pole open interval has timed out, the three poles of the breaker have closed, and the three-pole reclosing reset time (3PRCD) has timed out.
8. This path implies that the single-pole open reclosing has failed (CY1FAIL), which could include the breaker pole not opening in a certain amount of time, the breaker pole not closing when the close command has been sent, or even the opening of the other two poles (externally) during the open-pole period.

This path could also imply the failure of any supervision of the close signal; which is normally not done in the single-pole reclose cycle (79CY1). Some techniques, however, may require the supervision of the close signal, as will be discussed below.

As with any of the other states, the forced travel to the lockout state via 79DTL is included.

9. This path implies a failure of the three-pole reclosing cycle, denoted by (CY3FAIL), which could include a breaker failure of opening the three poles, the failure of the breaker to close the three poles after the close signal has been sent or the failure of any supervision of the close command (the lack of synch-check, for example).

The above description of two typical reclosing schemes has illustrated typical practical considerations in a reclosing scheme for SPT systems. Reclosing is always needed for SPTs and may be optional for 3PTs.

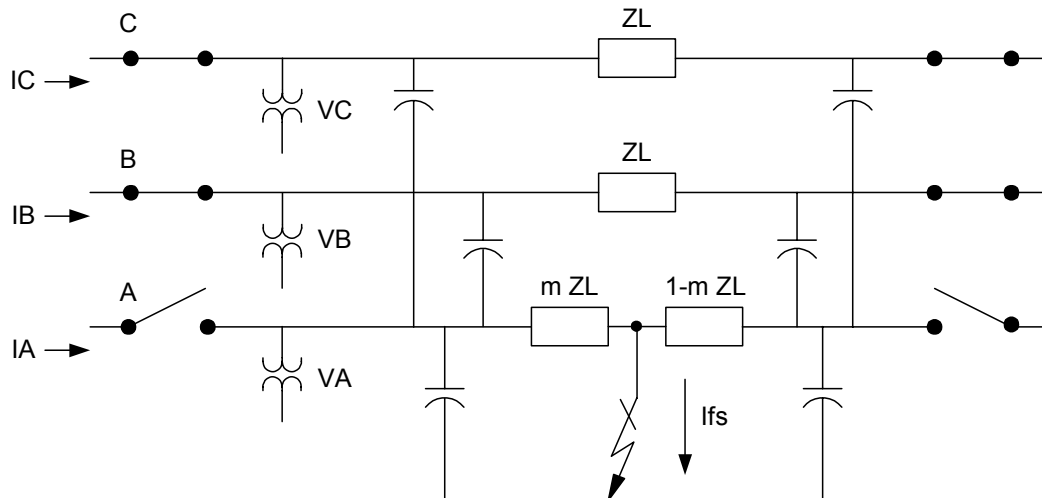
The philosophy to be chosen when selecting the reclosing for an SPT scheme depends on power system considerations such as the following [22].

- Proximity to generation plants
- Voltage level
- System stability
- Power transmission reliability
- Short-circuit fault statistics
- Power network topology

With electrostatically and electromagnetically coupled energy supporting the secondary arc from the remaining two healthy phases during the pole open period, it is necessary to increase the single-pole reclosing dead time to allow the arc to deionize. The increased stability margin brought by the SPT scheme justifies a dead time longer than the three-pole reclosing dead time. With high system voltage levels and longer transmission lines, a neutral inductor may be required to extinguish the secondary arc [18] [19].

### Adaptive Single-Pole Reclosing

More than in three pole reclosing, in single-pole reclosing the concept of adaptive single-pole reclosing is a practical consideration. When the three poles are open, the three conductors are de-energized making sure that the fault arc is going to extinguish. During an open pole, for single-pole reclosing, the other two phases are still energized carrying current and holding the full line to ground voltage. This means mutual inductive and capacitive coupling from the two energized phases to the open phase conductors.



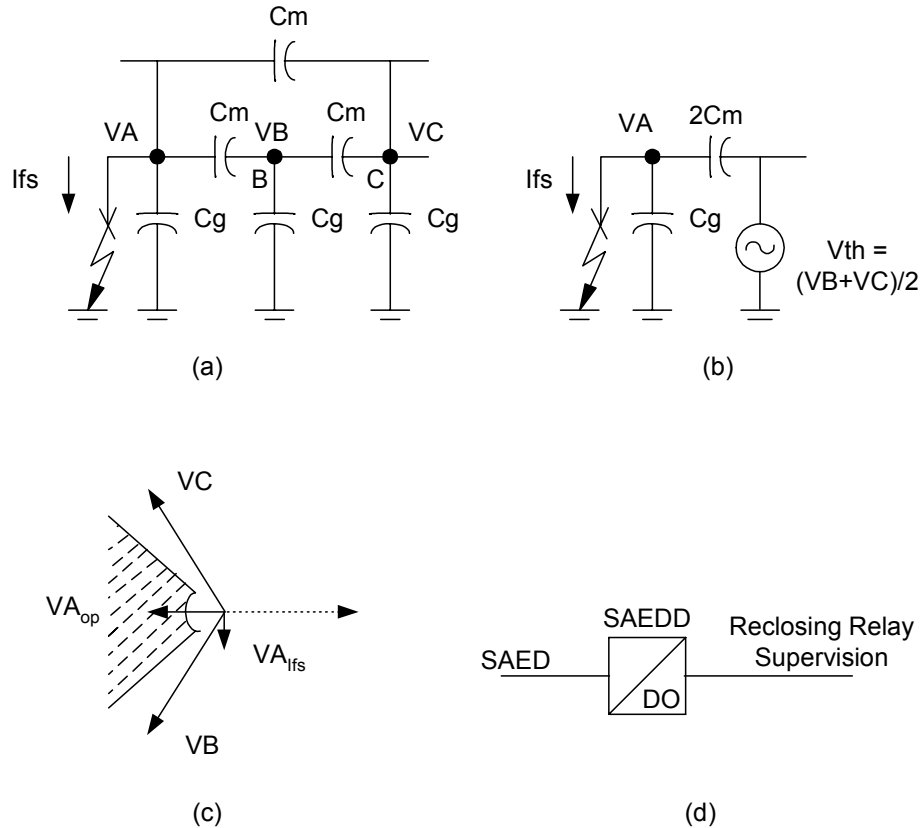
**Figure 26** Secondary Arc Current

The literature defines the primary fault arc current as the current flowing in the fault with all three breaker poles closed. Figure 26 illustrates the concept of secondary arc current as the current flowing in the fault point because of the coupling from the other two phases. Some design methods and studies, outside the scope of this work, consider shunt reactors to ensure the clearing of the secondary arc current.

For protective relaying, and single-pole reclosing in particular, the issue is to allow sufficient time for the secondary arc to disappear. Of course, a long open-pole period increases the chances of

clearing the secondary arc. For an adaptive single-pole-trip reclosing scheme, the idea is to verify that the secondary arc has extinguished and then reclose [16]. There is no need to wait for a long open-pole dead time if there is a method to estimate whether the secondary arc is present.

There are several papers on the subject, and for practical applications, it is advisable to do simulation testing, because the use of this technique is not yet widespread. The inductive coupling is recognized as the smallest and the capacitive coupling as the largest contributor to the secondary arc current,  $I_{fs} = I_m + I_c$ . When shunt reactors are present, these cancel the contribution of the shunt capacitance to the secondary arc current and the inductive component increases.



**Figure 27** Secondary Arc Extinction Detector (SAED)

One simple methodology [16] implements a Secondary Arc Extinction Detector (SAED) which relies on line-side measurements (as shown in Figure 26) and is based on the theory shown in Figure 27. Figure 27 illustrates the secondary arc for an open A phase. It shows the capacitive coupling between phases ( $C_m$ ) and ground ( $C_g$ ). The diagram is a simplistic representation of a line that is assumed to be fully transposed. The accepted equivalent for the circuit shown in (a) is the single source ( $V_{th} = (V_B + V_C)/2$ ) equivalent shown in (b).

When the secondary arc current is present ( $I_{fs}$ ), the arc resistance ensures that the voltage  $V_{A_{I_{fs}}}$  (open-phase voltage with the secondary arc present) is in phase with  $I_{fs}$ .  $I_{fs}$  angle is determined by the larger capacitive mutual impedance ( $2C_m$ ) and will be leading  $V_{th}$  by  $90^\circ$ . In practice, of course, the angle will be smaller; but the above reasoning helps with the concept.

When the secondary arc current is not present, the circuit in (b) is a simple voltage divider and the VAOP (open-phase voltage with no secondary arc present) is in phase with  $V_{th}$ . This implies that

a region on the plane could be defined, as shown in (c) where the logic can conclude that there is no secondary arc. The SAED signal in (d) is the result of this logic, which can be qualified with a timer (SAEDD) and used to supervise the single-pole reclosing of an SPT relaying scheme.

## SUMMARY

The purpose of this paper is to illustrate some considerations in the design and implementation of SPT relaying schemes. A simple example demonstrated that single-line-to-ground faults are the least damaging to the power system and that an open-pole condition allows for the secondary arc to extinguish, while at the same time allowing power transfer. These conditions increase power system stability.

SPT relaying schemes are implemented with SPT breakers and require individual control of the trip coils of each pole of the breakers. These breakers are more expensive than 3PT breakers at lower HV voltage levels; but breakers at EHV levels, because of their phase-clearance requirements, already have the ability to trip individual phases.

Protective relaying schemes are the same for SPT systems as for 3PT systems. Directional comparison systems rely heavily on local phase selection. When additional channels are available, such as relay-to-relay communications, POTT2 or POTT3 protective relaying schemes are a practical option for protecting parallel lines from cross-country faults. Current-only systems, like alpha-plane line differential schemes, have inherent phase-selection capabilities that make them ideal for SPT applications and even for segregated pole-trip schemes. Modern alpha-plane line differential schemes implement a phase-selection algorithm based on the total differential current when the phase units do not operate during high-resistance ground faults.

Once a faulted phase has been selected and the SPT relaying system opens the proper pole, a pole-open condition is created in the power system. Ground directional units should be disabled during this condition and some considerations should be evaluated in adjacent lines to prevent misoperation of ground directional units.

Power swings can happen during the open-pole period and properly designed SPT relaying systems should make use of Z1 (positive-sequence impedance) to block phase and ground distance units.

SPT line protection systems require a reclosing scheme, with the reclosing relay transiting through various states based on conditions. The single-pole reclosing cycle (79CY1) is mandatory and the three-pole reclosing cycle (79CY3) is optional in an SPT relaying system.

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