The Complexity of Protecting Three-Terminal Transmission Lines

North American Electric Reliability Council

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CONCLUSION AND SUMMARY

Three-terminal lines are relatively common throughout North America, and many good reasons exist for using this configuration for transmission facilities. However, protection of three-terminal lines presents serious challenges and requires very careful design and application to maintain overall system reliability

The protection challenges presented by three-terminal lines include the following:

- Transmission line relay loadability
- Sequential clearing for transmission line faults
- Compromises in the ability of the protection to detect faults
- Compromises in relay coordination between the three-terminal line protection and the protection on adjacent facilities
- Increased complexity of associated communications system
- Increased susceptibility to false tripping for heavy transient loading conditions and stable power swings.

The discussions and related examples presented in this technical report convey general protection considerations and philosophies for three-terminal line protections. The protection scheme examples are listed for illustration and indicate possible methods of applying and/or setting relay zones of protection. The actual protection scheme used and the associated settings for a three-terminal line will be application dependent. The protection scheme must take into consideration the specific topology of the three-terminal line, and the protection scheme and associated settings used must be adequate to meet the necessary clearing times and the reliability and security needs of the power system.

The intent of this is paper is to describe the most common types of three-terminal protection complexities found in the industry. These complexities should be considered when evaluating high-voltage transmission plans that include multi-terminal lines. Analyses of past cascading outages have indicated that because of the relay settings necessary to protect three-terminal lines, they were susceptible to protection system operations.

Three-terminal and other multi-terminal line construction projects are generally a trade-off of planning economics and protection complexities, and can, sometimes, lead to compromises in reliability.

Three-terminal line configurations require an increase in complexity of the line protection systems. This is due to the fault current flow from a third terminal affecting the voltage and current present at the other two terminals. In the case of distance based line protection, this current causes the relays to underreach line faults beyond the third terminal tap point.

The underreach is overcome by extending the relay reach. This reach extension limits the load carrying capability and increases the likelihood for operation on stable power swings. The paper also discusses several other possible three-terminal protection complexities such as overreaching for “outfeed” conditions, Zone 1 reach limitations, and the use of sequential tripping and its impact on reliability and security.

The current differential principle is considered to be suited to protect three-terminal lines and it does not need to contend with problems associated with voltage, loading, and swings. However, a three-terminal line may affect line current differential protection schemes if outfeed conditions occur during internal line faults. The protection system should be set to operate in the presence of the outfeed condition. Also, if used, it should be noted that the line differential backup protection schemes are subject to the same type of complexities.

INTRODUCTION

The North American power system consists of thousands of high voltage transmission lines transmitting electrical power between generators and load centers. They represent the foundation of the power system. The majority of transmission line construction is of overhead type and therefore, is easily susceptible to various transient and permanent faults. These faults can lead to damage of the line itself and can cause power system instability. It is of the utmost importance that protective relay systems are capable of clearing all faults within the designed operating time, and have a high degree of dependability and security.

Typically, there are three types of line configurations used within the industry. These line configurations include (a) radial (one-terminal), (b) two-terminal, and (c) multi-terminal of which three-terminal is possibly the most prominent multi-terminal type. It should be noted that "terminals" in this context, refers to source terminals and not-tapped transformer terminals or stations. The reader unfamiliar with these configuration types should refer to Appendix A. The two-terminal line configuration is the most dominant type followed by radial, and the three-terminal lines are the exceptions.

Three-terminal and other multi-terminal line construction projects are generally a trade-off of planning economics and protection complexities, and can lead to compromises in reliability. Two-terminal lines with long tap(s) supplying remote load from the main line may display many of the same protection and loadability issues as three-terminal lines. These types of configurations and those with multiple tapped transformer stations (low voltage tie breaker closed) are beyond the scope of this discussion. However, it should be noted that some of the same types of complexities may be experienced with these types of configurations as three-terminal lines.

The complexity of protecting these line configurations increases from the relatively simple radial, to the more difficult two-terminal, and to the still more difficult three-terminal. Relaying three-terminal lines has been and continues to be a challenge for protection engineers.

Appendix A provides a brief description of some of the common types of line protection schemes used in the industry. It is intended to provide a basis for readers unfamiliar with such protection schemes to better understand the discussion for suitability of such schemes for three-terminal line protection. For a more detailed discussion on line protection schemes, the reader is referred to the IEEE Standard C37.113-1999, *Guide for Protective Relay Applications to Transmission Lines* [see reference 4 noted in Appendix D].

This paper addresses Recommendation TR-19 from the *Transmission and Generation Performance Report Blackout of August 14, 2003 – Detailed Power System Forensic Analyses and Modeling*[1], and describes three-terminal lines and highlights the associated protection complexities from a phase loadability perspective. These complexities should be considered when evaluating transmission plans that include multi-terminal lines.

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1 TR-19 — NERC should review and report on the advantages and disadvantages of the use of multi-terminal line configurations on the EHV system, and any associated complex protection and control (sequential) schemes. Particular attention should be paid to the performance of such configurations and its protection during emergency operation conditions, including expected system swings.

1.0 Three-Terminal Lines

Three-terminal and other multi-terminal line construction projects are generally a trade-off of planning economics and protection complexities, and sometimes may lead to compromises in reliability.

1.1 Justifications for Three-Terminal Lines

There are a number of factors that influence the decision to configure a transmission line with three terminals, such as economics, constrained lead time, regulatory approvals, right-of-way availability, line overloads, and system performance requirements.

- There is an economic benefit in the construction of three terminals because it avoids the expense of all or a portion of a substation and typically reduces the transmission line miles.
- Use of three-terminal lines may be more expeditious in addressing system needs.
- Right-of-way may be limited or not obtainable for new lines and stations.
- Regulatory approvals may be problematic. There may be opposition to the construction of new facilities and the construction of a three-terminal line may reduce the overall project impact.
- Three-terminal line configuration may mitigate the possibility of transmission line overloads due to single contingency events. However, this is very dependent on system topology.

1.2 Effect of Infeed at the Tee Point – Apparent Impedance

For a fault on a transmission line, a distance relay will measure impedance equal to the line positive sequence impedance, provided there are no sources of fault current between the line terminal at which the relay is located and the fault. The distance relay measures impedance by comparing the voltage drop between its location and the fault with the current at the relay.

Referring to Figure 1 on the next page, the actual line impedance from the relay terminal (Terminal A) to the fault is not always the impedance measured by the relay. This is because the third line terminal (Terminal C) tapped (Tee point) to a line is an additional source of current for a line fault. Current will be supplied to a fault that occurs on the line section beyond the tap of Terminal C through both Terminal A and Terminal C. The voltage drop resulting from the input of fault current from each of these sources into the common section of the line will be measured by the distance relay at the Terminal A. Since the current input from Terminal C is not applied to the relay at Terminal A, the impedance measured by this relay is higher than the actual impedance from the Terminal A to the fault. The relay will underreach; that is, for a given relay setting the relay does not cover the same length of line it would if the additional current source were not present.

Consider a typical apparent impedance effect as follows in Figure 1 below.

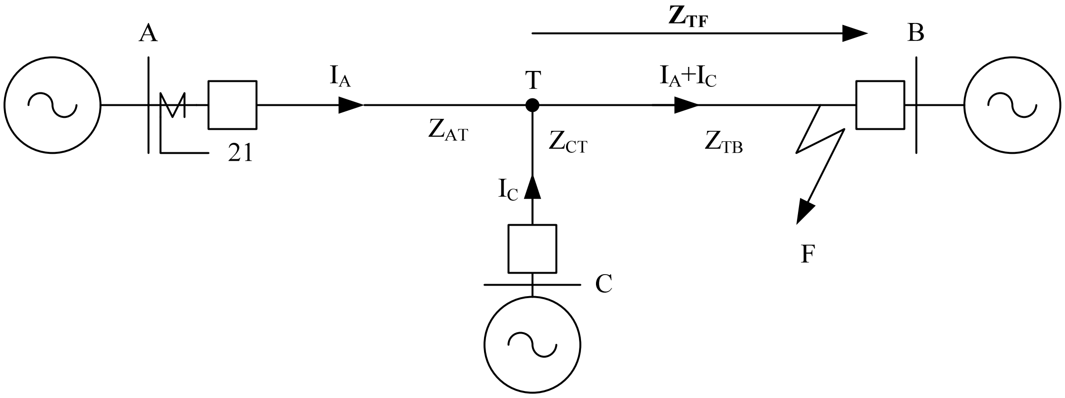


Figure 1 — Infeed Effect

Voltage at Terminal A with **zero infeed** from Terminal C:

$$V_A = V_{AT} + V_{TF} = I_A Z_{AT} + I_A Z_{TF} = I_A \left(Z_{AT} + Z_{TF} \right) = I_A Z_{AF}$$

Impedance as measured from Terminal A:

$$Z_{AF} = \frac{V_A}{I_A}$$ This equals the true impedance.

Voltage and impedance measured at Terminal A (relay location) for fault F, with Terminal C **closed (infeed)** is:

Voltage:

$$V_A' = V_{AT} + V_{TF} = I_A Z_{AT} + \left(I_A + I_C \right) Z_{TF}$$

Impedance as measured at Terminal A:

$$Z_{app} = Z_{AF} + \frac{I_C Z_{TF}}{I_A}$$

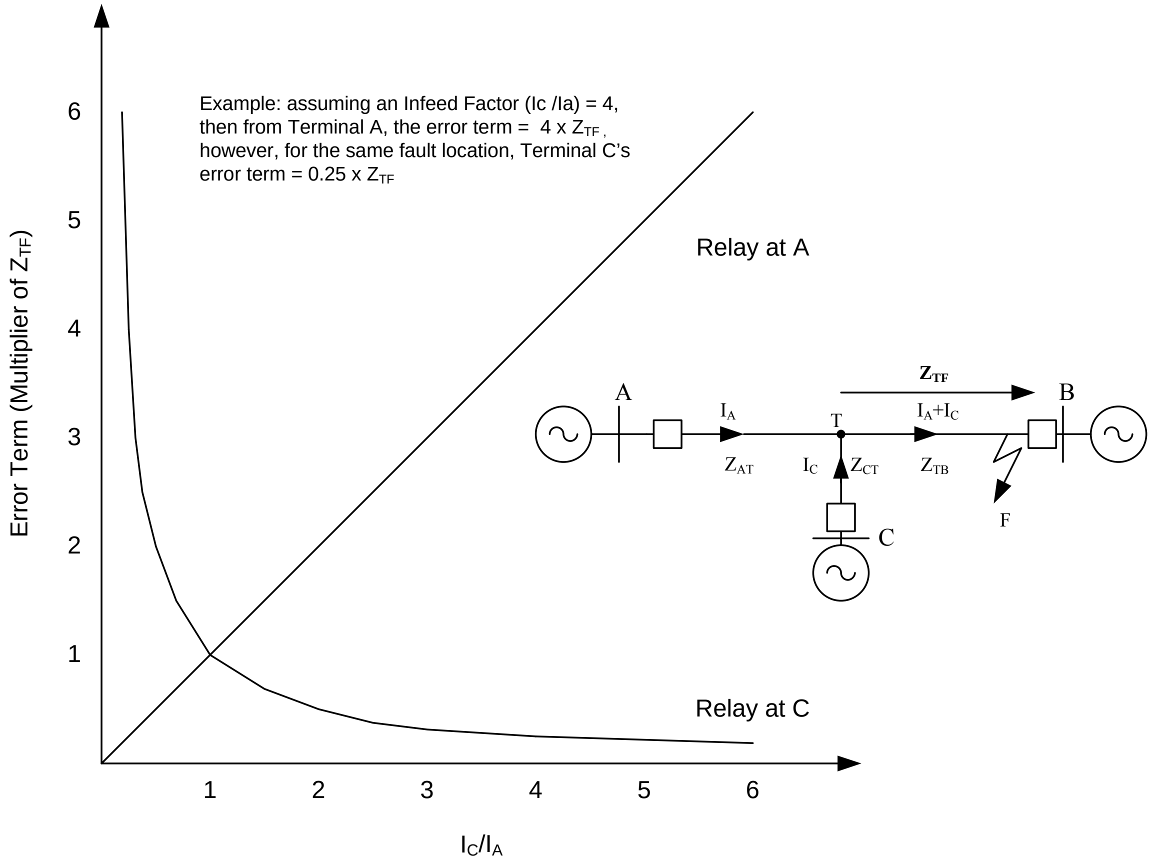
Z_{app} = The impedance that appears at the distance relay terminal which is referred to as apparent impedance

$\frac{I_C}{I_A}$ = The infeed factor, for Terminal A; the ratio of tapped infeed current to relay location current.

$\frac{I_C Z_{TF}}{I_A}$ = error term

The effect of the fault infeed I_C from Terminal C is to increase the apparent impedance viewed from Terminal A and, therefore, reduce the reach of the relay for a given setting. The underreaching tendency is a function of the ratio $\frac{I_C}{I_A}$. This relationship is depicted in Figure 2, where the error term $Z_{TF} \times \frac{I_C}{I_A}$ is plotted as a function of the ratio $\frac{I_C}{I_A}$, from Terminal A and Terminal C's perspective.

For the same fault location, the impedance viewed from Terminal C is:



$$Z_C = Z_{CT} + Z_{TF} + Z_{TF}\left({}^{I_A}\!/\!{}_{I_C}\right)$$

Figure 2 — Infeed Error Term Measured From Terminals A and C

From Figure 2, the two curves intersect at $I_C / I_A = 1$, resulting in the conclusion that if the error term is greater than Z_{TF}, as viewed from one terminal, it will be less than Z_{TF} when viewed from the other. The importance of this relationship is discussed in the report section on sequential tripping (section 1.12).

As an example:

The actual impedance from Station A to the fault at Station B, with the line terminal at Station C open is:

$$Z_{A-B} = 1\,\Omega + 1\,\Omega = 2\,\Omega$$

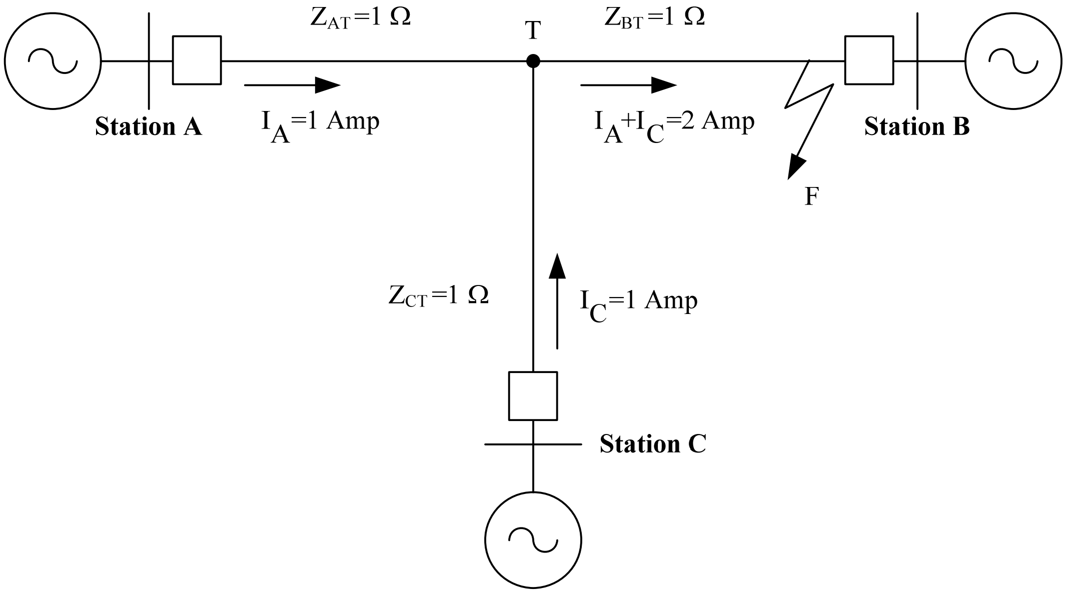


Figure 3 — Apparent Infeed Example

The apparent impedance from Station A to the same fault, with the line terminal at Station C closed is:

$$Z_{app_{A-B}} = \frac{V_A^{'}}{I_A} = \frac{(1\times1)+(1\times2)}{1} = 3\,\Omega$$

To overcome this effect, the relay setting has to be calculated in terms of the widely varying apparent impedance measured by the distance relay located at the line terminal. The setting required providing complete coverage of the line can be much larger than the setting necessary without the three-terminal configuration. The measured impedance is typically referred to as apparent impedance.

It should be noted that these apparent impedance effects limit the ability to provide remote backup functions for adjacent circuits.

Relay schemes must be set considering the effects of varying system conditions in deriving the maximum credible apparent impedance. Reasonable contingencies that weaken the source at the relay terminal should be considered in determining a relay setting. This magnifies the degree to which the relay setting must be raised due to apparent impedance effects. Typically, fault calculations are conducted to determine the maximum apparent impedance as measured from each of the three terminals. By evaluating potential contingencies, source impedances are maximized or minimized to generate the maximum infeed affect. The longest Tee length determines the fault location. As an example, for Terminal A, with a fault at Terminal C, assuming Z_{TC} is larger than Z_{TB}, the source impedance at Terminal A should be maximum (minimum system), and at Terminal B, the source impedance should be minimum (maximum system). This will result in the largest infeed factor.

A similar conclusion may be arrived at when considering a phase-to-ground fault provided the Z_{L0}/Z_{L1} ratio for each branch of the protected line is the same. The infeed effect for phase-to-ground faults is very much a function of the system grounding and needs to be determined by conducting system fault studies for the specific application.

1.3 Outfeed

Section 1.2 above, describes the effect of providing a fault "infeed" at the "Tee" location for a three-terminal line which causes a distance relay to underreach. It is also possible, based on system configuration, to experience an outfeed at the "Tee" location for a fault internal to the protection section. For these cases, the same equations apply, but instead of an underreaching effect, the tendency is to overreach.

For Example:

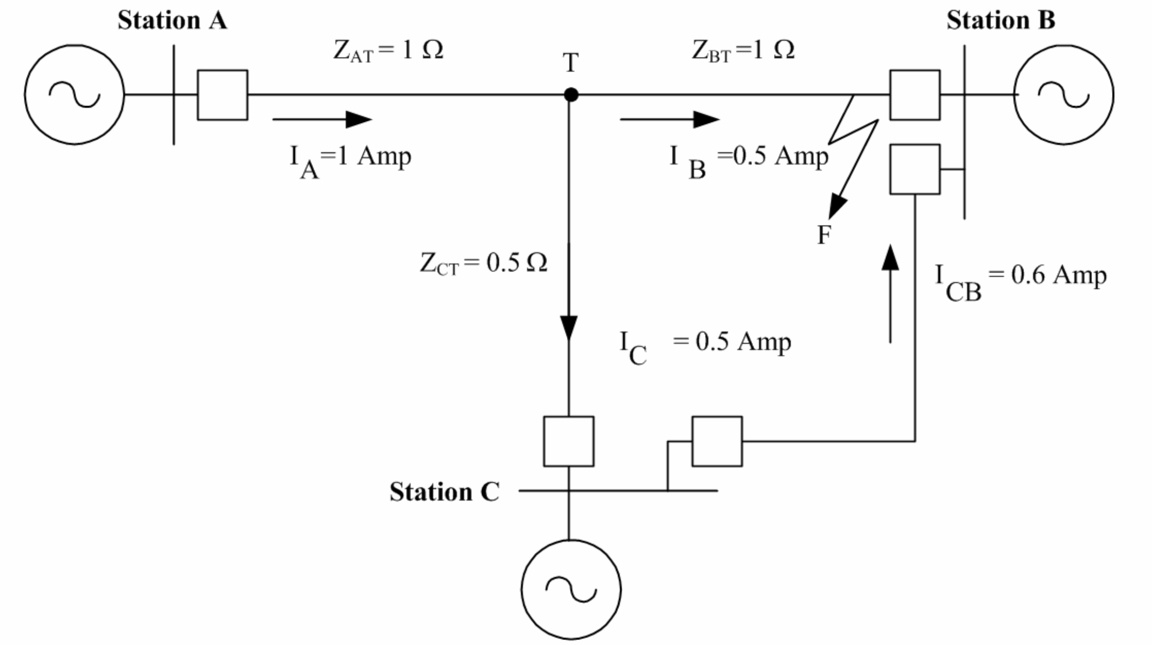


Figure 4 — Outfeed Example

For Terminal A relaying, the actual line impedance to the fault is 2.0 Ohms, however, the apparent impedance measured is:

$$Z_{app_{A-B}} = \frac{V_A'}{I_A} = \frac{(1\times 1)+(0.5\times 1)}{1} = 1.5\,\Omega$$

The relay overreaches.

This particular phenomenon, although not too common, will influence the Zone 1 settings at each terminal, and may cause delayed or sequential tripping.

Another concern regarding outfeed, for DCB schemes, is that directional comparison would be blocked from tripping. DCB relays at Station C would send a block to Stations A and B for the internal line fault at F. The pilot scheme may be momentarily blocked for an internal fault until one terminal clears, when an outfeed occurs and current at one terminal looks to be in the external direction. This also affects POTT schemes.

The planner needs to be aware of such conditions when completing stability studies as the overall line clearing time may be increased by the time it takes Terminal B or C to clear, until the outfeed condition ceases. In addition, the protection engineer should ensure that there is adequate coordination margin for relays looking through the terminal that may be delayed in tripping due to the outfeed condition.

1.4 Decrease in Line Loadability

The settings typically required to provide protection coverage of a three-terminal line, where fault infeed is experienced, will be much larger than the setting necessary without the third terminal. This setting can reach many multiples of the actual impedance of the protected line, resulting in a decrease of the line loadability unless some form of load blinder or encroachment logic is applied.

To illustrate, consider the following 230 kV example in Figure 5:

It should be noted that the impedances defined below represent the values based on system fault calculations to obtain the maximum credible apparent impedance for reasonable system conditions.

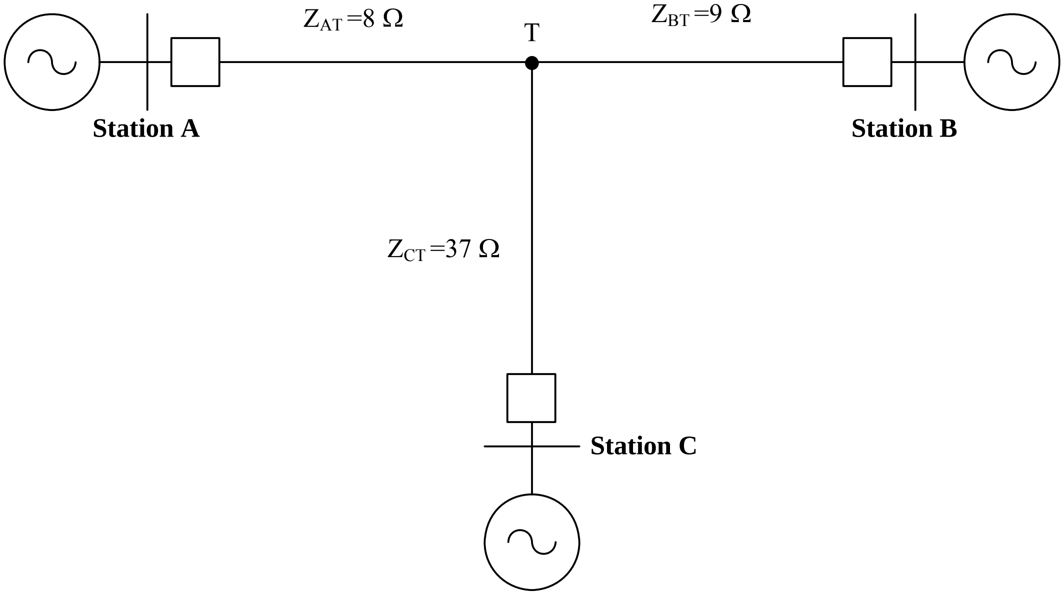


Figure 5 — Three-Terminal Line Loadability Example

Table 1 — System Data for the Example Used in Figure 5

DATA	TERMINAL A	TERMINAL B	TERMINAL C
Z_1 to Closest Terminal	17 Ohm @ 82 degrees Pri.	17 Ohm @ 82 degrees Pri.	45 Ohm @ 82 degrees Pri.
Z_1 Apparent Impedance	79 Ohm @ 82 degrees Pri. (Fault @ C, Brk. Open) **Apparent = 465% of Z Line**	95 Ohm @ 84 degrees Pri. (Fault @ C, Brk. Open) **Apparent = 559% of Z Line**	96 Ohm @ 82 degrees Pri. (Fault @ B, Brk. Open) **Apparent = 213% of Z Line**

Assume that the line originally was configured as a two-terminal line between Terminals A and B – Terminal C is open. The distance Zone 1 and Zone 2 settings, at Terminal A, will typically be set as follows:

Zone 1 = 80% of Z_{line} = 0.8 x 17 = 13.6 Ohms Primary

Zone 2 = 125% of Z_{line} = 1.25 x 17 = 21.3 Ohms Primary

The Zone 2 represents the largest reach setting; therefore, in this case, it represents the limiting protection element for loadability. Refer to Figure 6.

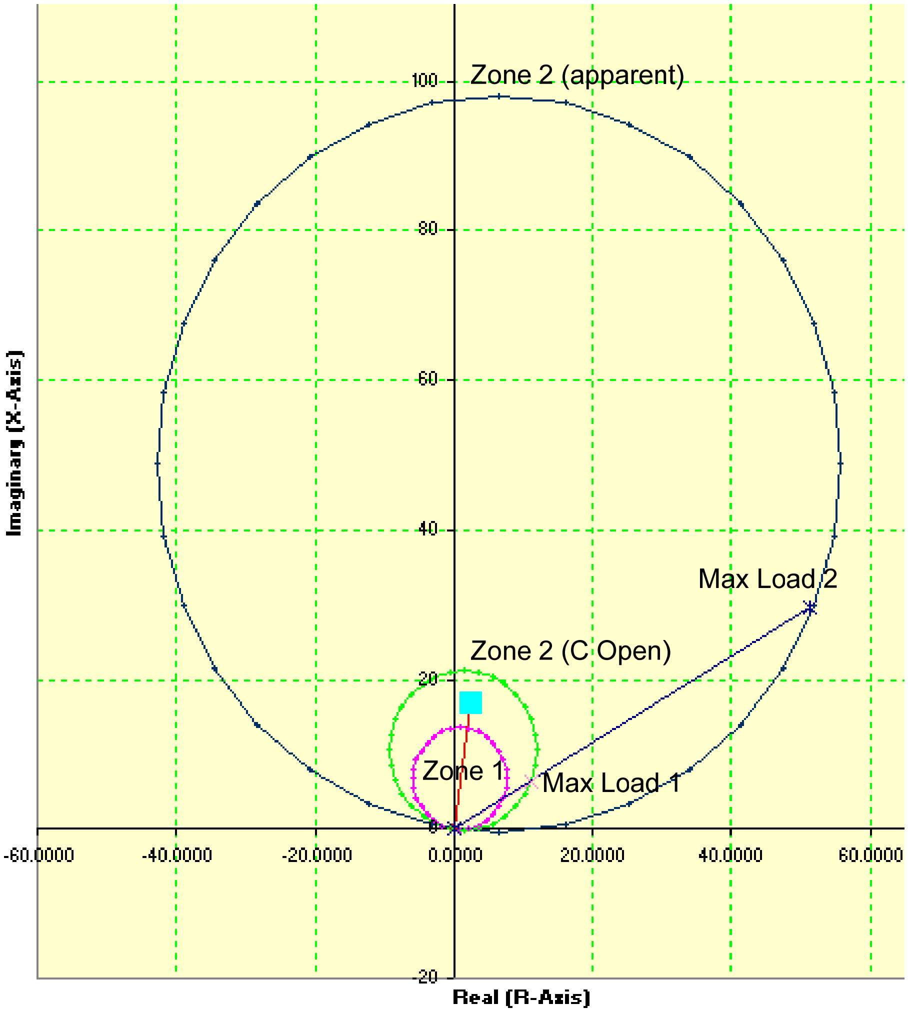


Figure 6 — RX Plot Illustrating Line Loading for the Example of Figure 5

Figure 6 represents an impedance plot of the operating characteristics of the Zone 1 and Zone 2 Terminal A, phase mho distance elements.

If Terminal C is closed, the line becomes a three-terminal line. From Table 1.0, above, the maximum three-phase apparent impedance at Terminal A is 79 ohms primary. Therefore, the new Zone 2 settings will have to be increased to 1.25 x 79 = 98.75 ohms primary.

Figure 6 depicts Zone 2 settings, as a two-terminal line (Zone 2 with C Open) and the Zone 2 requirement as a three-terminal line (Zone 2 apparent). It should be noticed that the infeed effect necessitates a Zone 2 setting of 4.6 times the settings as a two-terminal line, and therefore, represents a much larger operating characteristic.

The larger operating characteristic reduces the line loadability, as the line protection must not trip according to the following loadability requirement [1]:

> 1.5 times the maximum current line rating, at 85% nominal voltage, and at a load angle of 30 degrees.

Referring to Figure 6 above, a load line is drawn from the origin at an angle of 30 degrees. The Zone 2 element loadability constraints can be calculated as:

Zone 2 as a Two-Terminal Line (Maximum Load 1)

21.25 X COS (83°– 30°) = 12.75 Primary Ohms

12.75 Ohms = (0.85 x 230) / (1.732 X *I*)

I = (0.85 X 230) / (12.75 X 1.732) = 8.85 kA

Zone 2 as a Three-Terminal Line (Maximum Load 2)

98.5 X COS (83°– 30°) = 59 Primary Ohms

59 Ohms = (0.85 x 230) / (1.732 x I)

I = (0.85 X 230) / (59 X 1.732) = 1.9 kA

Which represents a 78% (from 8.85 kA to 1.9 kA) reduction in loadability.

It should be noted that three-terminal lines must meet the NERC requirements as per reference [1]. A technical exception 8 is provided for lines that can not meet this requirement — it has been included, as a reference in this paper as Appendix C. In addition, the NERC, SPCTF technical paper *Methods to Increase Line Relay Loadability* [reference 3 in Appendix D], provides methods and recommendations to increase loadability of protective relaying functions by augmenting, repositioning, and reshaping, mho element impedance relays without decreasing protection coverage.

1.5 Protection System Security is More Reliant on Communication Reliability

On multi-terminal lines, the Zone 2 protection zone reaches are generally set farther and over-current settings are made more sensitive to cover infeed considerations. This results in reaches much farther beyond remote line terminals than Zone 2 relays set on two-terminal lines. Thus, these relays will see more external faults and are more prone to false tripping for communication failures when using a DCB scheme (i.e., failure to receive a block on a DCB scheme).

1.6 Susceptibility to Trip for Stable Power Swings

Due to the need for extended Zone 2 coverage to accommodate the apparent impedance effect, it is possible that stable power swings may encroach into the relay phase characteristics. While susceptibility to tripping during power swings is typically thought of as a concern for Zone 1 protection where tripping occurs without intentional time delay, tripping during power swings has been observed for Zone 2 and Zone 3 relays providing nonconditional time delayed tripping as well as Zone 2 relays operating in communication-assisted protection schemes.

1.6.1 Nonconditional Time-Delayed Overreaching Relays

The exposure to operation of relays providing nonconditional time delayed tripping is significantly increased when relay reaches are extended to account for infeed effects on three-terminal lines or infeed effects associated with providing remote backup protection. The increased size of the relay operating characteristic increases the amount of time that an apparent impedance swing will remain inside the relay characteristic. Figure 7 illustrates the impact of increasing the apparent impedance characteristic to accommodate a three-terminal line. Note the reach of the Zone 2 and Zone 3 relay characteristics relative to the Zone 1 reach. In the following figures the triangular markers on the apparent impedance trajectory represent a time interval of 250 ms between each marker and the apparent impedance after the line trips is recorded as 0+j0, resulting in straight line from the apparent impedance just prior to the trip to the origin on the R-X plane. The apparent impedance in this example remains inside the Zone 3 relay characteristic for longer than the Zone 3 timer setting of 650 ms, resulting in a trip of the line terminal. The apparent impedance trajectory is just changing direction at the time the line terminal trips as depicted on the green (solid) trace in Figure 7. The blue (dashed) trace depicts the apparent impedance trajectory with tripping of the line terminal blocked, indicating a stable swing.

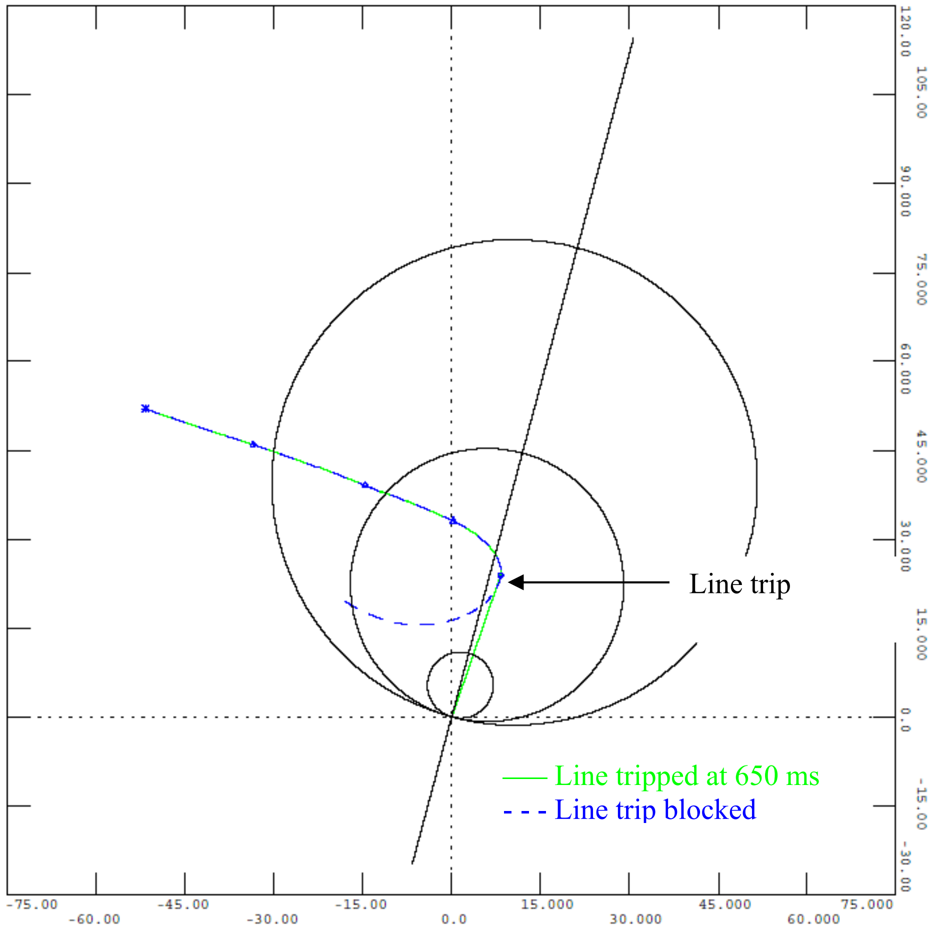


Figure 7 — Apparent Impedance Trajectory Through a Zone 3 Relay Characteristic

1.6.2 Communication Assisted Protection Schemes

Communication assisted protection schemes are also more susceptible to operation during system swings when relay reaches are increased to account for infeed effects. During typical system loading conditions the security of communication assisted protection schemes is improved relative to nonconditional tripping relays because all line-terminals must see the fault within the protected zone in order to initiate tripping. During system swings however, it is possible for the apparent impedance to appear within the protected zone at all terminals resulting in a protection operation. As relay reaches are increased the likelihood that the apparent impedance is within the relay characteristic also is increased.

Direct Underreaching Transfer Trip (DUTT) schemes have limited susceptibility since the tripping relays do not overreach the end of the line and the Zone 1 relay reaches are not increased to account for infeed effects. Permissive Overreaching Transfer Trip (POTT) and Directional Comparison Blocking (DCB) schemes do have increased susceptibility on multi-terminal lines since the tripping relay reach must be increased to account for infeed effects. The susceptibility for operation of POTT schemes is limited to swings for which the apparent impedance is inside the protected zone at all relay terminals. The susceptibility for operation is greatest for DCB schemes since the apparent impedance could be seen as outside the reach of the carrier trip relay at one or more relay terminals, but also outside the reach of the carrier blocking relays at all terminals. Figures 8 and 9 illustrate this phenomenon for a two-terminal line.

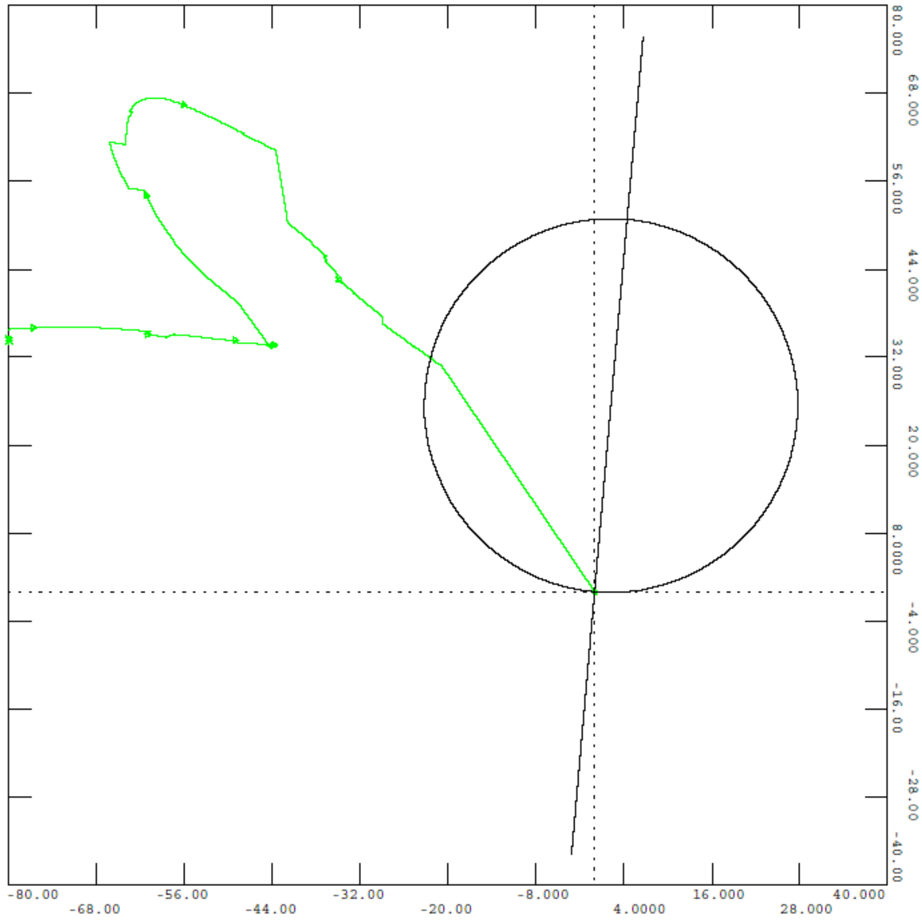


Figure 8 — Receiving Terminal Apparent Impedance Trajectory Entering Trip Relay Characteristic

Note that the apparent impedance trajectory at neither line terminal is in the third quadrant where the reverse Zone 3 carrier blocking relay characteristic would be located. In this case, the apparent impedance at the receiving terminal entered the Zone 2 carrier trip relay characteristic resulting in a line trip (see Figure 8). At the same time the sending end apparent impedance is approaching the Zone 2 carrier trip relay characteristic from the fourth quadrant, such that a blocking signal is not sent to the receiving terminal (see Figure 9). This phenomenon can easily be extended to the case of a three-terminal line.

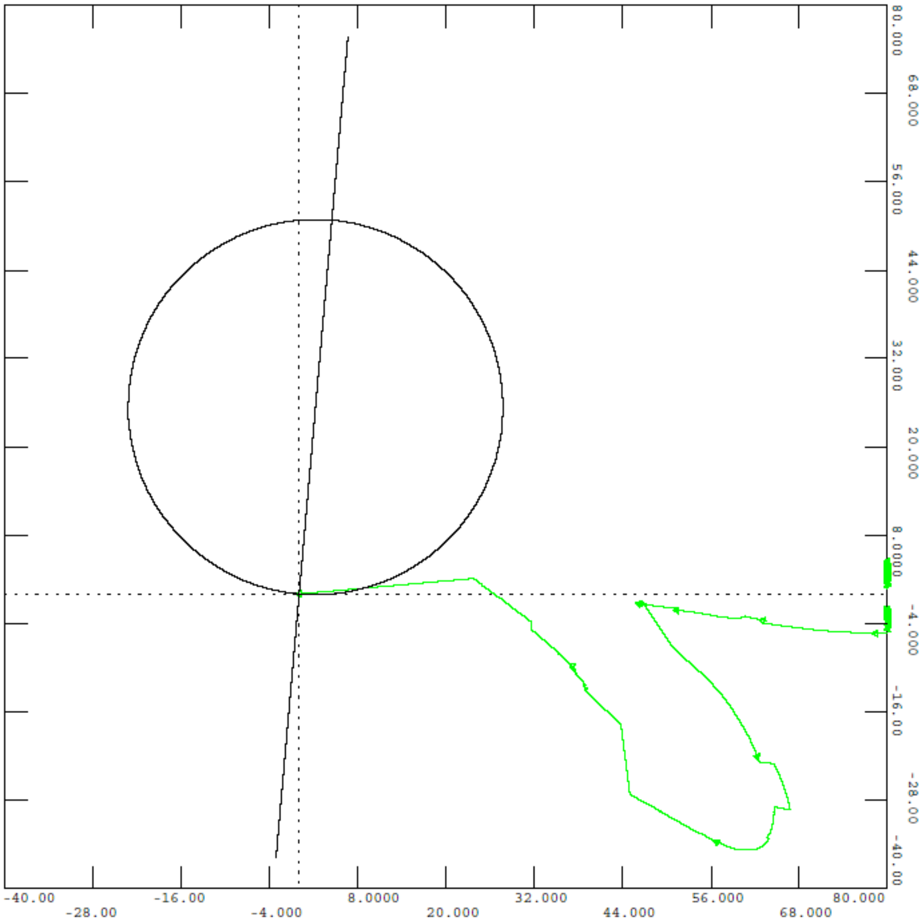


Figure 9 — Sending Terminal Apparent Impedance Trajectory Outside Trip and Blocking Relay Characteristic

1.7 Zone 1 Reach Limitations

The location of the “Tee” point and the length of the three “legs” of a three-terminal line can vary based on transmission line configuration. The Zone 1 reach settings, from each terminal, must not operate for a fault external to the protected section (selectivity). They must also not operate under conditions with zero infeed at the Tee point, or possibly with the outfeeding condition.

If high-speed clearing is required from all terminal for faults in the vicinity of the Tee, and if the Zone 1 reach cannot cover faults up to the Tee point, then a communication assisted design such as direct underreaching transfer tripping scheme is required. At least one Zone 1 relay must see the fault for the scheme to work. For trip dependability, Zone 2 shall be used in either a POTT or DCB scheme. It should be noted that the Zone 1 settings are based on zero infeed at the Tee point for security reasons. However, with normal operation and a Tee infeed, the actual Zone 1 apparent impedances measured will be much higher and will underreach. For some three-terminal applications, the Zone 1 protection scheme coverage may be greatly limited.

Consider the following three-terminal line (see Figure 10), with approximately equal branch lengths:

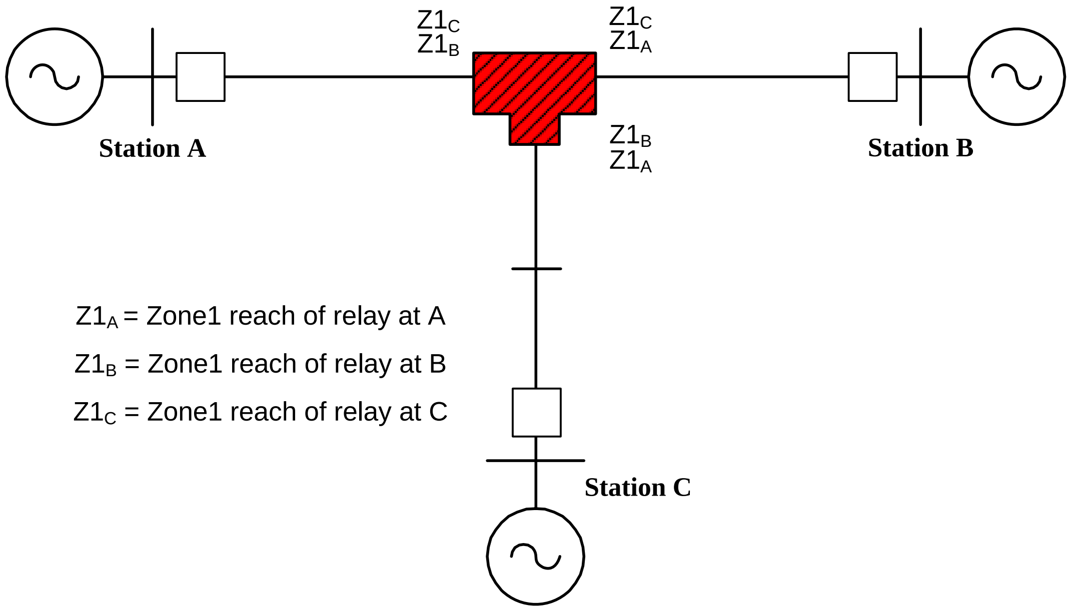


Figure 10 — Zone 1 Coverage for a Three-Terminal Line Having Equal Branches (Shaded Area Represents the Region of Overlapping Zone 1s)

High-speed tripping is achieved at all terminals without the need for communications only for the shaded section in Figure 10. Provided that the reach settings at each of the three terminals permit operations beyond the Tee point (overlap), Zone 1 tripping is obtained for faults anywhere on the protected line, using a DUTT scheme. Three-terminal configurations can limit Zone 1 reaches at multiple terminals and thus limit or severely limit the ability of Zone 1 relays to detect faults with resistance.

Consider the following three-terminal line (see Figure 11), with unequal branch lengths:

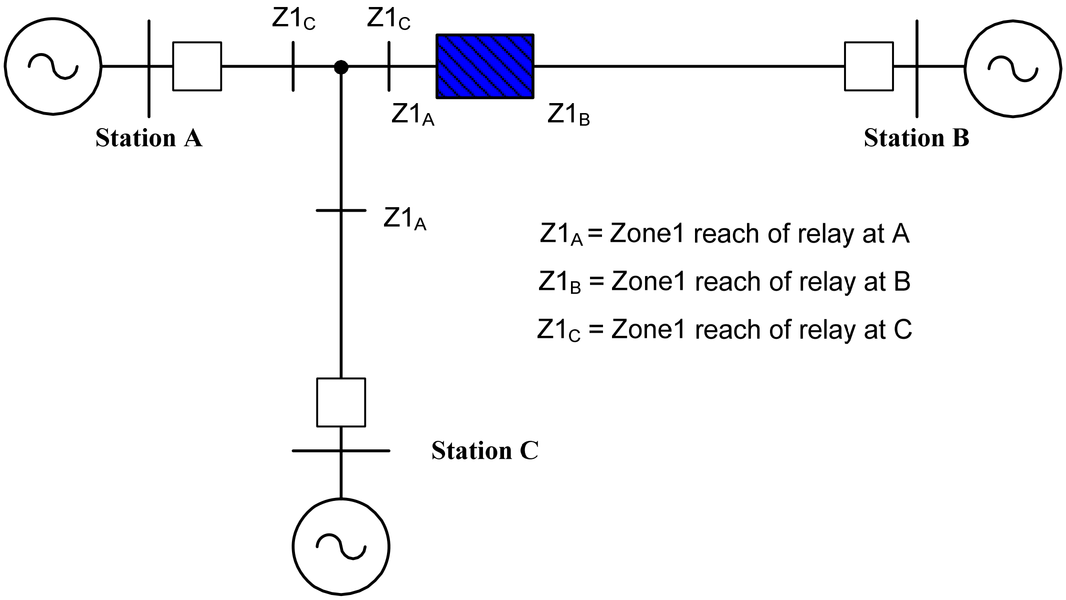


Figure 11 — Zone 1 Coverage for a Three-Terminal Line Having Unequal Branches (Shaded Area Represents the Region Where the Fault is Undetectable by any Zone 1 Relay)

With unequal branch lengths, problems may be apparent when choosing a reach setting for the relay on the longest branch. For the above configuration, the section defined by $Z1_A - Z1_B$ is not covered for faults from any of the terminal Zone 1 relays. If this is unacceptable, then high-speed clearing must be achieved by using an appropriate pilot scheme, such as POTT or DCB.

1.8 Stepped Distance Schemes

Stepped distance relay schemes applications are complicated by the following factors.

1. Zone 1 reach limitations.
2. Zone 2 and Zone 3 setting requirements will, generally, be very large due to infeed effects.
3. The larger Zone 2 and Zone 3 settings may not meet the line loadability requirements.
4. The larger Zone 2 and Zone 3 settings may not coordinate with adjacent lines due to their extended reach, or if they can coordinate, it may result in unacceptable clearance times.
5. The Zone 2 and Zone 3 settings may reach through tapped step-down transformers and must coordinate for low voltage faults.
6. The longer clearing times may not be acceptable from a system stability perspective.

Therefore, three-terminal line protection systems generally require the use of communication assisted schemes.

1.9 Direct Underreaching Transfer Tripping

A Zone 1-based direct underreaching transfer-tripping scheme is a suitable scheme for three-terminal line protection. For this type of scheme, a fault within the protected line must be detected by at least one Zone 1 relay terminal for operation.

As discussed in Section 1.7 above, for trip dependability, Zone 2 should be used in either a POTT or DCB scheme. It should be noted that the Zone 1 settings are based on zero infeed at the Tee point for security reasons. However, with normal operation with a Tee infeed, the actual apparent impedances measured will be much higher and Zone 1 protection scheme coverage may be greatly reduced.

1.10 Permissive Overreaching Schemes

A permissive overreaching scheme is very secure; requiring all three terminals to detect the fault before tripping can be initiated at any given terminal. Tripping requires the local overreaching Zone 2 distance element operation and receipt of a permissive trip signal from the two remote terminals. For this scheme to operate successfully, the reach of the permissive Zone 2 elements must be set to detect all line faults for all infeed conditions. The Zone 2 permissive setting is generally set for 125% of the maximum apparent impedance as measured from each terminal.

A modified (standard in most modern relays) POTT scheme that is commonly applied is one where if the breaker is open, the relays echo back permission to high-speed trip to the other terminals. In addition, if the terminal is very weak and does not detect a fault when a permissive signal is received, the relay can be programmed to echo back permission to trip to the stronger terminals that see the fault. Both of these schemes allow high-speed tripping of all terminals on the line.

For some three-terminal applications, where the infeed factor is several multiples of the actual line impedance, it may not be possible to set the Zone 2 permissive elements.

Typically, that is due to the following reasons:

1. The required Zone 2 reach may not meet the line loadability requirements, and may impose more restrictive line loading limits.
2. The larger Zone 2 settings may not coordinate with adjacent lines due to their extended reach, unless the Zone 2 tripping times are increased to provide the coordination.
3. The Zone 2 unconditional timed tripping elements, if used, may reach through tapped step-down transformers and must coordinate for low voltage faults.
4. The Zone 2 relays could trip for stable power swings.

For such cases, an alternate scheme will be required.

1.11 Directional Blocking Schemes

A directional blocking scheme is more trip dependable than a permissive scheme, however it is less secure. This type of scheme requires the use of forward and reverse fault detecting protection elements at each terminal. Tripping is initiated if a local Zone 2 overreaching distance element or a ground overcurrent element operates, and a remote-blocking signal is not received within channel coordination time (a short time varying by equipment manufacturer and type of channel, usually ranging up to 50 ms). If a remote blocking signal is received from any of the remote terminals, then tripping will be prevented. Reverse directional distance elements and ground current elements are used to initiate the sending of the blocking signals.

Similar to the permissive scheme, high-speed tripping is achieved at all terminals if the Zone 2 overreaching protection elements are set to detect all line faults for all infeed conditions. It is subject to the same protection issues as the permissive scheme discussed above. However, directional blocking has an advantage over a permissive scheme when system changes over time alter the infeed error ratio, preventing one of the terminals from seeing a fault. Under such conditions a permissive scheme would not be able to high-speed trip at any terminal, but the directional blocking scheme will trip, albeit sequentially (discussed below), making it less dependent on the source impedances.

1.12 Directional Blocking with Sequential Tripping[2]

Directional blocking with sequential tripping schemes accept that at least one terminal must open before the relays at the remaining terminals can detect the fault, and that no blocking elements operate. Moreover, once the first terminal is open (removing the infeed effect); the other two terminals must be able to detect the fault.

The rationale for operation of such a scheme, namely apparent impedance impacts, is described in section 1.2 of this paper. The following example illustrates the relationships between the apparent impedance at different terminals, as described previously in Figure 2.

Consider the following three-terminal line where the line fault is at Station B, resulting in $Z_{TF} = Z_B$:

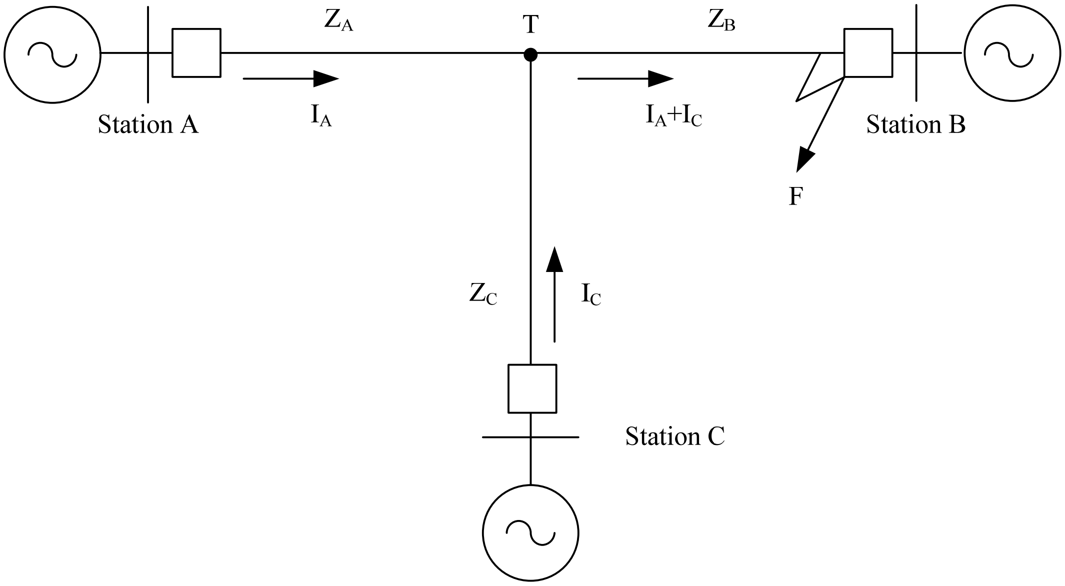


Figure 12 — DCB with Sequential Tripping

The apparent impedances at Terminals A and C are shown below, assuming the infeed factor term is $I_C/I_A = 4$.

At Terminal A:

$Z_{A\ relay} = Z_A + Z_B + Z_B\ (I_C/I_A)$

Actual $Z_{line} = Z_A + Z_B$

Then $Z_{A\ relay} = Z_{line} + 4\ Z_B$

However, for reasons outlined in section 1.11, the relay at Terminal A can only be set for $Z_{A\ relay} = Z_{line} + 2\ Z_B$. Therefore, the relay at A would not operate for that fault location.

---

[2] IEEE Standard 100-2000 (*The Authoritative Dictionary of IEEE Standards Terms*), defines sequential tripping as: “A situation where one or more relay terminals of a line cannot detect an internal line fault, typically because of infeed, until one or more terminals has already opened and removed the infeed.”

At Terminal C:

$Z_{C\ relay} = Z_C + Z_B + Z_B\ (I_A/I_C)$

Actual $Z_{line} = Z_C + Z_B$

Then $Z_{C\ relay} = Z_{line} + 0.25\ Z_B$

Assuming the relay at Terminal C is set to detect this fault, the sequential tripping scheme relies on relay C to trip first. In doing so, the relay at Terminal A would now measure $Z_A + Z_B$ only, and would trip subsequent to Terminal C.

This scheme relies upon the operation of one of the three-terminal relays for fault clearance. For this reason, this type of scheme should be used with backup protection either local or remote. If local backup protection is used, then redundancy of relay input sources and devices are necessary, as a failure of one input source or relay will prevent one or more remote terminals from detecting the faults.

Issues with Applications of Sequential Clearing

For some three-terminal lines, one relay terminal may not be able to detect a fault at the remote end of the line due to the infeed effect of the third line terminal. In these situations, one terminal of the line must open before the other terminal(s) can detect the fault.

The interdependency of the two terminals causes fault clearing times to double. Some of the issues associated with longer fault clearing times include, but are not limited to the following:

- Increased fault clearing times decrease or eliminate critical clearing stability margins resulting in dynamic instability.
- Remote backup clearing times may be extended or clearing time margins reduced.
- Breaker failure clearing times will increase at the sequential terminals.
- Voltage recovery post fault can take longer due to the longer clearing times.
- Damage at the point of fault will increase.
- Transformers supplying fault current may exceed their mechanical through-fault duration curve limits.
- The longer tripping times may have a negative impact on loads.

Some schemes use high-speed communications (transfer trip) to send a trip command from the one terminal that can detect the fault to the other terminals that cannot detect the fault. In such schemes, the possibility of a communications failure must be considered.

Application of high-speed communication, preferably redundant communications, may avoid the impact of longer clearing times on the interconnected system. For those systems that use sequential clearing as an acceptable practice, it is essential to the reliability of the interconnected system that stability studies be performed to verify the stability of the system. Such studies must include time delayed clearing (breaker failure clearing) to meet NERC reliability standards.

1.13 Line Differential

The current differential principle was initially used, and continues to be used, in the form of pilot-wire protection. Modern microprocessor-based protection relays and digital communications make line differential schemes more versatile. The scheme performs a differential comparison on a per-phase basis and communicates using one of several types of communication media.

The current differential principle is suited to protect three-terminal lines and it does not need to contend with problems associated with voltage, loading, and swings. Moreover, with current differential relays at each terminal, there is no infeed error. Phase-comparison relay schemes share many of the advantages of line current differential, but are not discussed further in this document.

A typical differential scheme is depicted below in Figure 13.

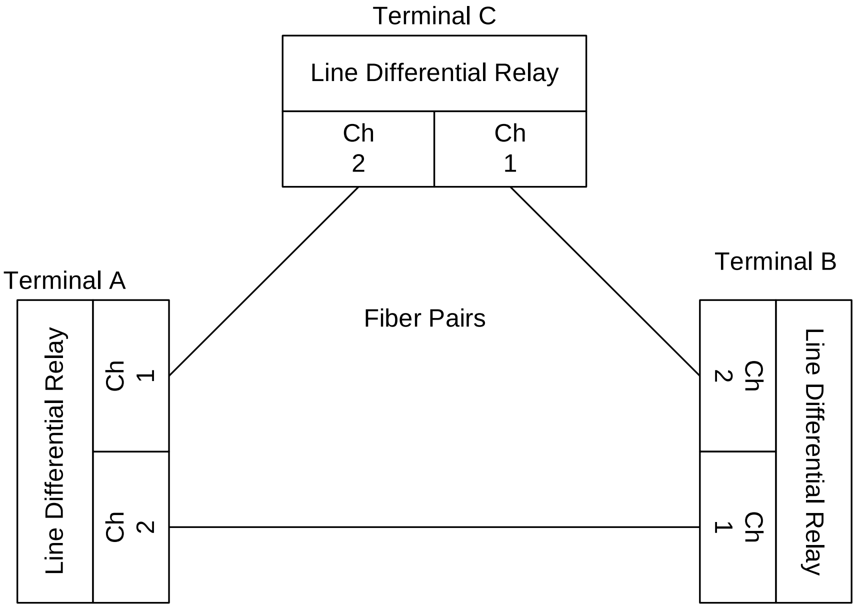


Figure 13 — Three-Terminal Line Differential Scheme

In this implementation of a three-terminal line protection scheme, each of the line differential relays connects to its two remote units using two channels — Channel 1 and Channel 2. Channel 1 of any given relay connects to Channel 2 of the next relay, forming a ring between all three units. Under normal operation, with all communications channels in service, each relay receives two remote current waveform samples and makes its local tripping decision based on a comparison with its locally acquired samples. A local trip decision also causes transfer trip to be sent to the two remote terminals. If one of the three bidirectional communications paths is interrupted, two of the three remaining relays will still be able to receive remote samples from the other two and is still capable of making a local tripping decision and sending transfer trip.

Current differential protection systems are very dependant on a functioning communication channel at all terminals of the line, and the loss of this channel may prevent high-speed clearing of faults. If high-speed clearing of faults is needed for stability, the application of protection system redundancy should be considered. The current differential system should be backed up by a pilot system or a second communication channel.

An example of one implementation of a line differential protection system for a three-terminal line, using redundant and diverse communication paths over a SONET network, is illustrated in Appendix B.

APPENDICES

APPENDIX A — LINE CONFIGURATIONS AND PROTECTION SCHEMES

1.0 Line Configurations

1.1 Radial Lines

Radial lines are lines that supply loads from a single power source — Terminal A. Nondirectional overcurrent or distance relays are normally used to protect these types of lines. Communication assisted tripping is not generally necessary.

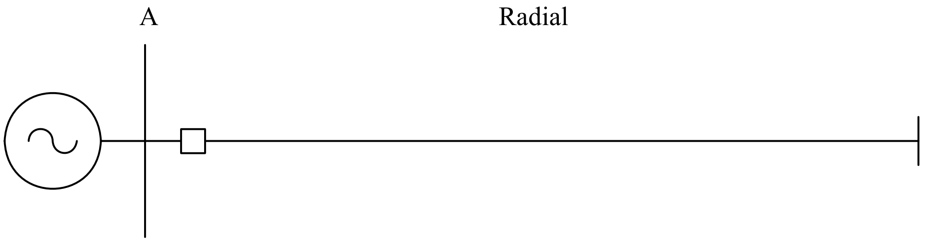


Figure A-1a — Radial Configuration

1.2 Two-Terminal Lines

Two-terminal lines are used for bulk power transfer and to supply loads from two power sources — Terminals A and B. To obtain proper selectivity and coordination, the industry normally uses directional distance relays for phase and ground fault detection. Directional ground overcurrent relaying is sometimes applied in addition to, or in place of, directional ground distance relay functions.

One or two communications-based protection groups are normally utilized with two-terminal line applications at transmission voltages greater than 200 kV.

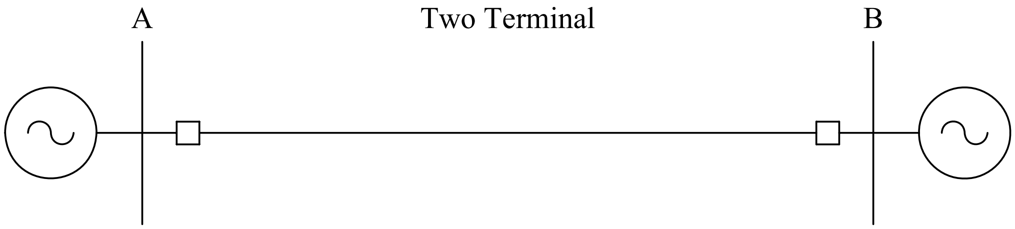


Figure A-1b — Two-Terminal Line Configuration

1.3 Three-Terminal Lines

Three-terminal lines are used for bulk power transfer and to supply loads from three power sources — Terminals A, B, and C. Protection systems are similar to that of two-ended lines except with more sophisticated techniques. In many cases, an existing two-terminal line is converted to a three-terminal line as part of a program to reinforce the power system. At least one (or in the general case, two) communications-based protection groups are normally utilized with three-terminal line applications.

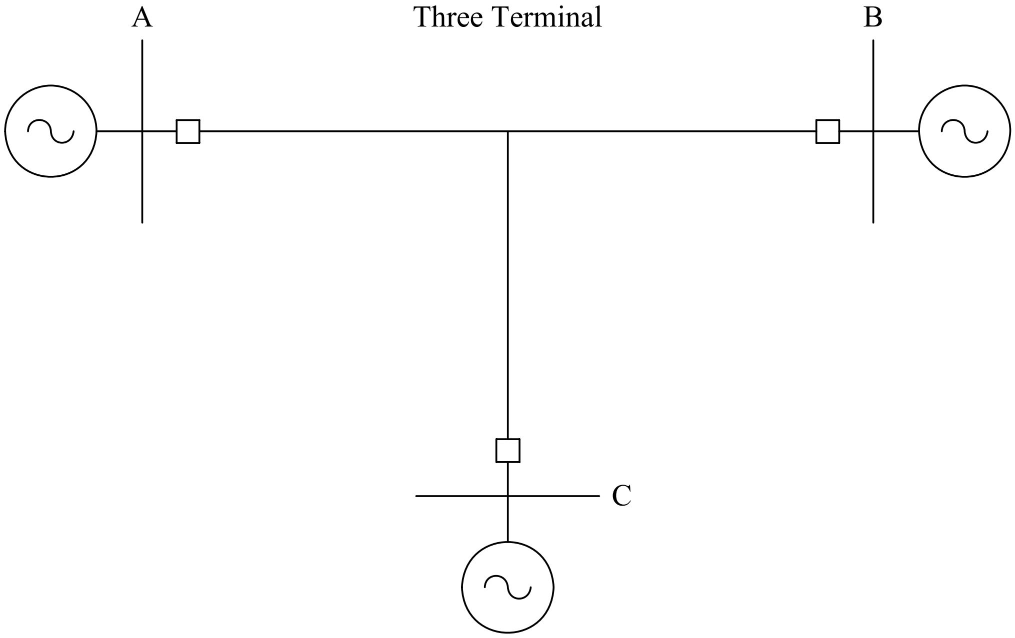


Figure A-1c — Three-Terminal Line Configuration

2.0 Two-Terminal Line Protection Systems

This section briefly describes some of the most common types of line protection schemes used in the industry. It is provided as a reference for readers unfamiliar with such schemes. For a more detailed discussion on line protection schemes, the reader is referred to the IEEE Standard C37.113-199, *Guide for Protective Relay Applications to Transmission Lines* [reference 4].

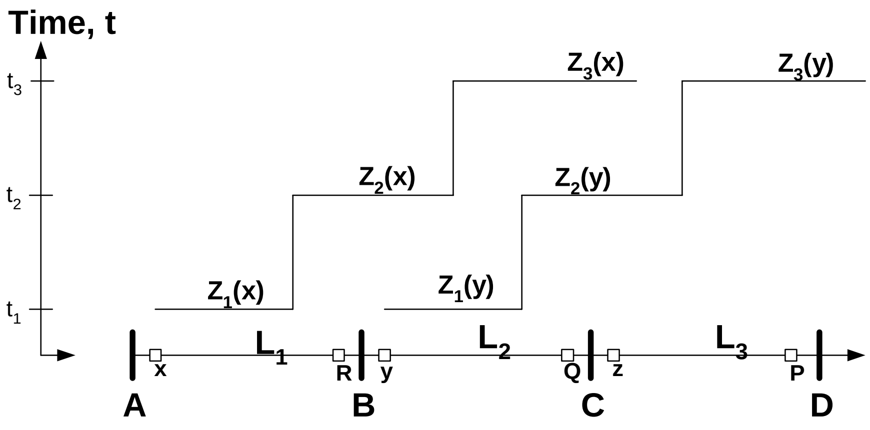
Just as transmission lines vary widely in their characteristics and configurations, so too do their protection schemes. Several fundamental factors influence the choice of protection schemes applied to a given line.

- Type of line: overhead, cable, line length, single line, parallel line, radial, two-ended, three-ended, etc.
- Line function and importance effect on service continuity and timing requirement for isolation from the system.
- Coordination and compatibility with associated lines and systems.

2.1 Nonpilot Schemes

Most high-voltage transmission lines are protected by distance relays. Compared to overcurrent relays, distance relays are inherently directional, less susceptible to source impedance variations, and have higher loadability limits.

Step distance protection is generally used for nonpilot applications of distance relaying. An example of such a scheme is illustrated in Figure A-2 (next page).



$Z1(x)$ - 80% L_1 t_1 - no intentional time delay]

$Z_2(x)$ - 100% L_1 + 25% L_2 t_2

$Z_3(x)$ - 100% ($L_1 + L_2$) + 25% L_3 t_3

$t_1 < t_2 < t_3$

Figure A-2 — An Example of a Stepped Distance Scheme for Terminal A

In this stepped distance scheme example, three protection zones are used for Terminal A:

Zone 1: Set with no intentional time delay and covers 80% of the line so not to overreach Terminal B (selectivity).

Zone 2: Set to cover 100% of L_1 plus at least 25% of L_2, covering faults for the section between 80–100% of L_1, with a time delay selected to coordinate with Terminal B protection systems.

Zone 3: This zone is typically applied as a backup protection for single protection failures at Terminal B (breaker failure, battery, etc.). It is set to cover 100% ($L_1 + L_2$) plus at least 25% of L_3, and is time coordinated with protection systems at Terminals B and C.

2.2 Pilot (Communication-Assisted) Schemes

The three most commonly used communication assisted distance protection schemes in the industry are Direct Underreaching Transfer Trip (DUTT), Permissive Overreaching Transfer Trip (POTT), and Directional Comparison Blocking (DCB). The DUTT scheme is used with the Zone 1 elements and the DCB and POTT schemes use Zone 2 overreaching elements.

DUTT has the advantages of minimal susceptibility to power system swings. DUTT has the disadvantage of dependency on communication channels for faults external to overlapping coverage regions.

The POTT scheme has the advantage of being more secure, as it requires permission from the remote relays to trip, and it can provide higher-speed tripping. It has the disadvantage of being dependent upon the communication channel time for all line faults.

The DCB is the most trip dependable, because its operation is not dependent on the communication channel or operation of the remote relays. It is the least secure in that a loss of communication can result in line trips for faults not on the line. The DCB scheme requires a forward reaching element (Zone 2), and a reverse directional element.

Generally, a complimentary use of high-speed schemes is used for the protection of most 200 kV and above transmission lines.

2.3 Direct Underreaching Transfer Trip

Attributes of a direct underreaching transfer trip scheme include the following:

- The direct underreaching transfer trip scheme uses the Zone 1 distance elements typically set at 70% to 90% of the line.
- The Zone 1 elements trip locally and will transfer trip via communication channel to the remote end. Receipt of a transfer trip signal (from the remote end) will also initiate a local trip (see Figure A-3 below).
- This scheme requires only one Zone 1 operation to trip both ends of the protected line, but to do so; it is dependent upon having reliable communication channels. This scheme will not detect faults beyond the Zone 1 reach upon total loss of communication channels, or if the remote breaker is open.
- This scheme is generally implemented with dual communications channels, and it is augmented with either a POTT or DCB scheme for breaker open operations (refer to sections 2.4 and 2.5), and/or a time backup protection.

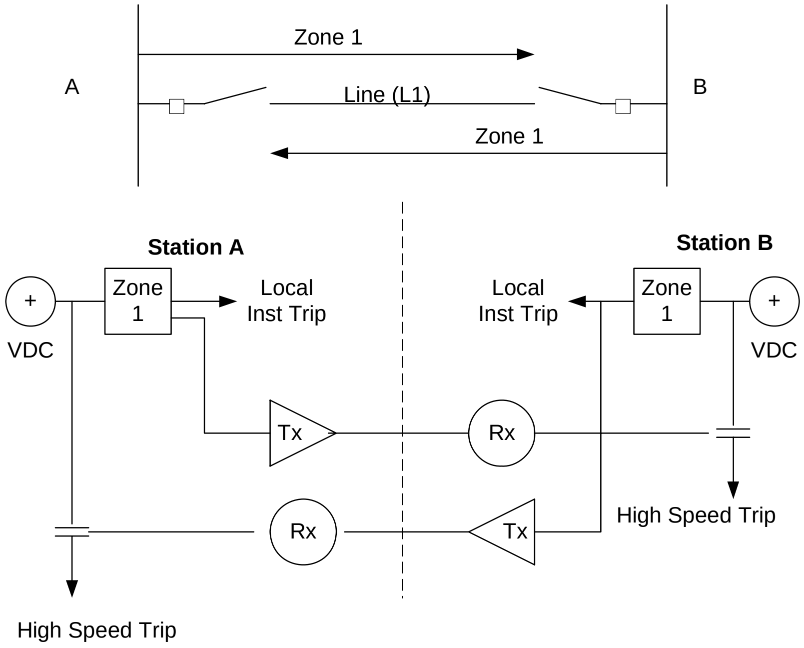


Figure A-3 — Direct Underreaching Transfer Trip

2.4 Permissive Overreaching Scheme

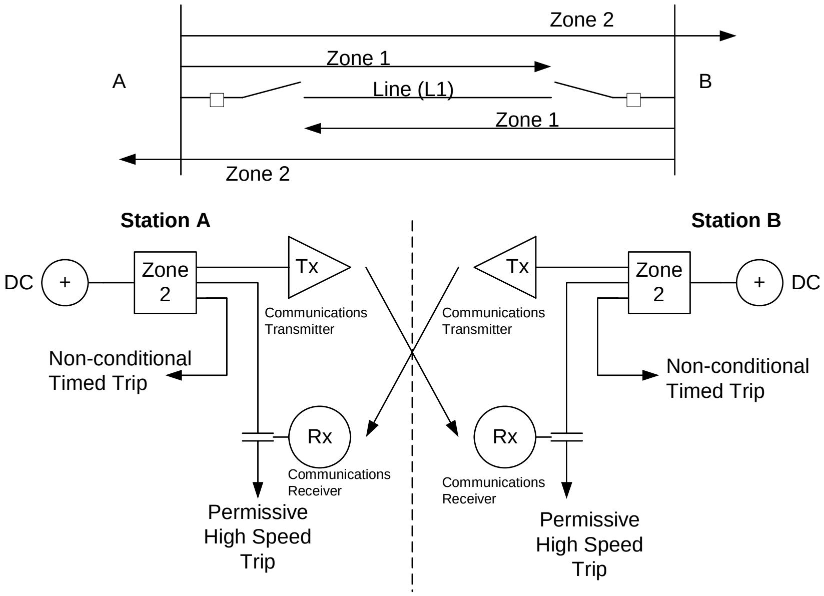


Figure A-4 — A Permissive Overreaching Scheme

Attributes of a permissive overreaching scheme include the following:

- The Zone 2 overreaching elements key permissive signals to the remote end.
- Upon receipt of a permissive signal from the remote end, the Zone 2 elements are permitted to trip locally without any time delay.
- If the remote end line is open, either due to the remote line disconnect switch being open or the remote breakers being open, the permissive signal is echoed back to the local end ("Permissive Echo"). With the receipt of the permissive echo signal, the Zone 2 overreaching elements generally initiate similar protection schemes as mentioned above.

2.5 Directional Comparison Blocking

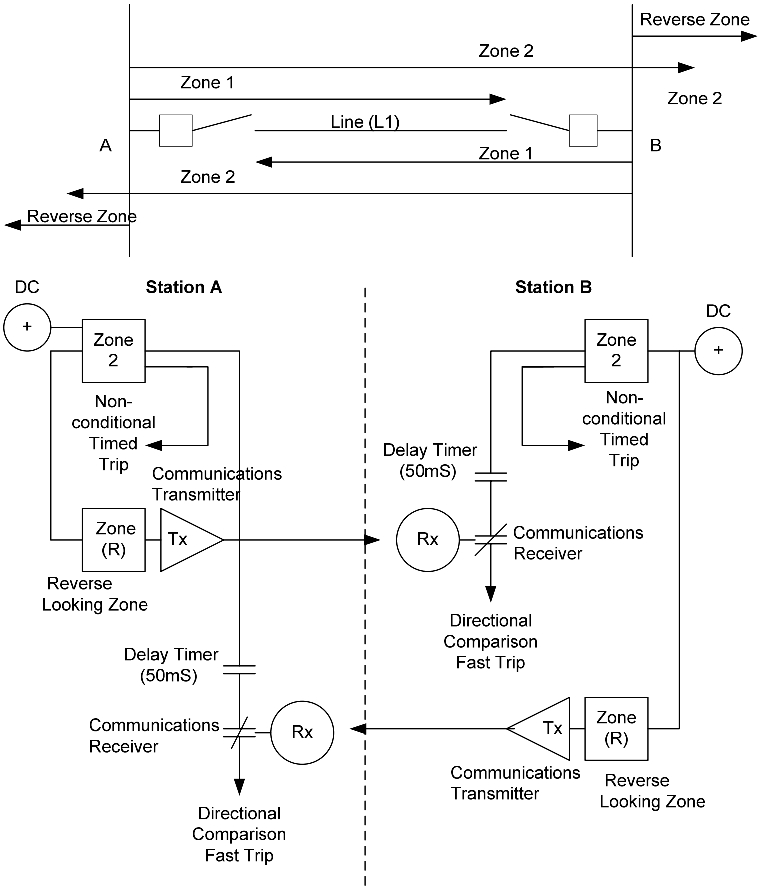


Figure A-5 — A Typical Directional Comparison Blocking Scheme

Attributes of a directional comparison blocking scheme include the following:

- Operation of the Zone 2 elements initiates a timer (channel coordination time, usually ranging up to 50 ms). If a blocking signal is received, within channel coordination time, the Zone 2 elements will not trip locally. If a blocking signal is not received within the channel coordination time, the Zone 2 elements will trip locally.
- The reverse directional Zone 3 elements initiate a blocking signal to the remote terminal, and must be set to cover more line impedance, with margin, than that measured by the forward looking Zone 2 relays at the remote end.

APPENDIX B — EXAMPLE OF USING REDUNDANT AND DIVERSE PATHS OVER A SONET SYSTEM

The following is one implementation of a line differential protection system for a three-terminal line. The protection system uses redundant local protection systems, consisting of an "A" group line differential relay, and a "B" group line differential, one at each of the three-terminal — six measuring relays.

An example of protection system using redundant and diverse paths over a SONET system is depicted below.

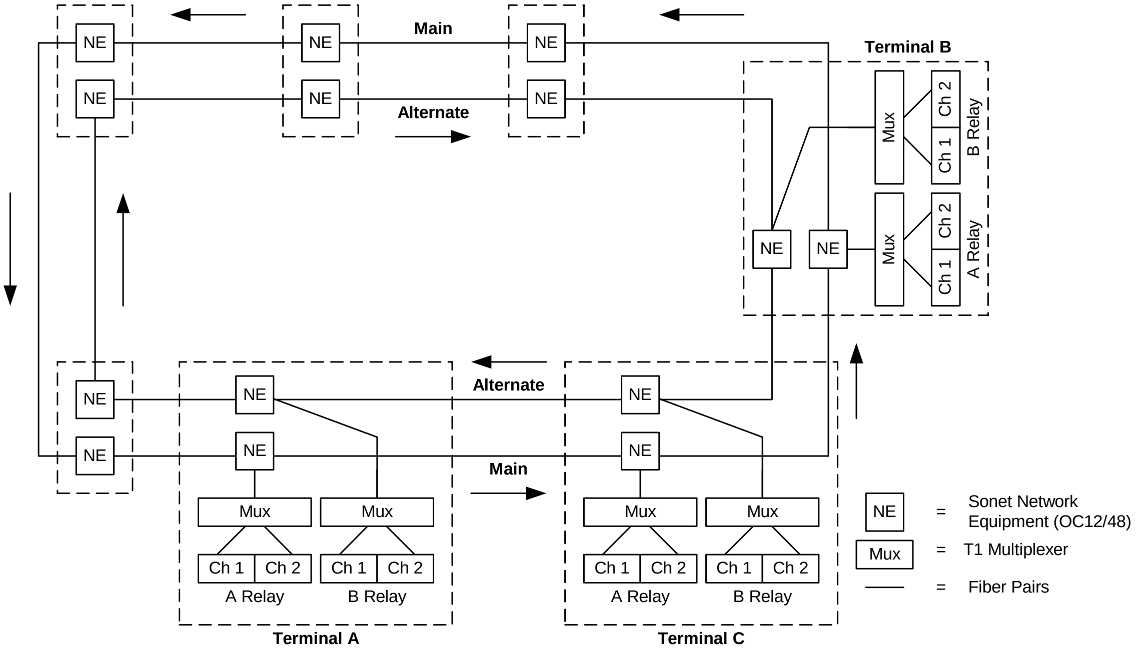


Figure B-1 — An Example of a Three-Terminal Line Differential Scheme Used With Redundant Local Protection Systems

With this implementation, redundant line differential relays with redundant and diverse communication media paths, the backup distance protection systems are only asserted upon total loss of communication failure, and they are designed to trip unconditionally after a time delay (i.e., 400 ms).

Three-terminal lines can be further complicated by the presence of tapped load stations not equipped with a current differential relays. In a line differential application, these tapped load stations represent an error current that may cause a false operation due to load or inrush currents.

Similarly, faults on the low-voltage side of the tapped load stations can cause the line differential system to trip for an out-of-zone fault. For such fault contingencies, the local tapped load protection systems should operate to isolate the fault and not disrupt the line.

To overcome this complexity, the following techniques may be used:

1. Line differential relays have minimum current sensitivity settings. This setting can be set at a threshold that is above any error current caused by the current outflows. The line differential current setting must ensure fault coverage for all line faults under all expected operating conditions.
2. The line differential operating element (87) can be supervised with a phase distance element. The distance element should be set "short" of the low-voltage tapped station — it should not detect a low-voltage bus fault. However, it must be set to operate for all line faults under all expected operating conditions.
3. If the maximum infeed error is such that, the required distance element setting will result in operation for a low-voltage fault, sequential tripping can be considered. Again, it should be noted that the trip dependability for this scheme relies upon the operation of one of the three-terminal relays for fault clearance. For this reason, this type of scheme should be used with local redundant protection systems, using a design that mitigates common mode of failures.
4. Alternatively, the tapped stations can send blocking signals to the three-terminal stations to block line tripping for low-voltage faults.

APPENDIX C — TECHNICAL EXCEPTION 8[3]

Exception 8 — Three (or more) Terminal Lines and Lines with One or More Radial Taps

Three (or more) terminal lines present protective relaying challenges from a loadability standpoint due to the apparent impedance as measured by the different terminals. This includes lines with radial taps. For this exception, the loadability of the line may be different for each terminal of the line so the loadability must be done on a per-terminal basis:

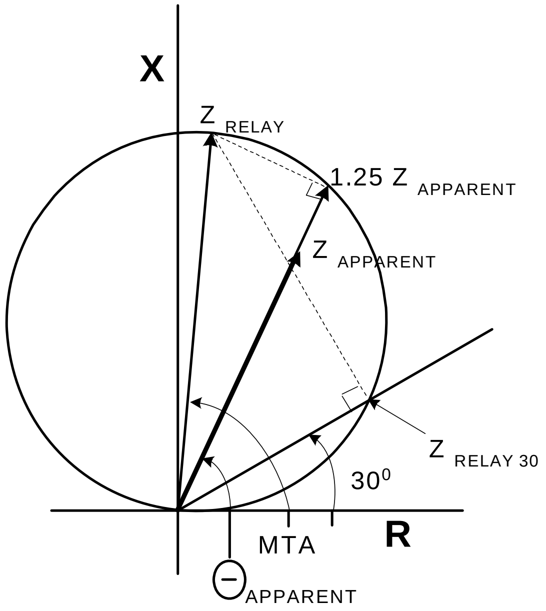


Figure 8 – Three (or More) Terminal Lines and Lines With One or More Radial Taps

The basis for the emergency current loading is as follows:

V_{relay} = Phase-to-phase line voltage at the relay location

$Z_{apparent}$ = Apparent line impedance as measured from the line terminal. This apparent impedance is the impedance calculated (using infeed where applicable) by the TPSO for a fault at the most electrically distant line terminal for system conditions normally used in their protective relaying setting practices.

$\Theta_{apparent}$ = Apparent line impedance angle as measured from the line terminal

Z_{relay} = Relay setting at the maximum torque angle

MTA = Maximum torque angle, the angle of maximum relay reach

$Z_{relay30}$ = Relay trip point at a 30 degree phase angle between the voltage and current

I_{trip} = Trip current at 30 degrees with normal voltage

---

[3] An excerpt from *Relay Loadability Exceptions — Determination and Application of Practical Relaying Loadability Ratings*, Version 1.2, dated August 8, 2005.

$I_{emergency}$ = Emergency current (including a 15% margin) that the circuit can carry at 0.85 voltage at a 30 degree phase angle between the voltage and current before reaching the trip point

For applying a mho relay at any maximum torque angle to any apparent impedance angle:

$$Z_{relay} = \frac{1.25 \times Z_{apparent}}{\cos(MTA - \Theta_{apparent})}$$

The relay reach at the load power factor angle of 30° is determined from:

$$Z_{relay30} = \left[\frac{1.25 \times Z_{apparent}}{\cos(MTA - \Theta_{apparent})}\right] \times \cos(MTA - 30°)$$

The relay operating current at the load power factor angle of 30° is:

$$I_{trip} = \frac{V_{relay}}{\sqrt{3} \times Z_{relay30}}$$

$$I_{trip} = \frac{V_{relay} \times cos(MTA - \Theta_{apparent})}{\sqrt{3} \times 1.25 \times Z_{apparent} \times cos(MTA - 30°)}$$

The emergency load current with a 15% margin factor and the 0.85 per unit voltage requirement is calculated by:

$$I_{emergency} = \frac{0.85 \times I_{trip}}{1.15}$$

$$I_{emergency} = \frac{0.85 \times V_{relay} \times cos(MTA - \Theta_{apparent})}{1.15 \times \sqrt{3} \times 1.25 \times Z_{apparent} \times cos(MTA - 30°)}$$

$$\boxed{I_{emergency} = \left(\frac{0.341 \times V_{relay}}{Z_{apparent}}\right) \times \left(\frac{\cos(MTA - \Theta_{apparent}}{\cos(MTA - 30°)}\right)}$$

APPENDIX D — REFERENCES

1. *Relay Loadability Exceptions — Determination and Application of Practical Relaying Loadability Ratings, Version 1.2*, August 8, 2005, NERC System Protection and Controls Task Force
2. *Protection System Review Program, Beyond Zone 3*, August 2005, NERC System Protection and Controls Task Force
3. *Methods to Increase Line Relay Loadability,* June 7, 2006, NERC System Protection and Controls Task Force
4. IEEE Standard C37.113-1999, *Guide for Protective Relay Applications to Transmission Lines*

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