

A Tutorial on Calculating Source Impedance Ratios for Determining Line Length

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A Tutorial on Calculating Source Impedance Ratios for Determining Line Length

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Abstract—Classifying the length of a line is an important step in determining the transmission line protection philosophy and relay settings. The length of a line can be defined by physical distance, impedance, or its source impedance ratio (SIR). The SIR is the ratio of the source impedance, Z_s , to the line impedance, Z_L . The SIR is well established in the industry as the preferred method for classifying the electrical length of a line for the purpose of setting protective relays.

Many references discuss setting criteria and performance specifications relative to the SIR. However, very few references define the proper method for calculating the source impedance to use in the ratio. The transmission system is a complex network with many sources and branches, and the topology of the network can have a major effect on the results, depending on the method used. This paper analyzes several methods in common usage and presents a simple method that provides a better result. The effect of the SIR on line relay settings and examples of various transmission network topologies are discussed.

I. INTRODUCTION

The length of the line is often used to help determine the protection scheme that is specified. It is also used to guide the relay setting engineer in determining what elements can be applied and/or selecting margins. The length of a line can be defined by physical distance, impedance, or its source impedance ratio (SIR). The SIR is the ratio of the source impedance, Z_s , to the line impedance, Z_L . The SIR is well established in the industry as the preferred method for classifying the electrical length of a line for the purpose of applying protective relays. IEEE C37.113, IEEE Guide for Protective Relay Applications to Transmission Lines [1] classifies line length based on SIR as follows:

- Long line (SIR < 0.5)
- Medium line (0.5 < SIR < 4)
- Short line (SIR > 4)

Many references discuss setting criteria and performance specifications relative to SIR. Often, protective element operating time or transient overreach accuracy is specified at a particular SIR or is given as a series of curves for various SIR values versus multiple of pickup, for example. Application and setting guidelines for short lines are given particular emphasis as a special case—mainly for setting underreaching elements [2] [3] [4], but sometimes for setting overreaching elements as well [5]. This paper focuses on short

lines because they have the most impact on protection elements and their settings.

While SIR is widely discussed in industry literature, very few references define the proper method for calculating the source impedance to use in the ratio. The transmission system is a complex network with many sources and branches, and the topology of the network can have a major effect on the results, depending on the method used.

This paper looks at several methods in common usage and presents a simple method that provides a better result. The effect of the SIR on line relay settings is discussed and examples of various transmission network topologies are used to illustrate the concepts.

II. CLASSIFYING LINE LENGTH

As stated in the introduction, the length of a line can be defined by physical distance, impedance, or its SIR. The nominal voltage and the short-circuit level of the system have a much greater effect on whether a line is considered short than either the length or impedance of the line.

Reference [1] gives an example of a typical 500 kV line and a typical 69 kV line to illustrate this point. In the example, the short-circuit level of the extra-high voltage (EHV) system is assumed to be 10 times higher than the short-circuit level of the subtransmission system. In the example, a 6.208-ohm (primary) EHV line that is 11.6 miles long is considered short by the SIR = 4 criteria. This is compared with a 1.166-ohm (primary) subtransmission line that is 1.39 miles long that meets the SIR = 4 criteria. So, we can see that simply looking at miles or ohms is not a good indicator.

A. Physical Distance

The physical length of a line in miles or kilometers is often a factor in determining the line protection system used because it often influences communications channel choices for communications-assisted protection schemes. Short lines often make possible communications paths such as point-to-point microwave, line-of-sight radio channels, or fiber-optic channels. Stringing a fiber-optic cable a short distance between terminals is often more economically feasible for a physically short line. But, for purposes of calculating settings and determining what elements must be disabled, it may not be as useful.

B. SIR

SIR is useful in classifying line length because the SIR is a convenient way to characterize a voltage divider network. We are interested in answering the question, “What is the difference in voltage and current at the relay for a fault at the boundary of the zone of protection (at the remote bus) versus an in-zone fault?” Fig. 1 illustrates the circuit.

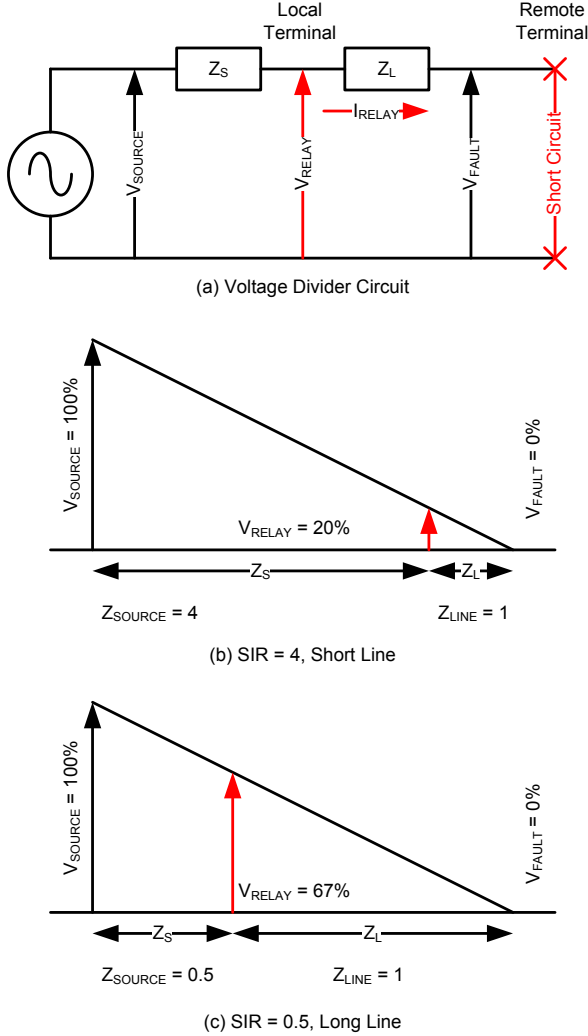


Fig. 1. SIR as Voltage Divider Circuit

It can be seen that for an $SIR > 4$, the voltage at the relay will be less than 20 percent nominal. The impact of SIR on protection elements is discussed further in the following section.

This voltage divider nature of SIRs is also useful in justifying the application of pilot protection. The voltage dip at the local bus for an end-zone fault is large for a high SIR line terminal. We can see from Fig. 1b that time-delayed clearing for an end-zone fault on the $SIR = 4$ line would cause the voltage to dip to 20 percent of nominal. Waiting for Zone 2 time-delayed clearing would impress this low voltage on adjacent loads for a significant time, which may result in initiating load transfer schemes, starting standby generation, motor stalling, and dropout of sensitive electronic loads [6].

An accurate method for calculating SIR is important to predict these issues.

III. SHORT LINE PROTECTION CHALLENGES

One of the primary principles of relay coordination is to ensure that underreaching elements never overreach the zone of protection under all possible conditions and transients. Because an underreaching element cannot see out-of-zone faults, it can trip with no intentional time delay. If one of these elements sees an out-of-zone fault and trips instantaneously, an overtrip (which is a security failure) occurs.

Transmission lines are often protected by distance relays and overcurrent relays. Even when communications-aided schemes are used, such as line current differential or a directional comparison scheme (directional comparison blocking [DCB] or permissive overreaching transfer trip [POTT], for example), we often still desire to use unconditional trip elements (instantaneous underreaching elements and time-delayed overreaching elements) to clear faults in case the communications channel is not available.

A. Distance Elements

For a distance element, the main protection issue presented by a high SIR is the voltage measured at the relay for an out-of-zone fault. If the SIR is high, the voltage will be small and measurement errors can dominate the reach calculation. Distance elements use a comparator that uses current and voltage. We can think of current as an operating quantity and voltage as a restraining quantity. Errors in measuring the voltage can result in reduced restraint and overreach.

Let us look at a Zone 1 underreaching element on an $SIR = 4$ line. The element is set with a typical margin of 80 percent of the line impedance. With instrument transformer errors and relay measurement errors, can the relay differentiate between a fault at the reach point and one at the remote bus? In this example, the nominal line-to-neutral voltage is 66.4 V. For an out-of-zone fault, assuming no fault resistance, the ideal secondary voltage at the relay would be 13.28 V. For the same fault at the Zone 1 reach point, the ideal voltage at the relay would be 11.07 V. This gives us a difference of 2.21 V between a fault at the reach point and an out-of-zone fault.

The big question now is, “What is the accuracy of the voltage transformer (VT) and the protective relay?” A typical capacitor-coupled voltage transformer (CVT) used for protection has an accuracy of at least 1 percent (steady state) and a transient response of less than 10 percent in the first cycle. Protective relays typically have a transient accuracy error of 5 percent or less. If we now add these errors quadratically, we obtain an overall measurement error of 11.2 percent. So the voltage for a fault at the remote bus with error could be as great as $13.28 \text{ V} \cdot 11.2\% = 1.49 \text{ V}$, which is 67 percent of the voltage difference of 2.21 V. This results in the relay having trouble differentiating between an in-zone and out-of-zone fault. Reference [7] provides an in depth discussion of CVT transient error.

B. Overcurrent Elements

For an overcurrent relay, when the SIR is high, the faulted circuit is dominated by the source impedance. The difference between the fault current magnitude for an in-zone fault and an out-of-zone fault can be smaller than the typical margins used for setting the pickup.

For example, if we calculate that the contribution through our terminal for an out-of-zone (remote bus) fault for our SIR = 4 line is 20 A secondary, we might apply a margin of 125 percent and set an instantaneous directional overcurrent element at 25 A. For the SIR = 4 line, a close-in fault will have a total impedance of $4/(4 + 1) = 0.8$ relative to the out-of-zone fault. So, the close-in fault will only be 25 A secondary. This instantaneous element will not reliably operate—even for a close-in fault. When presented with this situation, it is often best to simply turn the element off and rely on other schemes for high-speed fault clearing.

C. High SIR Setting Considerations

The SIR > 4 boundary for a short line defined in [1] is a somewhat arbitrary boundary that is meant to call attention to when a relay setting engineer should start being cautious about what elements can be applied and what margins to use. The actual accuracy of the instrument transformers and relay technology used varies from application to application and affects at what level SIR becomes a concern when applying underreaching elements.

A marginally high SIR might be addressed by simply using more conservative margins or by adding time delay. Alternatively, the relay setting engineer might turn on special logic in the relay that can help it reduce transient overreach or slow down tripping when high SIR is detected [7]. An extremely high SIR will likely be addressed by turning off the underreaching elements entirely and relying on a communications-aided protection scheme for high-speed fault clearing along the entire length of the line.

The exact level of SIR where these various actions might be taken is a matter of judgment and is part of the *art* in the art and science of protective relaying. Further, the reliability of the communications channels available for a communications-aided scheme will likely come into play in assessing how conservative the relay setting engineer should be when applying and setting underreaching, unconditional trip elements on shorter lines.

IV. SIR AS A MEASURE OF LINE LENGTH

From the previous discussion, we can see why using SIR to define line length for the purpose of setting relays is appropriate. However, this can complicate matters for the relay setting engineer. It can be somewhat confusing when a line is short from one terminal and medium or long from the other terminal. This can happen when one terminal is connected to a strong bus and the other is connected to a weak bus. To further complicate matters, the positive- and zero-sequence source impedances can vary considerably, such that a line could be short for ground faults and medium or long for phase faults, and vice-versa. It is also not unusual to find a

line that is medium or long for system normal conditions, but short under N – 1 conditions, with the strongest source behind the line terminal out of service.

The important message here is that it is necessary to calculate the SIR of the line being worked on at the start of performing setting calculations. In addition, it is recommended to calculate the SIR under system normal and under N – 1 conditions to make the engineer aware of how system topology changes can affect protective elements.

Reference [6] illustrates the importance of considering N – 1 conditions in determining protection schemes and settings. In the real-world example, a line that is medium under system normal conditions is described. But, under an N – 1 condition, an underreaching element overreached for an out-of-zone fault. The solution was to disable the underreaching elements and install a second high-speed line protection system. If the engineer had evaluated SIR under N – 1 conditions when the line was planned, dual pilot protection schemes could have been specified in the beginning and the misoperation would have been avoided. The good news is that, with modern fault study and mathematical calculation software tools, it is not a large burden to include SIR calculations in the first section of engineering calculations documentation.

V. DEFINITIONS OF SOURCE IMPEDANCE

Now that we know why SIR is the preferred method of defining line length, it is important to know how to properly calculate SIR to ensure that we are using appropriate information to make decisions. As previously mentioned, the SIR is the ratio of the source impedance, Z_S , to the line impedance, Z_L . Some references have suggested using the underreaching element reach set point as the denominator in the ratio [8]. This practice is sometimes advocated because it gives a more conservative result. Because, as discussed in Section III, we often use the SIR to determine the margin to use in calculating the reach, using this definition of SIR becomes circular logic and is not recommended.

The exercise of calculating the SIR is to help determine when an instantaneous underreaching element is in danger of overreaching the zone of protection. Thus, the condition of interest is a fault exactly at the zone boundary. For this reason, we recommend the classic definition of SIR with Z_L as the denominator.

The numerator of the ratio is the source impedance, Z_S . There are a number of ways that the source impedance can be defined and understanding that is the core purpose of this paper.

A. Thévenin Equivalent Impedance

The Thévenin equivalent impedance is defined as the open-circuit voltage at the terminal of interest divided by the short-circuit current at the terminal of interest. Because we are interested in the equivalent source impedance of the system behind the terminal of interest, we take that terminal out of service. This method is often mistakenly used by engineers to obtain the numerator value to use in the SIR calculation.

The problem with this definition of Z_S is that it disturbs the complex transmission network by removing the line from the network. The transmission system is a complex network with many sources and branches. When a branch is removed from service, the current redistributes through the network and makes the source appear stronger than it will be during an actual out-of-zone fault.

Fig. 2 illustrates the issue. As shown in Fig. 2a, reducing a complex power system around the line of interest to its simplest form results in the following:

- The line of interest.
- Two perfect sources with their associated impedance.
- A transfer branch that represents the surrounding power system that links the two terminals.

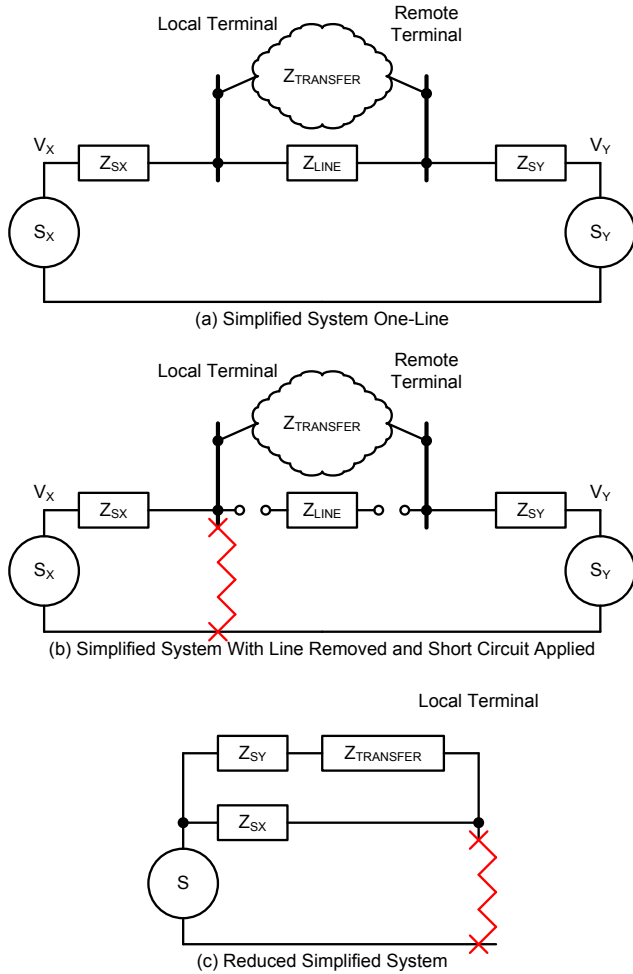


Fig. 2. Obtaining the Thévenin Equivalent Impedance

In many representations of a simplified two-source power system, this transfer impedance branch is neglected. However, the presence of this branch is very important in understanding the concepts that we are presenting. This branch exists in every reduced equivalent network for an interconnected grid and in all cases, except perhaps a tie line between two relatively isolated networks, is significant.

To take the Thévenin equivalent for the system behind the local terminal, we remove the branch of interest from service and place a short circuit on the bus, as shown in Fig. 2b. If we reduce this circuit by recognizing that the two perfect sources are equivalent, we get the network shown in Fig. 2c.

We can see that we now have two parallel branches: the equivalent source impedance (Z_{SX}) behind the local terminal and the transfer impedance branch ($Z_{TRANSFER}$) in series with the equivalent source impedance (Z_{SY}) behind the remote terminal. The parallel impedance ($Z_{THEVENIN}$) can be calculated using (1).

$$Z_{THEVENIN} = \frac{Z_{SX} \cdot (Z_{SY} + Z_{TRANSFER})}{Z_{SX} + Z_{SY} + Z_{TRANSFER}} \quad (1)$$

This parallel circuit artificially reduces Z_S used in the SIR calculation versus what it will actually be during a fault at the zone boundary. The reduced Z_S used in the SIR calculation will reduce the SIR, which will make the setting engineer think that the line is electrically longer than it is.

Another way to look at this is that, by removing the line from service to measure the source impedance, some of the fault contribution from the remote system will redistribute and flow through the transfer impedance to the local terminal, making it appear stronger than it is relative to the line.

B. Alternative Method to Determine Z_S

A second method for determining Z_S for use in calculating SIR is to simply place a fault on the local terminal. To remove the influence of the line of interest, the current contribution from the line is subtracted from the total fault current. Z_S is then determined by dividing the line-to-neutral nominal system voltage by the adjusted total fault current [9].

This method is superior to simply taking the Thévenin equivalent impedance because the power system is not disturbed by removing the line of interest. However, because the fault is still placed at the local terminal, this method does not recognize the influence that the many parallel branches of the transmission network have on the distribution of fault current contributions from the many sources in the transmission network. These contributions will distribute differently for a fault at the local terminal versus a fault at the remote terminal.

C. Recommended Method to Calculate SIR

Before discussing the recommended method to calculate SIR, the reader should understand that Fig. 2 and Fig. 3 have been reduced to a two-source-with-transfer-branch network only for the purpose of illustrating the concepts. It is not necessary to do this network reduction in an actual transmission line application. A modern fault study program will readily supply all current and voltage values required for the calculations.

The recommended method to calculate the source impedance (Z_S) for the purpose of classifying line length is to place a short circuit at the remote bus. This is the boundary of the line zone and the point that we do not want to overreach.

Thus, it represents a realistic condition that the relay will see in service. The source impedance is calculated as the voltage drop from the local source to the relay location divided by the fault current in the relay. Fig. 3 shows the same reduced power system shown in Fig. 2. But, this time we leave the line of interest in service, place a fault at the remote terminal, and record the voltage and current at the relay.

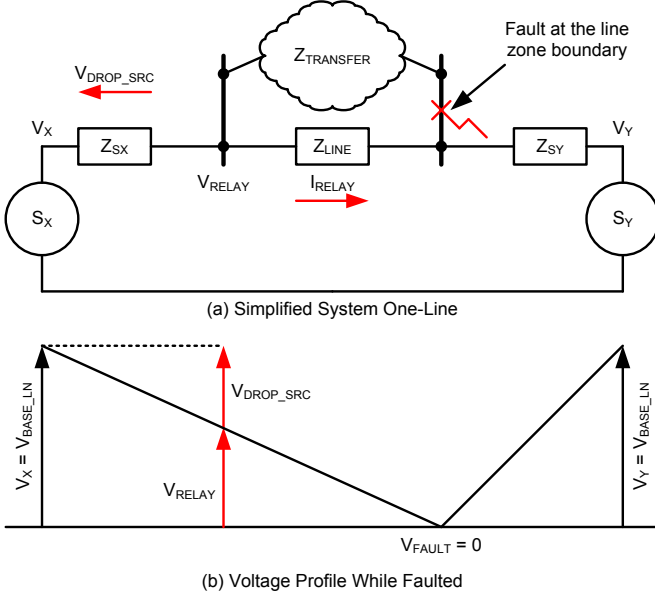


Fig. 3. Calculating Z_s Using the Voltage Drop Across the Local Source Impedance

Use (2) and (3) to calculate the source impedances for the phase and ground fault loops, respectively.

$$Z_{S_3PH} = \frac{V_{DROP_SRC}}{I_{RELAY}} = \frac{V_{BASE_LN} - V_{RELAY}}{I_{RELAY}} \quad (2)$$

$$Z_{S_SLG} = \frac{V_{DROP_SRC}}{I_{RELAY}} = \frac{V_{BASE_LN} - V_{RELAY}}{I_{RELAY} + (3I_{RELAY} \cdot k0)} \quad (3)$$

where:

V_{BASE_LN} is the system base voltage, phase-to-ground, which defines the voltage at the perfect source in primary units.

V_{RELAY} is the phase-to-ground voltage at the relay for a fault at the remote bus in primary units.

I_{RELAY} is the phase current at the relay for a fault at the remote bus in primary units.

$3I_{RELAY}$ is the zero-sequence current at the relay for a single-line-to-ground fault at the remote bus in primary units.

$k0$ is the zero-sequence compensation factor for the line as defined by (4).

$$k0 = \frac{Z_{0L} - Z_{1L}}{3 \cdot Z_{1L}} \quad (4)$$

where:

Z_{1L} is the positive-sequence line impedance.

Z_{0L} is the zero-sequence line impedance.

The source impedances obtained by (2) and (3) are used in (5) and (6) to obtain the SIR for the phase and ground loops, respectively. Z_{1L} is used in the denominator of (6) because we used $k0$ to define Z_{S_SLG} .

$$SIR_{3PH} = \frac{Z_{S_3PH}}{Z_{1L}} \quad (5)$$

$$SIR_{SLG} = \frac{Z_{S_SLG}}{Z_{1L}} \quad (6)$$

The variables in (2), (3), and (4) are complex numbers. They can be easily solved using common mathematics software. Or, given that the SIR is only used as a guideline, it is perfectly acceptable to use magnitudes only in the equations and assume that all of the currents or impedances have the same angle.

This method is similar to the method used to calculate an equivalent SIR during relay element injection testing. A testing engineer may need to do this to check relay performance against a graph of operating time versus SIR provided in the relay specifications. The tester estimates the test SIR as $(1 - V_T)/V_T$, where V_T is the test voltage in per unit of nominal [5].

This section defines the equations for SIR for both phase and ground faults. Because the definition of a short line is not a hard boundary, many practitioners check SIR for phase faults only and base their protection philosophy and setting calculations on that determination. If the setting engineer wants to be more rigorous or has particular concerns, calculating the SIR for both phase and ground elements can provide useful information.

When calculating SIR for a three-terminal line application, we must consider the effect of infeed. Infeed makes the closest terminal seem farther away, which is not the boundary case for not overreaching. We must ignore system normal with all three terminals in service when calculating SIR. The worst-case condition for SIR is a bus fault at the closest remote terminal with the third terminal out of service. Z_{1L} in this case would be the series impedance to the faulted terminal. For more uncommon three-terminal line applications with outfeed from one or both terminals, we must consider the worst-case apparent impedance (with margin) when setting the underreaching zone elements. The worst-case SIR in this case would depend on the amount of outfeed and must be evaluated on a case-by-case basis.

VI. EXAMPLES

In this section, we look at two real system examples. The first is a short line in a closely coupled system. Closely coupled systems generally offer one or more parallel paths between the two terminals of interest. These parallel paths that form the transfer branch impedance will allow flow of current in either direction for faults. The second is a tie line between two utilities that offers limited coupling between the two systems (very high transfer branch impedance).

A. Example 1: Short Line in Closely Coupled System

For this example, we have a line between Buses W and E as shown in Fig. 4, with the parameters listed in Table I. This line is one of two parallel circuits between the two buses. Bus W is weaker than Bus E with respect to source impedance. The two generators connected to Bus W are merchant generators. So, for $N - 1$, we will take both of the generators out of service.

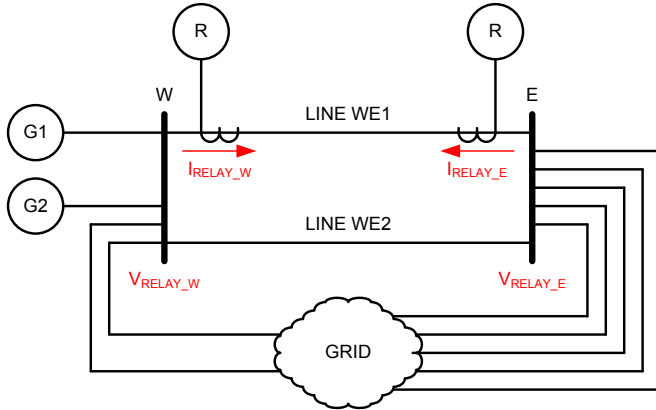


Fig. 4. Example 1: Short Line in a Closely Coupled System

TABLE I
EXAMPLE 1: LINE PARAMETERS

Parameter	Value
Voltage, line-to-line	138 kV
Voltage, line-to-neutral	79.7 kV
Line length	2.8 miles
Z_{1L} primary	$1.66 \Omega \angle 83.0^\circ$
Z_{0L} primary	$4.51 \Omega \angle 74.3^\circ$
k_0	$0.578 \angle -13.65^\circ$

Table II and Table IV (shown later) show the values provided by the fault study program for a three-phase fault and single-phase fault, respectively, at the remote terminal under $N - 0$ and $N - 1$ conditions and the resultant Z_S calculated using (2), (3), and (4).

TABLE II
EXAMPLE 1: VALUES FOR THREE-PHASE FAULT ON REMOTE TERMINAL

Case	V_{RELAY}	I_{RELAY}	Z_S	SIR
Terminal W, $N - 0$	9.3 kV	5,608 A	12.5Ω	7.6
Terminal W, $N - 1$	5.0 kV	3,016 A	24.8Ω	14.9
Terminal E, $N - 0$	19.0 kV	11,429 A	5.3Ω	3.2
Terminal E, $N - 1$	13.6 kV	8,209 A	8.0Ω	4.8

From this example, we can see that the line is definitely short when viewed from Terminal W. Underreaching Zone 1 elements should only be used with caution, if at all. From Terminal E, the line is not considered short under system normal ($N - 0$) conditions. So, use of Zone 1 elements would be acceptable. But, when we take the strongest line behind the terminal out of service ($N - 1$), we find that it is short. This terminal could use underreaching Zone 1 elements with a more conservative margin.

Table III shows the SIRs calculated using the three methods for comparison. As expected, the SIR for the closely coupled system predicted by using $Z_S = Z_{THEVENIN}$ gives the lowest values. The alternative method, where the current is subtracted from the line of interest, gives somewhat higher SIRs. Using either of these methods, the setting engineer would assume that this line is not electrically short.

TABLE III
EXAMPLE 1: VALUES FOR SIR USING THE THREE METHODS

Case	$SIR_{THEVENIN}$	SIR_{ALT}	SIR
Terminal W, $N - 0$	1.5	1.9	7.6
Terminal W, $N - 1$	1.9	2.6	14.9
Terminal E, $N - 0$	1.2	1.3	3.2
Terminal E, $N - 1$	1.6	1.8	4.8

Table IV shows the results for this line for single-line-to-ground (single-phase) faults. We can see that the line appears longer for single-phase faults. This is likely due to the presence of strong ground sources near these buses. Behind Bus E, there is a very short line to another generating station with three generator step-up transformers during $N - 0$ conditions. This line is removed for the $N - 1$ conditions for Terminal E.

TABLE IV
EXAMPLE 1: VALUES FOR SINGLE-PHASE FAULT ON REMOTE TERMINAL

Case	V_{RELAY}	I_{RELAY}	3I0	Z_S	SIR
Terminal W, $N - 0$	15.8 kV	5,888 A	6,444 A	6.6Ω	4.0
Terminal W, $N - 1$	6.6 kV	2,710 A	2,290 A	18.1Ω	10.9
Terminal E, $N - 0$	24.5 kV	10,184 A	8,027 A	3.7Ω	2.2
Terminal E, $N - 1$	16.9 kV	7,178 A	5,252 A	6.1Ω	3.7

B. Example 2: Tie Line Between Two Utilities

For this example, we have a line between Buses N and S as shown in Fig. 5, with the parameters listed in Table V. This line is a tie line supported by two strong sources on each side. For the SIR calculations, the generators behind each line terminal have been assumed to be out of service under the normal (N – 0) condition to consider worst case. An additional line (strongest source) was taken out of service when simulating the N – 1 condition.

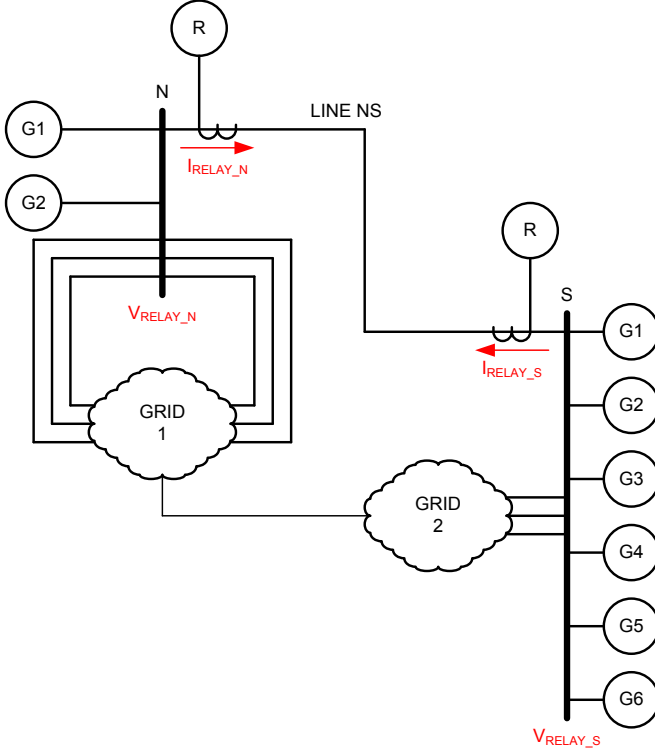


Fig. 5. Example 2: Tie Line Between Two Utilities

TABLE V
EXAMPLE 2: LINE PARAMETERS

Parameter	Value
Voltage, line-to-line	345 kV
Voltage, line-to-neutral	199.2 kV
Line length	51.25 miles
Z_{1l} primary	$31.09 \angle 84.0^\circ$
Z_{0l} primary	$90.32 \angle 73.0^\circ$
k_0	$0.644 \angle -16.76^\circ$

Accurate end user data on generator operation, maintenance, and outage cycles would typically define whether one should consider a generator in or out under a normal or contingency condition. When such data are not available or if the generators are in operation only under certain conditions, it would be best for the SIR calculation to assume them to be out of service. Also, for this example at 345 kV and other cases where a dual high-speed communications-aided protection scheme is applied to the line, it is helpful to consider them out of service for the N – 0

and N – 1 conditions. Assuming them to be out of service would typically provide the worst-case SIR and hence may result in conservative settings for the Zone 1 underreaching elements. This should help maintain security of the protection system while faults are still cleared at a high speed.

Table VI and Table VIII (shown later) show the values provided by the fault study program for a three-phase fault and single-phase fault, respectively, at the remote terminal under N – 0 and N – 1 conditions and the resultant Z_s calculated using (2), (3), and (4).

TABLE VI
EXAMPLE 2: VALUES FOR THREE-PHASE FAULT ON REMOTE TERMINAL

Case	V_{RELAY}	I_{RELAY}	Z_s	SIR
Terminal N, N – 0	128.8 kV	4,155 A	16.94Ω	0.54
Terminal N, N – 1	117.7 kV	3,802 A	29.88Ω	0.69
Terminal S, N – 0	101.3 kV	3,276 A	29.88Ω	0.96
Terminal S, N – 1	79.4 kV	2,576 A	46.5Ω	1.5

From this example, we can see that the line is very close to being classified as a long line from Terminal N and a medium length line when viewed from Terminal S. However, in both cases, due to the presence of strong sources there is little or no concern with respect to setting an underreaching element for phase faults. If these calculations had been performed with all generators in service, the line would definitely be pushed into the long line classification.

Table VII shows the SIRs calculated using the three methods for comparison. All three methods provide the correct classification of line length from both terminals. We can see here that the influence of the transfer impedance branch between the two terminals of this tie line is quite low, so all three methods provide similar results.

TABLE VII
EXAMPLE 2: VALUES FOR SIR USING THE THREE METHODS

Case	$SIR_{THEVENIN}$	SIR_{ALT}	SIR
Terminal N, N – 0	0.45	0.46	0.54
Terminal N, N – 1	0.57	0.58	0.69
Terminal S, N – 0	0.76	0.78	0.96
Terminal S, N – 1	1.15	1.19	1.5

Comparison of Table III and Table VII results indicates that the increase in SIR calculated for the recommended method versus the other methods is more pronounced in a closely coupled system because a large portion of the fault current for a remote bus fault could flow through the parallel transfer branch impedance. As the transfer branch impedance

increases, such as in this case of a tie line between two utilities, the difference in calculated SIR would be smaller.

Table VIII shows the results for this line for single-line-to-ground (single-phase) faults. Similar to results obtained for three-phase faults, there should be no concern in setting an underreaching element for ground faults.

TABLE VIII
EXAMPLE 2: VALUES FOR SINGLE-PHASE FAULT ON REMOTE TERMINAL

Case	V_{RELAY}	I_{RELAY}	$3I_0$	Z_s	SIR
Terminal N, N – 0	141.2 kV	3,375 A	1,852 A	12.7 Ω	0.4
Terminal N, N – 1	136.6 kV	3,283 A	1,764 A	14.2 Ω	0.5
Terminal S, N – 0	109.8 kV	2,719 A	1,302 A	50.1 Ω	0.8
Terminal S, N – 1	88.3 kV	2,172 A	1,085 A	38.6 Ω	1.2

VII. SUMMARY AND CONCLUSION

Identifying when a line is electrically short is important for determining the appropriate line protection scheme to apply and in determining proper margins for underreaching, unconditional trip protective elements. We want to ensure that our underreaching elements never overreach the zone of protection and trip for an external fault.

Using SIR is well established as the preferred method for determining the electrical length of a line for the purpose of setting line protective relays. The SIR is a useful way to quantify a voltage divider network that will show the relay voltage for a fault at the boundary of the zone of protection. If there is very little difference between the voltage at the relay for an in-zone versus an out-of-zone fault, instrument transformer and relay measuring errors will become significant and the relay will have difficulty in differentiating between an internal and external fault.

Distance relays use current and voltage signals to make a tripping decision. Current is an operating signal and voltage is a restraining signal. Errors in measuring the true fault voltage can result in overreach. For overcurrent relays, a high SIR will make the difference between the fault current magnitude for an in-zone fault and an out-of-zone fault less than the typical margins used in setting the overcurrent pickup.

Using SIR to determine the length of a line can create complications for the relay setting engineer. A line may be classified as short from one terminal and medium or long from the other terminal. Or, a line can be short for ground faults and medium or long for phase faults, and vice versa.

The important message is that it is often not obvious when a line should be considered short for the purpose of setting the relays. For this reason, it is important to calculate the SIR before enabling protective elements and calculating settings

for them. It is also recommended to check SIR under both N – 0 and N – 1 conditions to ensure awareness of the possible range of SIRs under differing system conditions. A line that is medium or long for system normal conditions can be short under N – 1 conditions.

The SIR > 4 boundary for a short line is not a strict boundary. It is only meant as a value over which the relay setting engineer should start being cautious about what elements can be applied for underreaching, unconditional trip protection and what margins to use.

The recommended method for calculating the SIR is to place a fault at the remote line zone boundary (the remote bus) and calculate the source impedance as the voltage drop from the so-called infinite bus to the relay divided by the current through the relay. This accurately represents the conditions that the relay will see. This method is simple to use and, with modern fault study and mathematical calculation tools, does not present a significant burden on the setting engineer to do every time.

Knowing the SIR is especially important for short lines. The traditional Thévenin equivalent impedance or the alternate method of removing the branch circuit contribution does not take into account the influence of the transfer branch impedance that connects the local and remote terminals during a remote bus fault, whereas the recommended method does. In closely coupled networks, the three methods provide significantly different results. It is important to understand that short lines, where understanding the SIR is most important, are often located in closely coupled networks. For this reason, the recommended method provides a much better indication of the electrical length of the line.

VIII. ACKNOWLEDGMENT

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