Electricity and New Energy

Distance Protection

Course Sample

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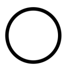
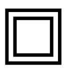
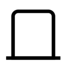
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
~	Alternating current
≂	Both direct and alternating current
3~	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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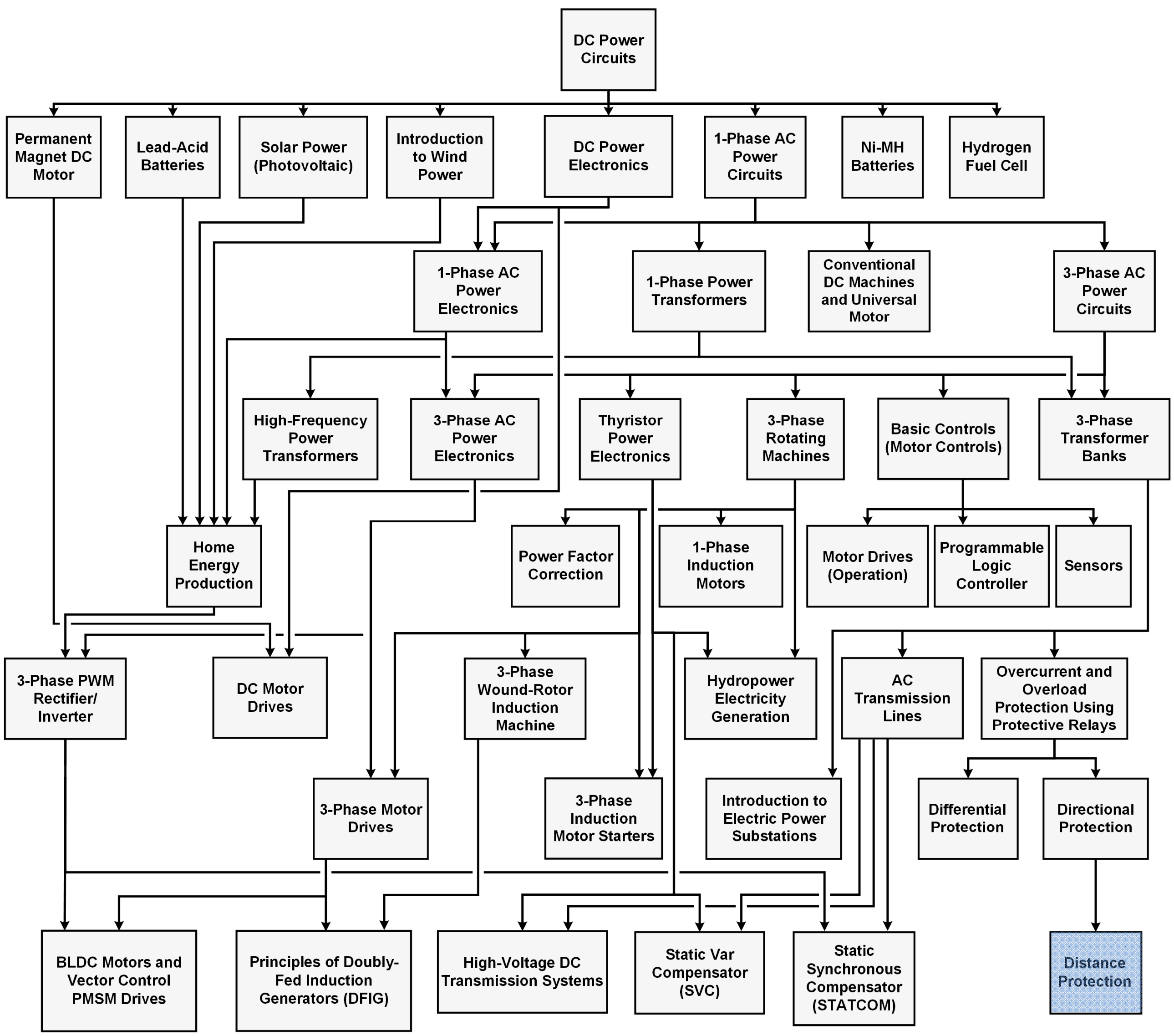
Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

Manual objectives

When you have completed this manual, you will be familiar with distance protection and how it is used to provide selective and fast clearance of faults on transmission and subtransmission lines. You will know that distance protection is based on the supervision of the power system impedance from the line ends. You will be familiar with the operation and settings of the distance relay (ANSI device no. 21) as well as with the self-polarized mho characteristic and the quadrilateral characteristic used in these relays. You will be able to relate the impedance characteristic of a distance relay to the measured fault impedance. You will also be familiar with time-stepped distance protection and know how it uses several distance zones to protect the whole length of each line segment. You will know how distance protection can be used to provide backup protection of adjacent line segments. You will understand how communication-assisted tripping schemes are implemented to allow fast clearing of faults anywhere on each line segment. You will be familiar with various communication-assisted tripping schemes used in distance protection.

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, part number 86350, *Single-Phase AC Power Circuits*, part number 86358, *Single-Phase Power Transformers*, part number 86377, *Three-Phase AC Power Circuits*, part number 86360, *Three-Phase Transformer Banks*, part number 86379, *Overcurrent and Overload Protection Using Protective Relays*, part number 52173, and *Directional Protection*, part number 52174.

Systems of units

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

Voltage symbol

Voltages are represented using the letter "E". In certain countries, the letter "U" is rather used to represent voltages.

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Sample

Extracted from

Instructor Guide

Distance Relay Impedance Characteristic

EXERCISE OBJECTIVE

In this exercise, you will become familiar with the self-polarized mho characteristic of distance relays and learn how to adjust it to protect a specific line segment. You will see the effect which the fault resistance has on the fault impedance. You will understand the effect which the fault resistance has on the reach of a distance relay having a self-polarized mho characteristic. You will become familiar with the quadrilateral characteristic of distance relays and learn how to adjust it to protect a specific line segment. You will be able to relate the impedance characteristic of a distance relay to the measured fault impedance. You will learn that distance relays take the ground impedance into account to properly interpret the impedance measured during ground faults. You will know how to test the impedance characteristic of a distance relay. You will know the relationship between the measured circuit impedance (secondary impedance) and the actual circuit impedance (primary impedance).

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Self-polarized mho characteristic
- Setting the mho characteristic of a distance relay to protect a specific line segment
- Effect of the fault resistance on the fault impedance
- Effect of the fault resistance on the reach of a distance relay with a mho characteristic
- Quadrilateral characteristic
- Setting the quadrilateral characteristic of a distance relay to protect a specific line segment
- Relationship between the measured fault impedance and the impedance characteristic of a distance relay
- Relationship between the line impedance and the ground impedance
- Testing the impedance characteristic of a distance relay
- Actual circuit impedance versus measured circuit impedance

DISCUSSION

Self-polarized mho characteristic

The relay characteristic angle is sometimes referred to as the RCA.

The **self-polarized mho characteristic** is a type of distance relay impedance characteristic that consists of a circle passing through the origin of the R-X plane, as mentioned in the introduction of this manual. Two settings in the distance relay define the self-polarized mho characteristic: the relay characteristic angle θ and the impedance reach Z_R.

The relay characteristic angle θ determines the angle of rotation of the diameter axis of the self-polarized mho characteristic from the R axis of the impedance diagram, as shown in Figure 15a. The impedance reach Z_R determines the diameter of the self-polarized mho characteristic, i.e., the reach of the distance relay along the diameter axis of the characteristic. This is illustrated in Figure 15b.

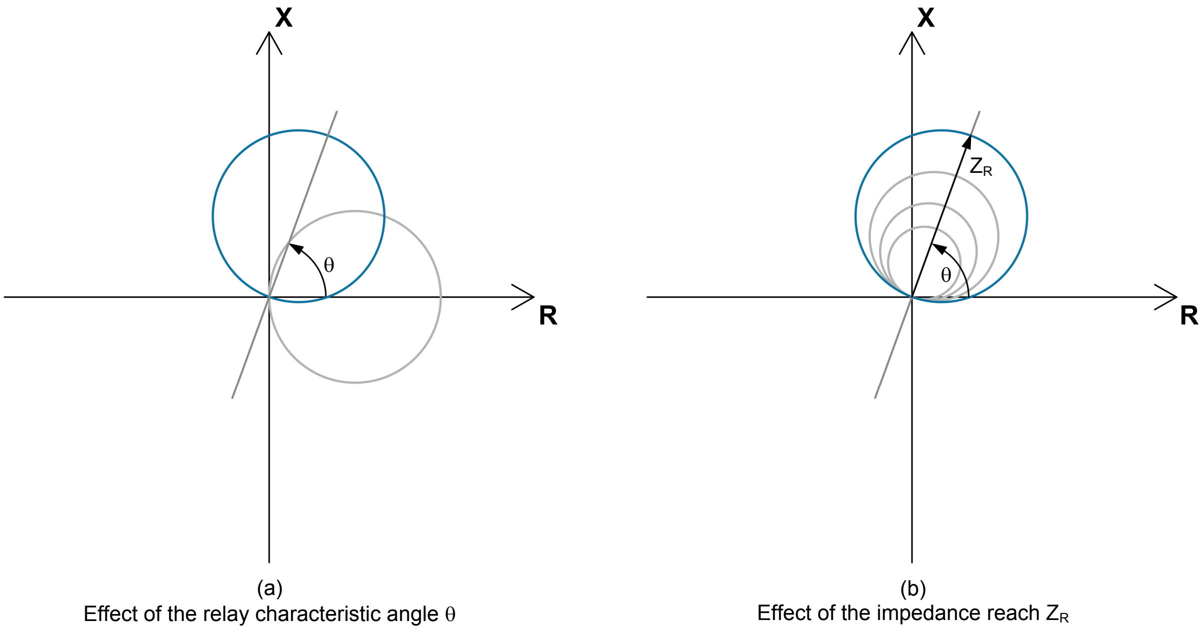


Figure 15. Settings of the relay characteristic angle θ and impedance reach Z_R in a distance relay define the self-polarized mho characteristic.

Setting the mho characteristic of a distance relay to protect a specific line segment

The relay characteristic angle θ and impedance reach Z_R of a distance relay with a self-polarized mho characteristic must be carefully adjusted to achieve proper distance protection of a specific power line. In brief, the relay characteristic angle θ is set to the value of the impedance angle θ_{Line} of the line segment to be protected. This aligns the diameter axis of the self-polarized mho characteristic with the fault impedance (Z_{Fault}) area which, in fact, is an axis when the fault resistance R_{Fault} is assumed to be null. The impedance reach Z_R is generally set to 80% of the magnitude ($|Z_{Line}|$) of the impedance of the line segment to be protected. The resulting impedance characteristic and the fault impedance area are displayed in the impedance diagram in Figure 16.

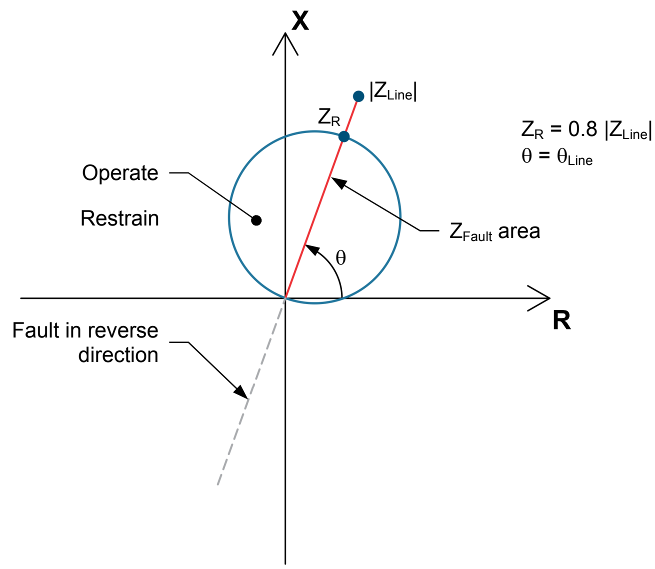
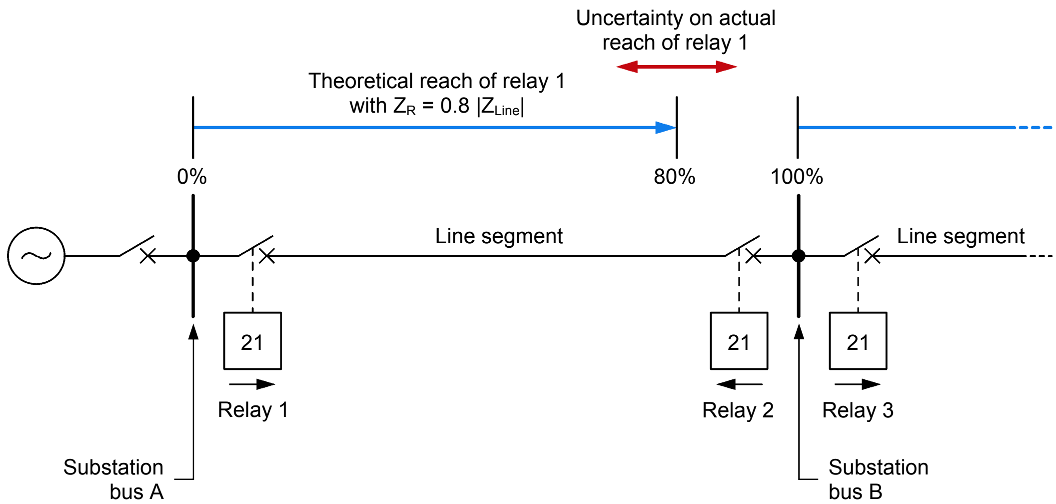


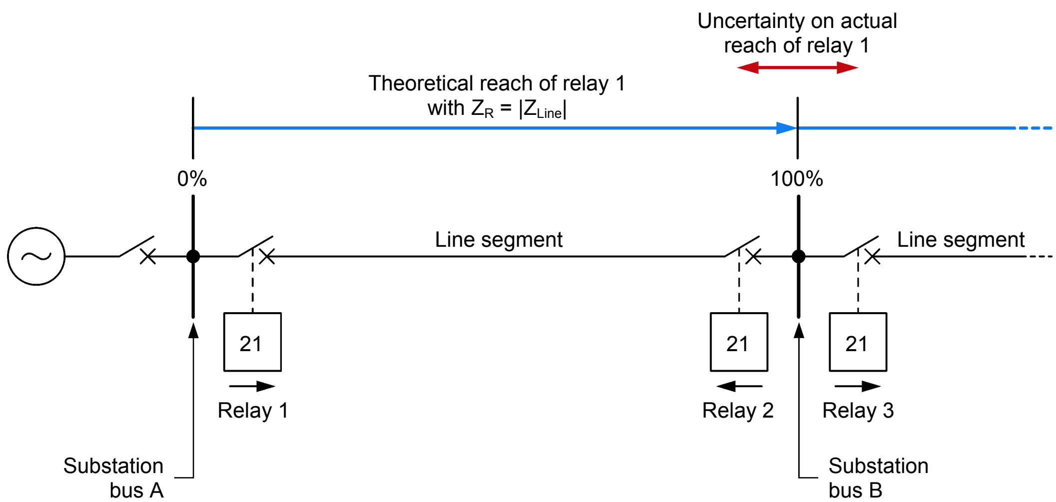
Figure 16. Self-polarized mho characteristic of a distance relay set to protect a specific line segment.

> The adjacent line segment is the segment of a power line following the line segment protected by a specific distance relay.

The primary objective of distance protection is to provide fast and selective clearance of line faults. This requires the distance relay to operate without delay, but only when it is certain that the fault is located on the line segment that it protects. In short, the distance relay must operate fast and achieve perfect selectivity. Due to the limited accuracy in the measurement of impedance by the distance relay as well as to inaccuracies in the line impedance (Z_{Line}) data, the impedance reach Z_R has to be set to a value below the magnitude $|Z_{Line}|$ of the impedance of the line segment to be protected. The purpose of such a setting is to create a safety margin ensuring that the distance relay cannot overreach, i.e., cannot detect faults located beyond the line segment that it protects (e.g., a fault located on the adjacent line segment). This is required to achieve perfect selectivity. Figure 17 shows the reach of a distance relay for settings of the impedance reach Z_R of 80% and 100% of the magnitude $|Z_{Line}|$ of the impedance of the line segment to be protected. Setting Z_R to 80% ensures that the distance relay cannot overreach even with the uncertainty on the actual reach of the relay associated with the limited accuracy of impedance measurement and inaccuracies in the line impedance (Z_{Line}) data. On the other hand, the distance relay can overreach when Z_R is set to 100%.



(a)
Relay overreach is prevented ($Z_R = 0.8\ |Z_{Line}|$)



(b)
Relay overreach is possible ($Z_R = |Z_{Line}|$)

Figure 17. Uncertainty on the actual reach of a distance relay due to the limited accuracy in the measurement of impedance and inaccuracies in the line impedance (Z_{Line}) data.

It is common practice to set the impedance reach Z_R to 80% of the magnitude ($|Z_{Line}|$) of the line segment impedance to create a safety margin ensuring that the distance relay cannot overreach. However, setting the impedance reach Z_R to a value below the magnitude $|Z_{Line}|$ of the line segment impedance leaves a certain portion of the line segment unprotected. In the case of distance protection applied to a radial feeder, the remote end of each line segment is left unprotected. For instance, when the impedance reach Z_R is set to 80% of the magnitude $|Z_{Line}|$ of the line segment impedance, a portion equal to 20% of the line segment length is left unprotected at the remote end of each line segment, as shown in Figure 18.

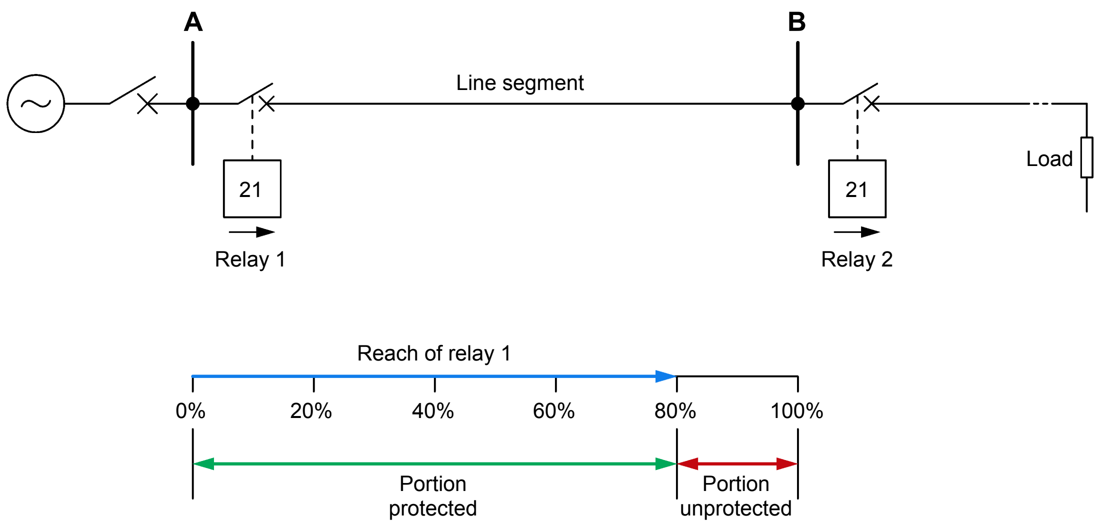


Figure 18. Portion of each line segment left unprotected when distance protection is applied to a radial feeder.

The situation is even worst when distance protection is applied to a power line used in a meshed network. In this case, the distance relays at both ends of a line segment must operate to clear a fault. Assuming that the impedance reach Z_R is still set to 80% of the magnitude $|Z_{Line}|$ of the line segment impedance, this results in a portion of 20% of the line segment length that is left unprotected at both ends of each line segment, as shown in Figure 19. Consequently, only the center portion of each line segment between 20% and 80% is protected.

Of course, leaving any portion of a line segment unprotected is not acceptable. This problem is resolved by adding a second **measuring element** that covers the whole length of the line segment to be protected. This is explained in further details in the next exercise of this manual.

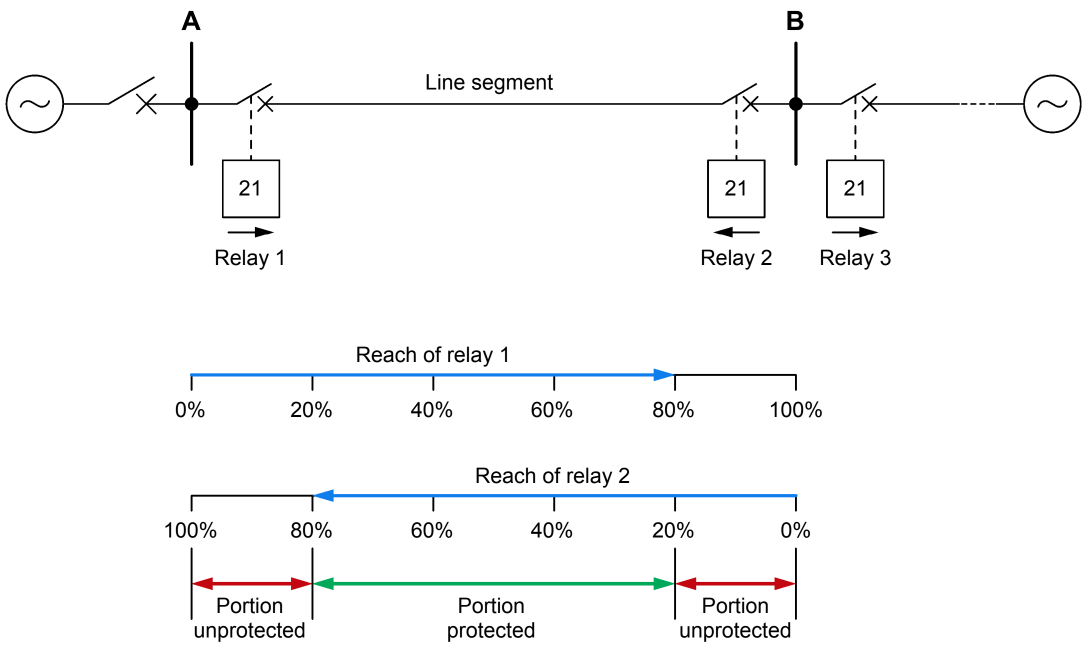


Figure 19. Portions of each line segment left unprotected when distance protection is applied to a power line in a meshed network.

Effect of the fault resistance on the fault impedance

The fault impedance area is an axis passing through the origin of the impedance diagram whose length and tilt depends on the magnitude ($|Z_{Line}|$) and angle (θ_{Line}) of the impedance Z_{Line} ($R_{Line} + jX_{L\ Line}$) of the line segment to be protected, as mentioned earlier in this manual. This holds true as long as the fault resistance R_{Fault} is null. This is usually the case for phase-to-phase faults which are generally caused by direct accidental contact of two conductors of different phases in a power system. Such faults are reliably detected by distance relays with a self-polarized mho characteristic, as explained in the previous section of this discussion.

On the other hand, the fault resistance R_{Fault} is often not null during phase-to-ground faults (commonly called ground faults). For instance, arcing can occur during a ground fault. From an electrical standpoint, arcing is equivalent to pure resistance. Furthermore, the conductivity of the fault path to ground can also contribute in increasing the fault resistance R_{Fault}. Figure 20 shows the effect of the fault resistance R_{Fault} on the fault impedance Z_{Fault} for ground faults at two different locations on a power line. The fault resistance R_{Fault} adds vectorially to the impedance $Z_{Line\ Fault}$ up to the fault location. This increases the magnitude of the fault impedance Z_{Fault} and decreases the angle φ of the fault impedance Z_{Fault}. Also notice that the fault resistance displaces the fault area axis horizontally toward the right of the diagram, the length of the displacement being proportional to the fault resistance R_{Fault}.

When referring to Earth, the word “earth” is used in British English, whereas the word “ground” is used in American English. The word “ground” is used throughout this manual.

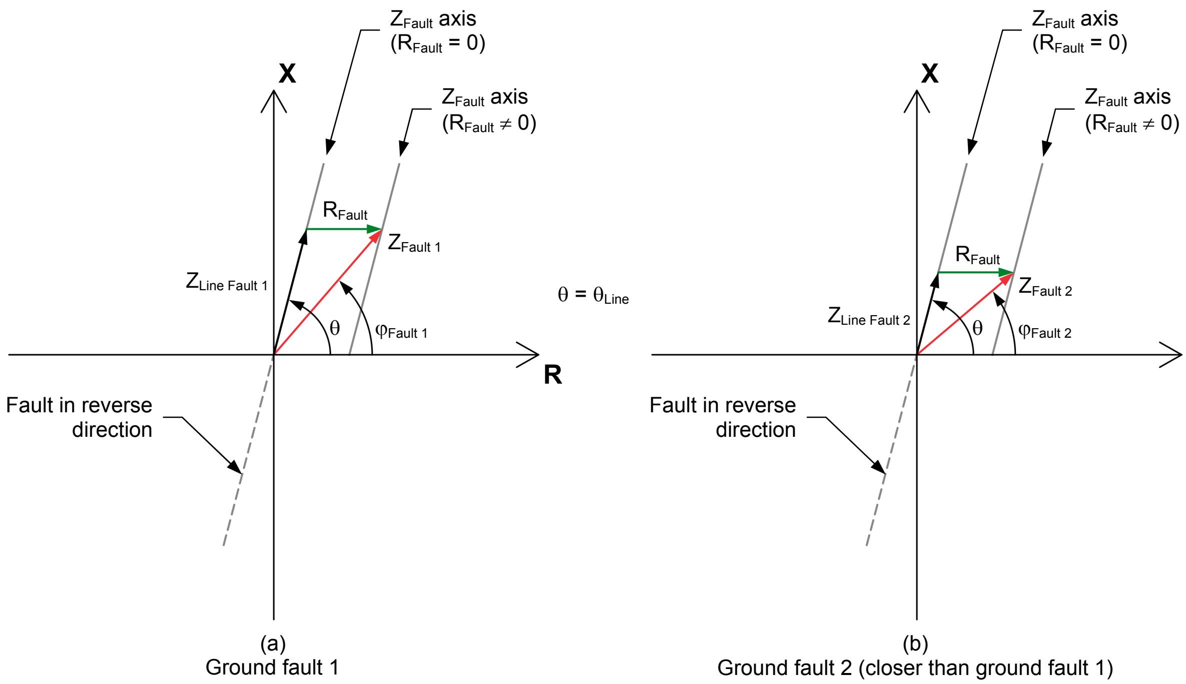


Figure 20. Effect of the fault resistance R_{Fault} on the fault impedance Z_{Fault} for ground faults at two different locations on a power line.

The value of the fault resistance R_{Fault} during ground faults is generally variable (due to arcing) and hard to predict, thereby causing uncertainty on the location of the fault impedance axis. To take into account the effect of the fault resistance R_{Fault} on the fault impedance Z_{Fault}, the fault impedance area is commonly shown as a box on the impedance diagram, as shown in Figure 21.

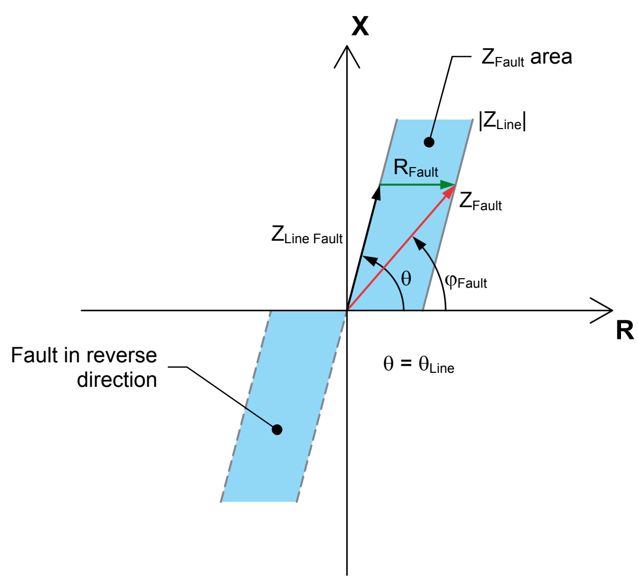


Figure 21. Fault impedance (Z_{Fault}) area including the effect of the fault resistance R_{Fault}.

The fault resistance R_{Fault} observed during ground faults can prevent reliable detection of these faults when its value is similar to the magnitude ($|Z_{Line}|$) of the impedance of the line segment to be protected. This is discussed in detail in the next section of this discussion.

Effect of the fault resistance on the reach of a distance relay with a mho characteristic

The impedance diagram in Figure 22 shows the effect which the fault resistance R_{Fault} has on the actual reach of a distance relay with a self-polarized mho characteristic. In this example, the protected line segment is assumed to be long which means that the magnitude ($|Z_{Line}|$) of the line segment impedance is several times the fault resistance R_{Fault}. Consequently, the horizontal displacement of the fault impedance (Z_{Fault}) axis due to the fault resistance R_{Fault} is moderate when compared to the diameter of the mho characteristic of the distance relay. This, however, is sufficient to slightly decrease the actual reach of the distance relay, as shown in Figure 22. Fortunately, the loss of reach in this situation is acceptable because it does not prevent the distance relay from detecting ground faults over the major portion of the protected line segment.

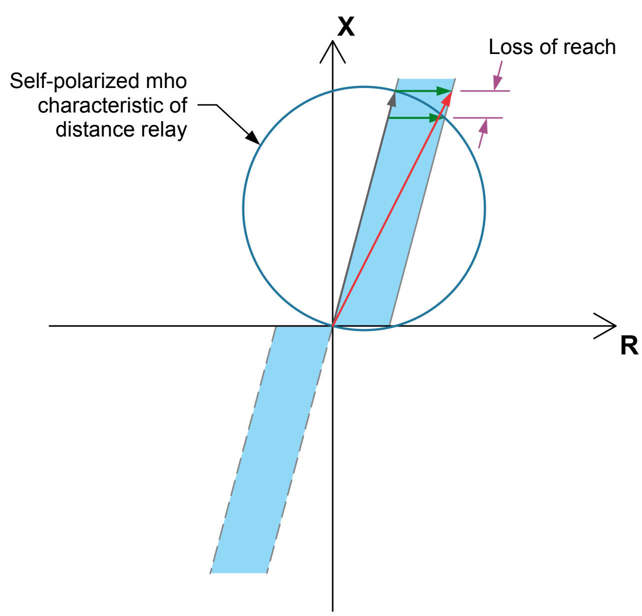
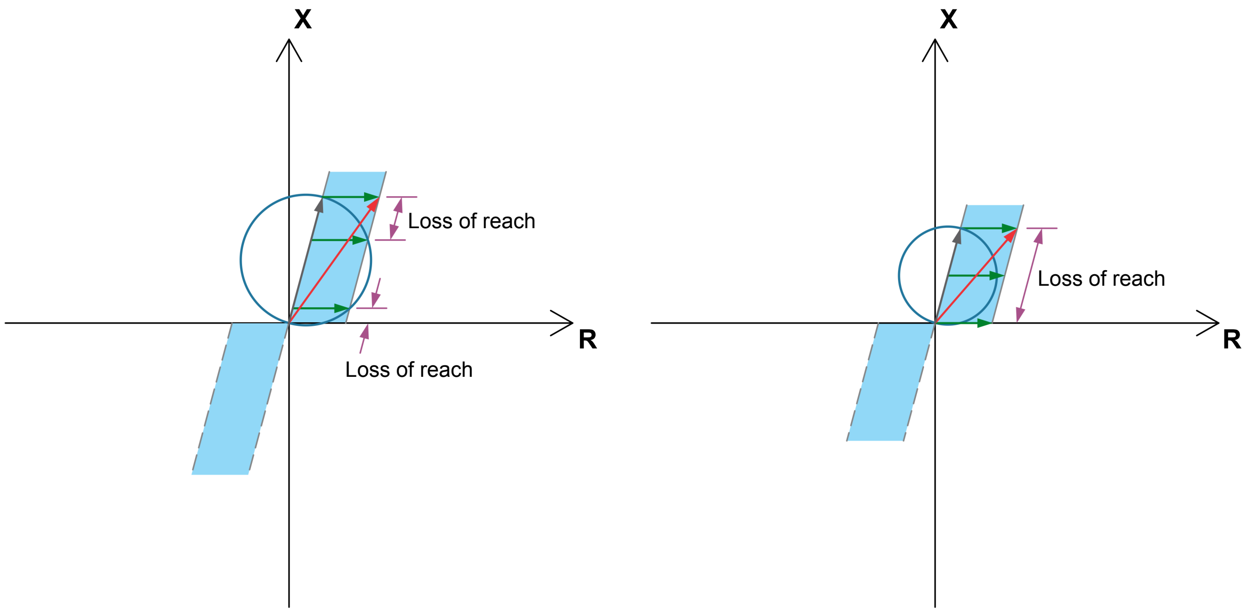


Figure 22. The fault resistance R_{Fault} has a limited effect on the actual reach of a distance relay protecting a long line segment.

When the length of the protected line segment decreases, the magnitude ($|Z_{Line}|$) of the line segment impedance also decreases and the impedance reach Z_R of the distance relay has to be decreased accordingly. This decreases the diameter of the self-polarized mho characteristic of the distance relay. Thus, the horizontal displacement of the fault impedance (Z_{Fault}) axis due to the fault resistance R_{Fault} (relative to the diameter of the mho characteristic) becomes more important, as shown in Figure 23a. Consequently, this increases the effect which the fault resistance R_{Fault} has on the actual reach of the distance relay. In the example given in Figure 23a, the decrease in the actual reach of the distance relay is important. Furthermore, ground faults occurring at the end of the line segment close to the distance relay are not detected because the fault resistance R_{Fault} causes the fault impedance Z_{Fault} to be outside the self-polarized mho characteristic of the relay. A loss of reach thus occurs at both ends of the line segment. This means that the distance relay is no longer reliable in detecting a ground fault on the protected line segment when its length decreases to the point that the magnitude ($|Z_{Line}|$) of the line segment impedance approaches the value of the fault resistance R_{Fault}.



(a)
Medium line segment
The fault resistance R_{Fault} reduces the actual reach of a distance relay as the length of the protected line segment decreases.

(b)
Short line segment
The fault resistance R_{Fault} can prevent a distance relay from detecting any ground fault.

Figure 23. The fault resistance R_{Fault} has a larger effect on the actual reach of a distance relay protecting a medium or a short line segment.

When the line segment to be protected is short, a distance relay can even fail to detect ground faults on the whole line segment, as shown in Figure 23b. In such a case, the fault resistance R_{Fault} is similar to or higher than the magnitude ($|Z_{Line}|$) of the line segment impedance. Consequently, the horizontal displacement of the fault impedance (Z_{Fault}) axis due to the fault resistance R_{Fault} is so important that the fault impedance Z_{Fault} for a ground fault located anywhere on the line segment lies outside the self-polarized mho characteristic of the distance relay.

To conclude, distance relays with a self-polarized mho characteristic are well suited to detect ground faults on medium-length and long line segments, i.e., line segments where the magnitude ($|Z_{Line}|$) of the line segment impedance is definitely larger than the fault resistance R_{Fault}. On the other hand, these distance relays are not suitable to detect ground faults on short line segments, i.e., line segments where the fault resistance R_{Fault} is significant with respect to the magnitude ($|Z_{Line}|$) of the line segment impedance. The solution to this problem is described in the next section of this discussion.

Quadrilateral characteristic

The self-polarized mho characteristic is not well suited to detect ground faults on short line segments, as explained in the previous section of this discussion. In this case, another type of impedance characteristic, such as the quadrilateral characteristic, should be used in the distance relay. A **quadrilateral characteristic** has a quadrilateral shape, as indicated by its name. The following three settings are commonly available in distance relays to define the quadrilateral characteristic: the relay characteristic angle θ, the reactive (X) reach, and the resistive (R) reach. The relay characteristic angle θ determines the tilt of the left and right side of the quadrilateral characteristic, as shown in Figure 24.

The quadrilateral characteristics shown in this manual have a generic shape. The shape of the quadrilateral characteristic in a specific distance relay may differ slightly from the generic shape used in this manual. This mainly depends on the way the characteristic is implemented in the relay. Also, additional settings may be available in certain relays.

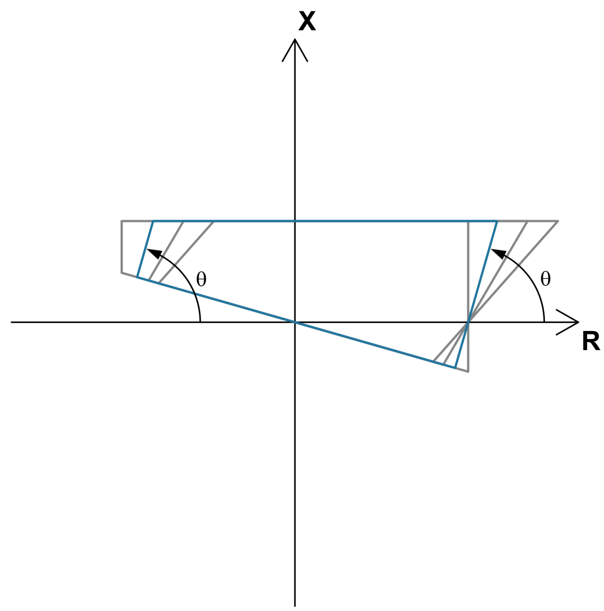


Figure 24. The characteristic angle θ of the distance relay determines the tilt of the left and right sides of the quadrilateral characteristic.

The reactive (X) reach determines the height of the quadrilateral characteristic along the reactance (X) axis of the impedance diagram, as shown in Figure 25a. The resistive (R) reach determines the width of the quadrilateral characteristic along the resistance (R) axis of the impedance diagram, as shown in Figure 25b.

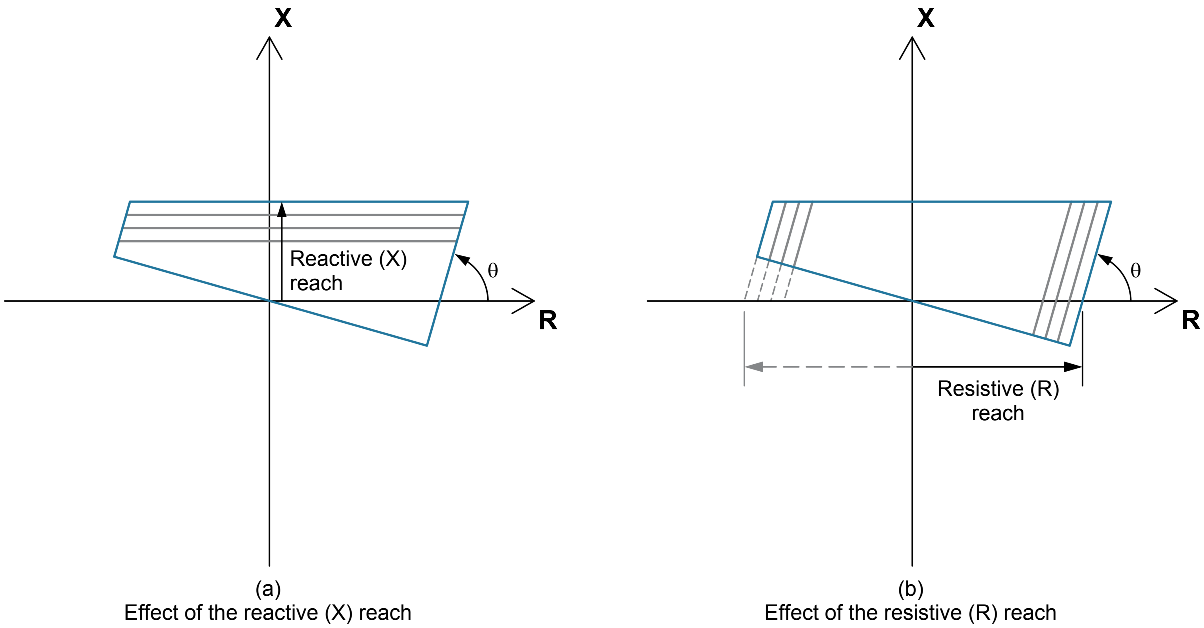


Figure 25. The reactive (X) reach and the resistive (R) reach respectively determine the height and width of the quadrilateral characteristic.

The quadrilateral characteristic is perfectly suited to detect ground faults on short line segments, because the resistive (R) reach can be set independently of the reactive (X) reach. This allows the fault resistance to be accounted for without affecting the reach of the distance relay. The next section of this discussion shows how to adjust the quadrilateral characteristic of a distance relay to protect a specific line segment.

Setting the quadrilateral characteristic of a distance relay to protect a specific line segment

The relay characteristic angle θ, the reactive (X) reach, and the resistive (R) reach of a distance relay with a quadrilateral characteristic must be carefully adjusted to achieve proper distance protection of a specific power line while taking the fault resistance R_{Fault} into account. Figure 26 shows the quadrilateral characteristic of a distance relay set to protect a specific line segment.

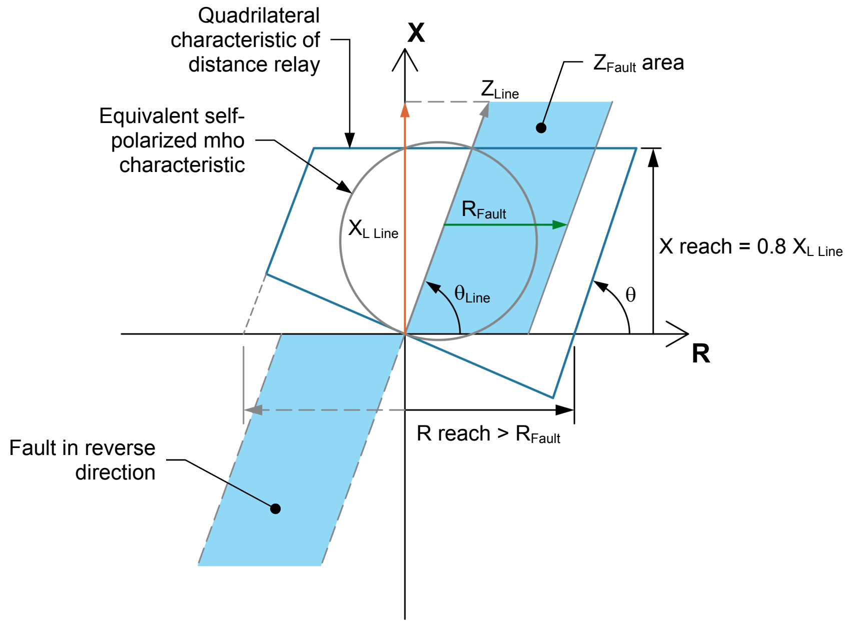


Figure 26. Quadrilateral characteristic of a distance relay set to protect a specific line segment.

The relay characteristic angle θ is set to the value of the impedance angle θ_{Line} of the line to be protected. This makes the tilt of the left and right sides of the quadrilateral characteristic the same as the tilt of the left and right sides of the fault impedance (Z_{Fault}) area. The reactive (X) reach, which sets the height of the quadrilateral characteristic, is generally set to 80% of the inductive reactance $X_{L\ Line}$ of the line segment to be protected. This ensures that the distance relay cannot overreach. Finally, the resistive (R) reach, which sets the width of the quadrilateral characteristic, is set to a value that exceeds the fault resistance R_{Fault} expected during ground faults. This ensures that the quadrilateral characteristic is wide enough to cover the entire fault impedance (Z_{Fault}) area expected. The fault resistance R_{Fault} is a parameter that is hard to estimate and whose value varies depending on the fault conditions. This explains why the resistive (R) reach is set to a value that exceeds the fault resistance R_{Fault} that is expected. Notice that contrary to the quadrilateral characteristic, a self-polarized mho characteristic having the same reach (see light-grey circle in Figure 26) does not cover the entire fault impedance area up to the selected reach.

During phase-to-phase faults, the fault resistance is generally null or close to zero. Consequently, the fault impedance (Z_{Fault}) area of phase-to-phase faults is significantly smaller than that of ground faults. This means that a quadrilateral characteristic with a considerably smaller area is sufficient to detect phase-to-phase faults. Certain distance relays have two resistive (R) reach settings for this purpose: one for ground faults and one for phase-to-phase faults. This is illustrated in Figure 27.

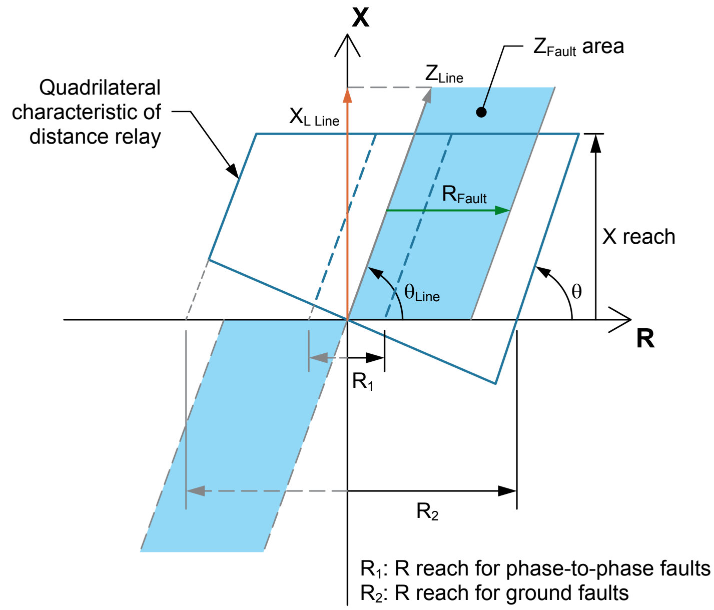
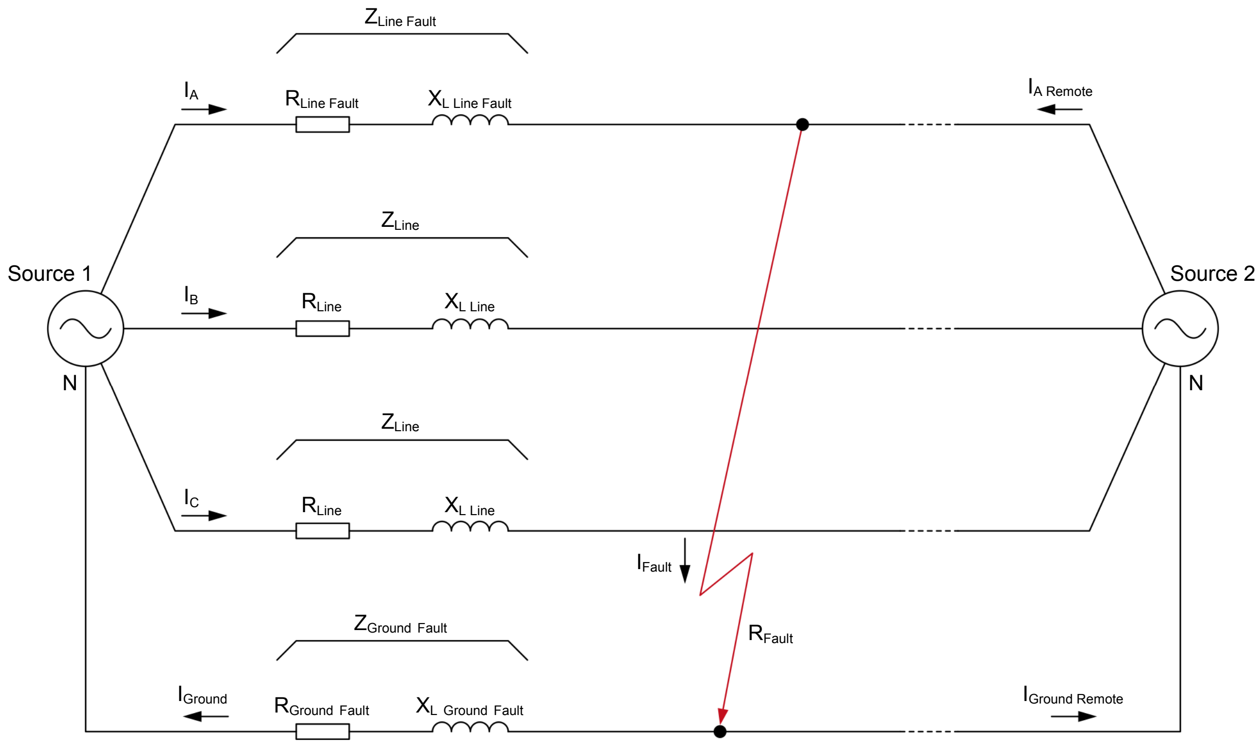


Figure 27. Certain distance relays have two resistive (R) reach settings: one for ground faults and one for phase-to-phase faults.

To summarize, the reactive (X) and resistive (R) settings of the quadrilateral characteristic make it a little more flexible than the self-polarized mho characteristic. Consequently, distance relays with a quadrilateral characteristic can be used to reliably detect ground faults and phase-to-phase faults on line segments of any reasonable lengths. On the other hand, distance relays with a self-polarized mho characteristic can also be used to detect all faults mentioned above except ground faults on short line segments. Despite this limitation, distance relays with a self-polarized mho characteristic are still widely used where applicable. The choice between distance relays with a self-polarized mho characteristic and distance relays with a quadrilateral characteristic often depends on the locally-established practice regarding line protection engineering.

Relationship between the measured fault impedance and the impedance characteristic of a distance relay

The circuit diagram in Figure 28 shows the flow of currents when a ground fault occurs on phase A of a power line in a meshed network (i.e., a line powered at both ends). Notice that the power source at each end of the line contributes to the fault current I_{Fault}. Also, notice that the ground fault unbalances the line currents thereby causing current to flow at the neutral of each power source. These neutral currents flow via the ground. The impedance $Z_{Ground\ Fault}$ in the diagram represents the impedance of the ground between power source 1 and the location of the ground fault.



$$\vec{I}_{Fault} = \vec{I}_A + \vec{I}_{A\,Remote}$$

$$\vec{I}_{Ground} = \vec{I}_A + \vec{I}_B + \vec{I}_C \neq 0\ \text{A} \qquad \vec{I}_{Ground\,Remote} = \vec{I}_{A\,Remote} - \vec{I}_B - \vec{I}_C \neq 0\ \text{A}$$

Figure 28. Flow of currents when a ground fault occurs on phase A of a power line in a meshed network.

The voltage E_A across the faulty phase of the line is given by Equation (1):

$$\vec{E}_A = \vec{Z}_{Line\,Fault}\,\vec{I}_A + \vec{R}_{Fault}\left(\vec{I}_A + \vec{I}_{A\,Remote}\right) + \vec{Z}_{Ground\,Fault}\left(\vec{I}_A + \vec{I}_B + \vec{I}_C\right) \tag{1}$$

The fault impedance $\vec{Z}_{Fault}$ measured by a distance relay located at the line end close to power source 1 can be calculated using Equation (2):

$$\begin{aligned}\vec{Z}_{Fault} &= \frac{\vec{E}_A}{\vec{I}_A} \\ &= \vec{Z}_{Line\,Fault} + \frac{\vec{R}_{Fault}\left(\vec{I}_A + \vec{I}_{A\,Remote}\right)}{\vec{I}_A} + \frac{\vec{Z}_{Ground\,Fault}\left(\vec{I}_A + \vec{I}_B + \vec{I}_C\right)}{\vec{I}_A}\end{aligned} \tag{2}$$

The impedance obtained using Equation (2) is not really meaningful. However, let's assume that there is no power source nor load at the remote end of the line (i.e., at the end of the line, close to power source 2 in Figure 28). This is representative of the situation that prevails when testing the impedance characteristic of a distance relay, as explained later in this discussion. Making this assumption zeroes currents $I_{A\ Remote}$, I_B, and I_C in the above equations. The voltage E_A across the faulty phase of the line thus becomes:

$$\begin{aligned} E_A &= \vec{Z}_{Line\ Fault}\,\vec{I}_A + \vec{R}_{Fault}\,\vec{I}_A + \vec{Z}_{Ground\ Fault}\,\vec{I}_A \\ &= \vec{I}_A\left(\vec{Z}_{Line\ Fault} + \vec{R}_{Fault} + \vec{Z}_{Ground\ Fault}\right) \end{aligned} \tag{3}$$

Consequently, the fault impedance Z_{Fault} measured by the distance relay can be calculated using Equation (4):

$$\begin{aligned} \vec{Z}_{Fault} &= \frac{\vec{E}_A}{\vec{I}_A} = \frac{\vec{I}_A\left(\vec{Z}_{Line\ Fault} + \vec{R}_{Fault} + \vec{Z}_{Ground\ Fault}\right)}{\vec{I}_A} \\ &= \vec{Z}_{Line\ Fault} + \vec{R}_{Fault} + \vec{Z}_{Ground\ Fault} \end{aligned} \tag{4}$$

Equation (4) means that the fault impedance Z_{Fault} measured by the distance relay is equal to the sum of the line impedance $Z_{Line\ Fault}$ up to the fault location, the fault resistance R_{Fault}, and the ground impedance $Z_{Ground\ Fault}$ up to the fault location. This corresponds to what is expected when it is assumed that there is no power source nor load at the remote end of the line. This fact must be taken into account when testing the impedance characteristic of a distance relay by emulating voltage and currents corresponding to a ground fault and assuming there is no power source nor load at the remote end of the line, as explained later in this discussion. Remember that the impedance reach Z_R and relay characteristic angle θ of a distance relay with a self-polarized mho characteristic, which define the size and position of the characteristic on the impedance diagram, are set as a function of the line impedance Z_{Line} only (i.e., it does not take into account the ground impedance Z_{Ground}). Similarly, the reactive (X) reach of a distance relay with a quadrilateral characteristic, which defines the height of the characteristic on the impedance diagram, is set as a function of the line inductive reactance $X_{L\ Line}$ only (it does not take into account the ground inductive reactance $X_{L\ Ground}$). This is further discussed later in this discussion.

Relationship between the line impedance and the ground impedance

The impedance Z_{Ground} of the ground where a power line passes is not equal to the impedance Z_{Line} of the power line. The line impedance Z_{Line} and the ground impedance Z_{Ground} are related by the vector K_0 as follows:

$$\vec{K}_0 = \frac{\vec{Z}_{Ground}}{\vec{Z}_{Line}} \tag{5}$$

where $\vec{K}_0$ is the vector relating the impedance of a specific power line to the ground impedance.

$\vec{Z}_{Ground}$ is the impedance ($R_{Ground} + jX_{L\ Ground}$) of the ground where the line considered passes.

$\vec{Z}_{Line}$ is the impedance ($R_{Line} + jX_{L\ Line}$) of the line considered.

The relationship between the line impedance Z_{Line} and the ground impedance Z_{Ground} can also be expressed using two scalar factors: K_R and K_X. Factor K_R relates the line resistance R_{Line} to the ground resistance R_{Ground} as follows:

$$K_R = \frac{R_{Ground}}{R_{Line}} \tag{6}$$

where K_R is the scalar factor relating the resistance of a specific power line to the ground resistance.

R_{Ground} is the resistance of the ground where the line considered passes.

R_{Line} is the resistance of the line considered.

Factor K_X relates the line inductive reactance $X_{L\ Line}$ to the ground inductive reactance $X_{L\ Ground}$ as follows:

$$K_X = \frac{X_{L\ Ground}}{X_{L\ Line}} \tag{7}$$

where K_X is the scalar factor relating the inductive reactance of a specific power line to the ground inductive reactance.

$X_{L\ Ground}$ is the inductive reactance of the ground where the line considered passes.

$X_{L\ Line}$ is the inductive reactance of the line considered.

For instance, when the line impedance Z_{Line} is 20 Ω ∠80° (3.47 + j19.7) Ω and the ground impedance Z_{Ground} is 15 Ω ∠70° (5.13 + j14.1) Ω, vector K_0 is equal to 0.75 ∠-10° while factors K_R and K_X are equal to 1.48 and 0.72, respectively.

Referring to what has been demonstrated in the previous section of this discussion, the fault impedance Z_{Fault} measured by a distance relay during a ground fault is equal to the sum of the line impedance $Z_{Line\ Fault}$ up to the fault location, the fault resistance R_{Fault}, and the ground impedance $Z_{Ground\ Fault}$ up to the fault location. Consequently, the distance relay needs to know the line impedance Z_{Line} and the ground impedance Z_{Ground} to properly interpret the fault impedance Z_{Fault} that it measures during a ground fault, i.e., to correctly determine whether or not the ground fault is within the set reach. The relay characteristic angle θ and either the impedance reach Z_R or the reactive (X) reach set in the distance relay provide the necessary information about the line impedance Z_{Line}. These settings, however, provide no information about the ground impedance Z_{Ground}. For this purpose, distance relays generally have settings for either vector K_0 or scalar factors K_R and K_X. With the values of the relay characteristic angle θ, the impedance reach Z_R or the reactive (X) reach, and the vector K_0 or the scalar factors K_R and K_X, the distance relay has all the information required to properly interpret the fault impedance Z_{Fault} that it measures during a ground fault.

Testing the impedance characteristic of a distance relay

The impedance characteristic of a distance relay can be tested by applying currents and voltages at the relay inputs that are similar to those measured during a ground fault. To make the test procedure as simple as possible, it is assumed that there is no power source nor load at the remote end of the protected line. Table 1 is an example of the initial values of the currents and voltages applied to the inputs of the distance relay to emulate a ground fault on phase A.

Table 1. Initial values of the currents and voltages applied to the inputs of a distance relay to emulate a ground fault on phase A.

Currents			Voltages		
I_A (A, ∠°)	I_B (A, ∠°)	I_C (A, ∠°)	E_A (V, ∠°)	E_B (V, ∠°)	E_C (V, ∠°)
0.1 ∠0°	0	0	30 ∠0°	30 ∠-120°	30 ∠120°

In this example, the nominal voltage and current of the distance relay inputs are 100 V and 1 A, respectively. The magnitude of current I_A is initially set to a low value to emulate a ground fault whose impedance is outside the impedance characteristic of the distance relay, i.e., a ground fault located beyond the reach of the distance relay. The phase angle of current I_A is set so that the ground fault is in the forward direction. Currents I_B and I_C are null because it is assumed that there is no power source nor load at the remote end of the line. Voltages E_A, E_B, and E_C are balanced, but their magnitude is set to a value that is relatively low with respect to the nominal voltage (100 V) of the relay inputs. This has the positive effect of lowering the magnitude of the fault current required to make the distance relay trip.

The magnitude of current I_A is then slowly increased to make the fault impedance Z_{Fault} decrease gradually. This eventually makes the distance relay trip. The magnitude and phase angle of current I_A at the moment the distance relay trips are recorded, then the magnitude of current I_A is set back to its initial value. The fault impedance Z_{Fault} that made the distance relay trip is calculated using the recorded magnitude and phase angle of current I_A and the magnitude and phase angle of voltage E_A.

The fault impedance Z_{Fault} obtained above represents a single point on the impedance characteristic of the distance relay. Other points on the impedance characteristic of the distance relay are tested by changing the phase angle of current I_A and then repeating the steps described in the previous paragraph. Table 2 is an example of the results obtained when testing the impedance characteristic of a distance relay.

Table 2. Example of the results obtained when testing the impedance characteristic of a distance relay.

E_A (V, ∠°)	I_A (A, ∠°)	Z_{Fault} (Ω, ∠°)
30 ∠0°	1.463 ∠0°	20.5 ∠0°
30 ∠0°	1.000 ∠-10°	30.0 ∠10°
30 ∠0°	0.777 ∠-20°	38.6 ∠20°
30 ∠0°	0.652 ∠-30°	46.0 ∠30°
30 ∠0°	0.577 ∠-40°	52.0 ∠40°
30 ∠0°	0.532 ∠-50°	56.4 ∠50°
30 ∠0°	0.508 ∠-60°	59.1 ∠60°
30 ∠0°	0.500 ∠-70°	60.0 ∠70°
30 ∠0°	0.508 ∠-80°	59.1 ∠80°
30 ∠0°	0.532 ∠-90°	56.4 ∠90°
30 ∠0°	0.577 ∠-100°	52.0 ∠100°
30 ∠0°	0.652 ∠-110°	46.0 ∠110°

Alternatively, the magnitude of voltage E_A can be decreased while the magnitude of current I_A is kept constant to gradually decrease the fault impedance Z_{Fault} and eventually make the distance relay trip. Table 3 is an example of the initial values of the currents and voltages applied to the inputs of the distance relay to emulate a ground fault on phase A when this alternate testing method is used. It is still assumed that the nominal voltage and current of the distance relay inputs are 100 V and 1 A, respectively.

Table 3. Initial values of the currents and voltages applied to the inputs of a distance relay to emulate a ground fault on phase A (alternate testing method).

Currents			Voltages		
I_A (A, ∠°)	I_B (A, ∠°)	I_C (A, ∠°)	E_A (V, ∠°)	E_B (V, ∠°)	E_C (V, ∠°)
1.0 ∠0°	0	0	100 ∠0°	100 ∠-120°	100 ∠120°

The magnitude of current I_A and the magnitude of voltage E_A are initially set to their respective nominal values to emulate a ground fault whose impedance is outside the impedance characteristic of the distance relay. Then, the magnitude of voltage E_A is slowly decreased to make the fault impedance Z_{Fault} decrease gradually until the distance relay trips. The magnitude and phase angle of voltage E_A at the moment the distance relay trips are recorded then the magnitude of voltage E_A is set back to its initial value. The fault impedance Z_{Fault} that made the distance relay trip is calculated using the recorded magnitude and phase angle of voltage E_A and the magnitude and phase angle of current I_A.

The impedance characteristic of a distance relay is defined by the relay characteristic angle θ and reach [either the impedance reach Z_R or the reactive (X) reach], both parameters being set as a function of the line impedance Z_{Line} only. On the other hand, the fault impedance Z_{Fault} measured by a distance relay during a ground fault is equal to the sum of the line impedance $Z_{Line\ Fault}$ up to the fault location, the fault resistance R_{Fault}, and the ground impedance $Z_{Ground\ Fault}$ up to the fault location, as mentioned earlier in this discussion. Consequently, care must be exercised when determining whether or not the measured values of the fault impedance Z_{Fault} at which the distance relay trips are in accordance with the relay settings. For instance, let us consider a distance relay with a self-polarized mho characteristic and the following settings:

- Relay characteristic angle θ: 85°
- Impedance reach Z_R: 80 Ω
- Vector K_0: 0.8°∠-20°

The resulting impedance characteristic of the distance relay is shown in Figure 29.

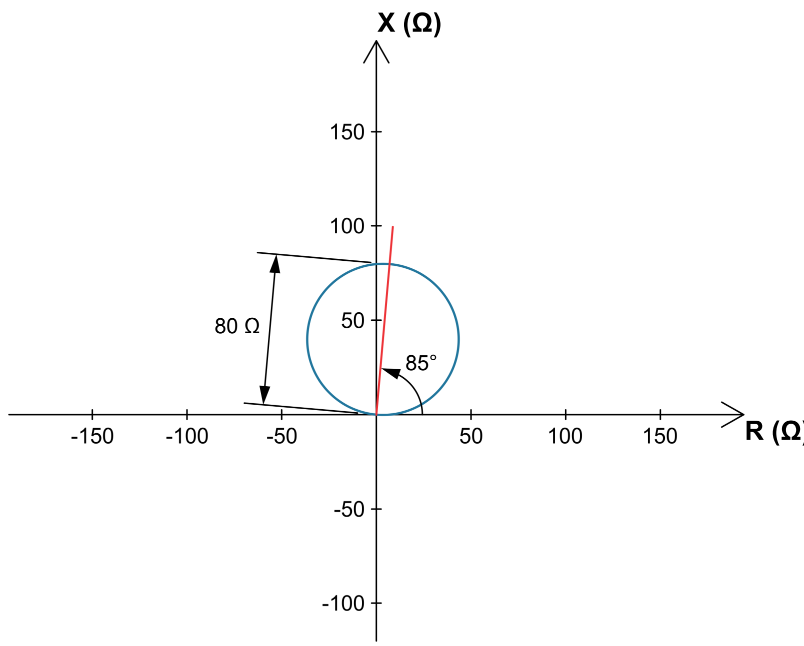


Figure 29. Self-polarized mho characteristic of a distance relay determined from the relay characteristic angle θ and impedance reach Z_R.

When it is assumed that the fault resistance R_{Fault} is null, the fault impedance Z_{Fault} measured by the distance relay during a ground fault is equal to the sum of the line impedance $Z_{Line\ Fault}$ up to the fault location and the ground impedance $Z_{Ground\ Fault}$ up to the fault location. The line impedance $Z_{Line\ Fault\ Limit}$ for a ground fault located at the limit of the impedance characteristic of the distance relay is as follows:

$$\vec{Z}_{Line\ Fault\ Limit} = Z_R \angle\theta \quad (8)$$

$$= (80\ \Omega\ \angle 85°) = (6.97 + j79.7)\ \Omega$$

Also, the ground impedance $Z_{Ground\ Fault\ Limit}$ for a ground fault located at the limit of the impedance characteristic of the distance relay is calculated as follows:

$$\vec{Z}_{Ground\ Fault\ Limit} = \vec{Z}_{Line\ Fault\ Limit}\ \vec{K}_0 \tag{9}$$

$$= (80\ \Omega\ \angle 85°)\ (0.8\ \angle\text{-}20°) = 64\ \Omega\ \angle 65° = (27.05 + j58.0)\ \Omega$$

Finally, the fault impedance $Z_{Fault\ Limit}$ for a ground fault at the limit of the impedance characteristic of the distance relay is calculated as follows:

$$\vec{Z}_{Fault\ Limit} = \vec{Z}_{Line\ Fault\ Limit} + \vec{Z}_{Ground\ Fault\ Limit} \tag{10}$$

$$= (6.97 + j79.7)\ \Omega + (27.05 + j58.0)\ \Omega = (34.02 + j137.7)\ \Omega = 142\ \Omega\ \angle 76.1°$$

The vector corresponding to the fault impedance $Z_{Fault\ Limit}$ calculated above is shown in the impedance diagram of Figure 30. The impedance characteristic of the distance relay, based on the fault impedance Z_{Fault} measured by the relay during ground faults, is a circle whose diameter axis corresponds to the vector representing fault impedance $Z_{Fault\ Limit}$. This impedance characteristic must be used to determine whether or not the measured values of the fault impedance Z_{Fault} at which the distance relay trips are in accordance with the relay settings. Notice that the mho characteristic based on the fault impedance Z_{Fault} measured by the relay during ground faults is larger and a little more tilted than the mho characteristic determined from the relay characteristic angle θ and impedance reach Z_R (characteristic shown in Figure 29).

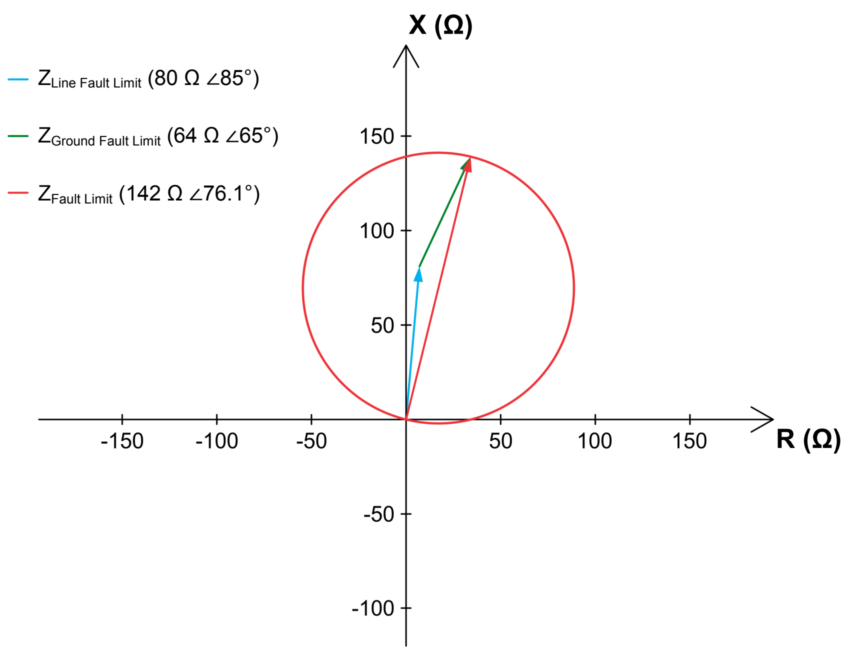


Figure 30. Self-polarized mho characteristic of a distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line).

The same applies to distance relays with a quadrilateral characteristic. For instance, let us consider the following settings:

- Relay characteristic angle θ: 85°
- Resistive (R) reach: 28 Ω
- Reactive (X) reach: 79.7 Ω
- K_R: 3.87
- K_X: 0.728

The resulting impedance characteristic of the distance relay is shown in Figure 31.

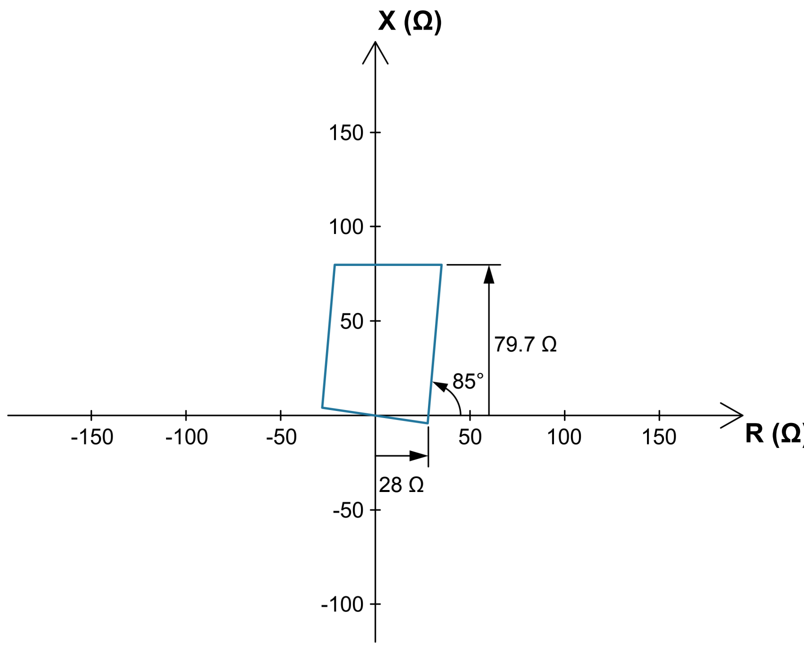


Figure 31. Quadrilateral characteristic of a distance relay determined from the relay characteristic angle θ, reactive (X) reach, and resistive (R) reach.

Assuming that the fault resistance R_{Fault} is null, the fault impedance $Z_{Fault\ Limit}$ for a ground fault at the limit of the impedance characteristic of the distance relay is as follows:

$$\vec{Z}_{Fault\ Limit} = \vec{Z}_{Line\ Fault\ Limit} + \vec{Z}_{Ground\ Fault\ Limit} \quad (11)$$

Consequently, the resistance $R_{Fault\ Limit}$ and the inductive reactance $X_{L\ Fault\ Limit}$ for ground faults at the limits of the impedance characteristic of the distance relay are as follows:

$$R_{Fault\ Limit} = R_{Line\ Fault\ Limit} + R_{Ground\ Fault\ Limit} \quad (12)$$

$$X_{L\ Fault\ Limit} = X_{L\ Line\ Fault\ Limit} + X_{L\ Ground\ Fault\ Limit}$$

Since $K_R = R_{Ground}/R_{Line}$ and $K_X = X_{L\ Ground}/X_{L\ Line}$, the resistance $R_{Fault\ Limit}$ and the inductive reactance $X_{L\ Fault\ Limit}$ for ground faults at the limits of the impedance characteristic of the distance relay become:

$$\begin{aligned} R_{Fault\ Limit} &= R_{Line\ Fault\ Limit} + K_R R_{Line\ Fault\ Limit} \\ &= (1 + K_R) R_{Line\ Fault\ Limit} \\ X_{L\ Fault\ Limit} &= X_{L\ Line\ Fault\ Limit} + K_X X_{L\ Line\ Fault\ Limit} \\ &= (1 + K_X) X_{L\ Line\ Fault\ Limit} \end{aligned} \tag{13}$$

Finally, the values of the resistance $R_{Line\ Fault\ Limit}$ and the inductive reactance $X_{L\ Line\ Fault\ Limit}$ for ground faults at the limits of the impedance characteristic of the distance relay are respectively equal to the values of the resistive (R) reach and reactive (X) reach set in the relay. Consequently, the resistance $R_{Fault\ Limit}$ and the inductive reactance $X_{L\ Fault\ Limit}$ for ground faults at the limits of the impedance characteristic of the distance relay are calculated as follows:

$$\begin{aligned} R_{Fault\ Limit} &= (1 + K_R)\ R\ reach \\ &= (1 + 3.87)\ 28\ \Omega = 136.4\ \Omega \\ X_{L\ Fault\ Limit} &= (1 + K_X)\ X\ reach \\ &= (1 + 0.728)\ 79.7\ \Omega = 137.7\ \Omega \end{aligned} \tag{14}$$

When the values of factors K_R and K_X differ (which is generally the case), the phase angle ($\theta_{Z\ Fault\ Ground}$) of the fault impedance Z_{Fault} measured by the relay during any ground fault, still assuming that the fault resistance R_{Fault} is null, differs from the relay characteristic angle θ. This must be taken into account when drawing the quadrilateral characteristic of the distance relay, i.e., the tilt of the left and right sides of the characteristic must be set to the value of phase angle $\theta_{Z\ Fault\ Ground}$. The value of phase angle $\theta_{Z\ Fault\ Ground}$ can be calculated from the values of the relay characteristic angle θ and factors K_R and K_X using the equation below:

$$\theta_{Z\ Fault\ Ground} = \tan^{-1}\left[\frac{(1 + K_X)\tan\theta}{(1 + K_R)}\right] \tag{15}$$

In the present example,

$$\theta_{Z\ Fault\ Ground} = \tan^{-1}\ [1.728\ \tan\ (85°)\ /\ 4.87] = 76.1° \tag{16}$$

The resistance $R_{Fault\ Limit}$ and the inductive reactance $X_{L\ Fault\ Limit}$ calculated above are shown as vectors in the impedance diagram of Figure 32. The impedance characteristic of the distance relay, based on the values of the resistance $R_{Fault\ Limit}$, the inductive reactance $X_{L\ Fault\ Limit}$, and the phase angle $\theta_{Z\ Fault\ Ground}$, is also shown in the impedance diagram.

This impedance characteristic shown in Figure 32 must be used to determine whether or not the measured values of the fault impedance Z_{Fault} at which the distance relay trips are in accordance with the relay settings. Notice that the quadrilateral characteristic based on the fault impedance Z_{Fault} measured by the relay during ground faults has an area that is significantly larger than the quadrilateral characteristic determined from the relay characteristic angle θ, the resistive (R) reach, and the inductive (X) reach (characteristic shown in Figure 31).

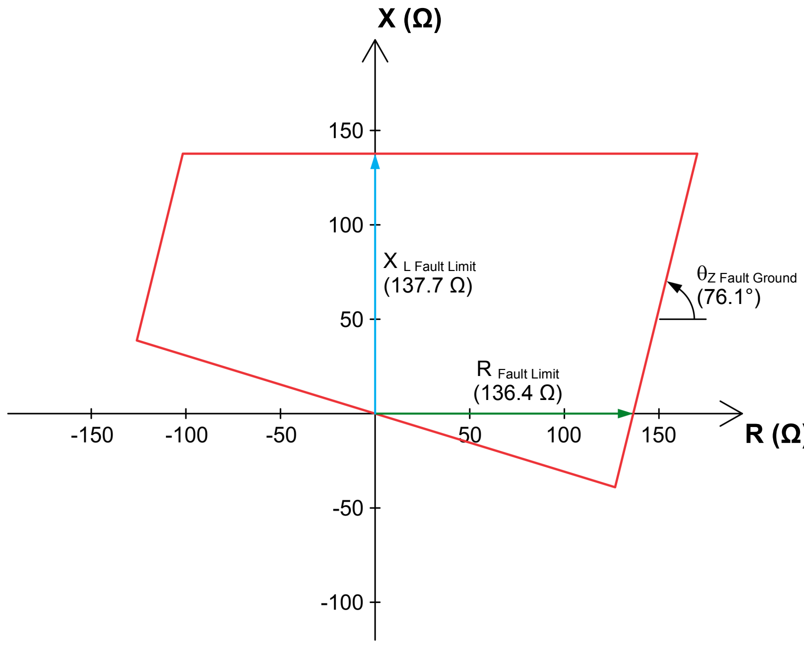


Figure 32. Quadrilateral characteristic of a distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line).

Figure 33. Commissioning of protective relays on site (photo courtesy of Elect PC).

Actual circuit impedance versus measured circuit impedance

A distance relay measures the voltage and current at a particular point in a power circuit via voltage transformers and current transformers. The relay then determines the impedance at this point of the circuit from the voltage and current at the secondary windings of these transformers. In most cases, the ratio of the voltage transformers differs from that of the current transformers. Consequently, the circuit impedance which the distance relay determines from the voltage and current at the secondary windings, which is referred to as the **secondary impedance**, generally differs from the actual circuit impedance (i.e., the **primary impedance**). In fact, the secondary impedance determined by the distance relay is related to the primary impedance as follows:

$$Z_S = Z_P \frac{CT\ ratio}{VT\ ratio} \tag{17}$$

where Z_S is the secondary impedance that the distance relay determines using the values of voltage and current at the secondary windings of the voltage and current transformers.

Z_P is the primary impedance determined using the values of voltage and current at the primary windings of the voltage and current transformers.

$CT\ ratio$ is the ratio of primary current to secondary current of the current transformers.

$VT\ ratio$ is the ratio of primary voltage to secondary voltage of the voltage transformers.

For instance, let us consider a distance relay measuring impedance at a particular point of a power system via voltage transformers having a ratio of 230 kV/100 V and current transformers having a ratio of 400 A/1 A. In this case, the secondary impedance Z_S is related to the primary impedance as follows:

$$Z_S = Z_P \frac{400\ \text{A}/1\ \text{A}}{230\ 000\ \text{V}/100\ \text{V}} = 0.1739\ Z_P \tag{18}$$

The difference between the secondary impedance Z_S (circuit impedance measured by the distance relay) and the primary impedance Z_P (actual circuit impedance) must be taken into account. For instance, voltages and currents with levels corresponding to the levels of the voltages and currents at the secondary windings of the voltage and current transformers are used when testing the impedance characteristic of a distance relay. Consequently, primary impedance values must be converted into secondary impedance values when testing the impedance characteristic of a distance relay. Similarly, secondary impedance values must also be used when setting the reach of a distance relay, unless the relay settings are based on primary impedance values.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Settings of the distance relay
- Impedance characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults
- Testing the impedance characteristic of the distance relay
- Optional manipulations
- Ending the exercise

PROCEDURE

Appendix C of this manual provides information on how to use software DIGSI® 5 to perform various tasks related to SIPROTEC® 5 protective relays. You should read this appendix before performing the exercise procedure.

Set up and connections

In this section, you will set up a protective relay so that it can be programmed and tested using a host computer.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

   Install the Numerical Distance Relay (Model 3813) and the host computer on your work surface.

   Insert the LED identification label for Exercise 1 into the front panel of the protective relay. The identification labels can be found in Appendix D.

2. Connect the protective relay and the host computer to an ac power wall outlet.

   Turn the protective relay on. Wait for the protective relay to complete its initialization routine (this generally takes about 45 s).

3. Connect the USB port of the protective relay to a USB port of the host computer.

4. Turn the host computer on, then start the DIGSI 5 software.

Settings of the distance relay

In this section, you will become familiar with the settings of the distance relay.

5. In DIGSI 5, open project file *Distance Relay Impedance Characteristic.dp5v6* created for the protective relay that you are using to perform the exercise. By default, the project files required to perform the exercises in this manual should be located in the following folder: *C:\ProgramData\Festo Didactic\Manual 52176, Distance Protection\...*

6. In DIGSI 5, display the single-line diagram showing the connection of the protective relay to the electric power circuit. Observe that in this project, the current inputs of the protective relay are connected to the electric power circuit (a feeder in an electric power substation) via current transformers having an 800 A/1 A ratio. Also, the voltage inputs of the protective relay are connected to the electric power circuit via Y-connected (star-connected) voltage transformers having a 400 kV/100 V ratio.

According to the VT ratio and CT ratio above, the relationship between secondary impedance values and primary impedance values is as follows:

$$Z_S = (\text{CT ratio / VT ratio})\ Z_P = 0.2\ Z_P \text{ or}$$

$$Z_P = 5\ Z_S$$

Ratios of 800 A to 1 A and 100 kV to 100 V ease calculations for primary and secondary impedance values. They are used here for educational purposes.

7. Access the settings related to the power line to be protected by successively selecting (double clicking) the items below in the *Project tree* area of DIGSI 5.

Relay 3813 (Siemens 7SA82) ► *Settings* ► *Line 1* ► *General*

Make the following observations about the line segment:

- The line segment length (parameter *Line length*) is 125 km (77.7 miles).
- The line inductive reactance per unit length (parameter *X per length unit*) is 0.080 Ω/km (0.129 Ω/mile). The inductive reactance $X_{L\ Line}$ of the line segment is thus equal to 10.0 Ω.

For the sake of simplicity, the line capacitance per unit of length is set to zero in this project.

- DIGSI 5 displays values of resistance, reactance, and impedance based on secondary impedance values (*Edit mode: Secondary*). Consequently, all values of resistance, reactance, and impedance in DIGSI 5 must be multiplied by 5 to obtain the corresponding values based on primary impedance values.
- The line impedance angle θ_{Line} (parameter *Line angle*) is 85°. Consequently, the magnitude ($|Z_{Line}|$) of the line segment impedance is 10.04 Ω.
- Vector K_0 [defined by parameters *K0* and *Angle (K0)*] for this line is equal to 0.800 ∠-15°. The corresponding scalar factors K_R and K_X (parameters *Kr* and *Kx*) are equal to 3.14 and 0.75, respectively.

The values of scalar factors K_R and K_X can be displayed in place of vector K_0 by setting parameter Set format residu. Comp. *in* Device settings *to* Kr, Kx.

8. In DIGSI 5, access the settings of the distance protection function of the protective relay. In the *Project tree* area of DIGSI 5, the distance protection function is called *21 Distance prot. 1* and is located in protection function group *Line 1*.

Observe that two impedance characteristics are defined in this project: characteristic *Z (MHO) 1*, which is a self-polarized mho characteristic, and characteristic *Z 1*, which is a quadrilateral characteristic. Each of these two characteristics can be enabled by setting the *Mode* parameter to *On*.

The impedance diagram in the working area of DIGSI 5 displays the two impedance characteristics, based on secondary impedance values.

The bottom side of the quadrilateral characteristics shown in the discussion is a straight line that is rotated about 20° with respect to the resistance (R) axis of the impedance diagram. In the Numerical Distance Relay, however, the bottom side of the quadrilateral impedance characteristic is slightly different. It consists of two straight lines, each being rotated a different angle with respect to the resistance (R) axis of the impedance diagram. This is due to the way quadrilateral characteristics are implemented in this particular type of distance relay.

9. In the *General* section of protection function *21 Distance prot. 1*, observe that the relay characteristic angle θ (parameter *Dist. Characteristic angle*) is set to 85°. This is the same value as the line impedance angle θ_{Line}.

Change the value of the relay characteristic angle θ while observing the impedance characteristics displayed in DIGSI 5. Notice that the relay characteristic angle θ determines the tilt of the diameter axis of the self-polarized mho characteristic as well as the tilt of the left and right sides of the quadrilateral characteristic.

Set the value of the relay characteristic angle θ back to 85°.

10. For the self-polarized mho characteristic [*Z (MHO) 1*] of protection function *21 Distance prot. 1*, observe that the impedance reach Z_R is set to 8.00 Ω. This corresponds to about 80% of the magnitude (10.04 Ω) of the line segment impedance.

Reduce the value of the impedance reach Z_R while observing the impedance characteristics displayed in DIGSI 5. Notice that the impedance reach Z_R determines the diameter of the self-polarized mho characteristic, i.e., the reach of the distance relay.

Set the value of the impedance reach Z_R back to 8.00 Ω.

11. For the quadrilateral characteristic (*Z 1*) of protection function *21 Distance prot. 1*, observe that the reactive (X) reach (parameter *X reach*) is set to 8.00 Ω. This corresponds to 80% of the line inductive reactance $X_{L\ Line}$.

Reduce the value of the reactive (X) reach while observing the impedance characteristics displayed in DIGSI 5. Notice that the reactive (X) reach determines the height of the quadrilateral characteristic along the reactance (X) axis of the impedance diagram, i.e., the reach of the distance relay.

Set the value of the reactive (X) reach back to 8.00 Ω.

12. Still for the quadrilateral characteristic (*Z 1*) of protection function *21 Distance prot. 1*, observe that the resistive (R) reach for ground faults [parameter *R (ph-g)*] is set to 4.00 Ω. Also observe that the resistive (R) reach for phase-to-phase faults [parameter *R (ph-ph)*] is set to 1.00 Ω.

Reduce the value of the resistive (R) reach for ground faults while observing the impedance characteristics displayed in DIGSI 5. Notice that the resistive (R) reach determines the width of the quadrilateral characteristic along the resistance (R) axis of the impedance diagram.

Set the value of the resistive (R) reach for ground faults back to 4.00 Ω.

Impedance characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults

In this section, you will determine the impedance characteristic of the distance relay based on the fault impedance measured by the relay during ground faults.

13. Use the settings of the distance protection function contained in the project to determine the fault impedance $Z_{Fault\ Limit}$ measured by the relay for a ground fault at the limit of the self-polarized mho characteristic of the distance relay. Assume that the fault resistance R_{Fault} is null and that there is no power source nor load at the remote end of the protected line.

$\vec{Z}_{Line\ Fault\ Limit} = Z_R$ ∠θ = (8.00 Ω ∠85°) = (0.697 + j7.97) Ω

$\vec{Z}_{Ground\ Fault\ Limit} = \vec{Z}_{Line\ Fault\ Limit}\ \vec{K}_0$

= (8.00 Ω ∠85°) (0.8 ∠-15°) = 6.4 Ω ∠70° = (2.19 + j6.01) Ω

$\vec{Z}_{Fault\ Limit} = \vec{Z}_{Line\ Fault\ Limit} + \vec{Z}_{Ground\ Fault\ Limit}$

= (0.697 + j7.97) Ω + (2.19 + j6.01) Ω = (2.89 + j13.98) Ω = 14.3 Ω ∠78.3°

14. Use the fault impedance $Z_{Fault\ Limit}$ determined in the previous step to draw (in Figure 34) the impedance characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults.

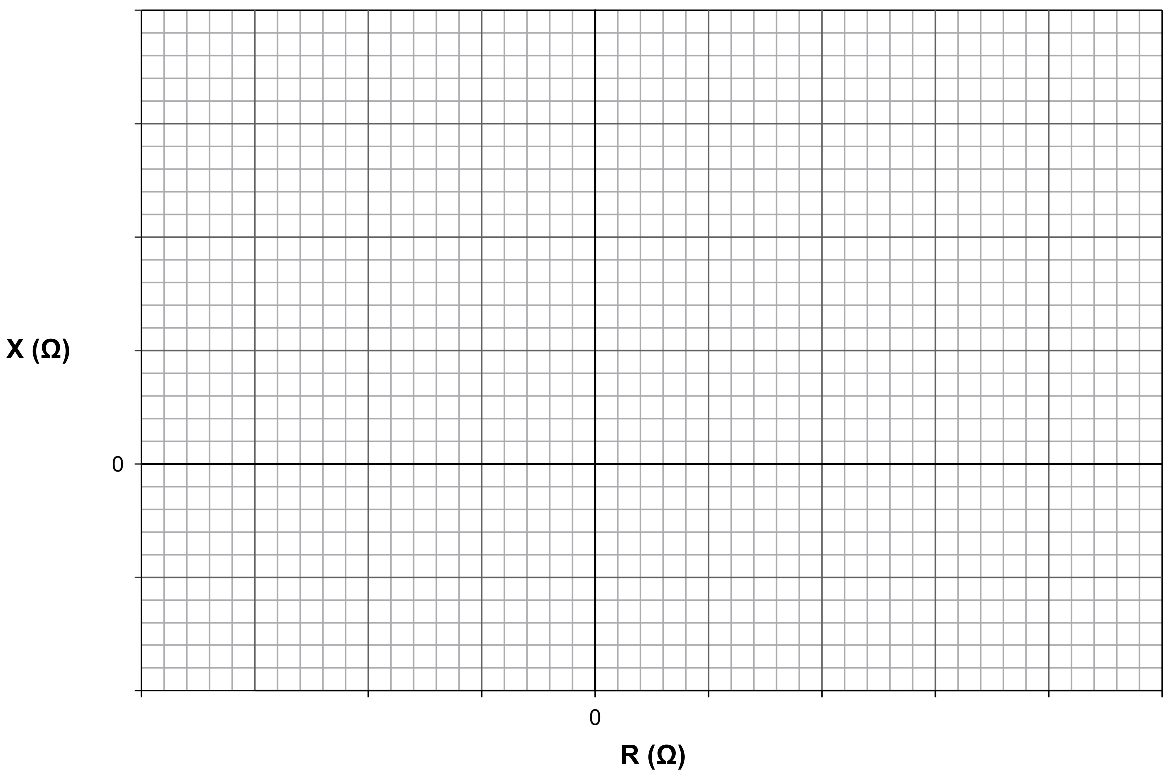


Figure 34. Self-polarized mho characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line).

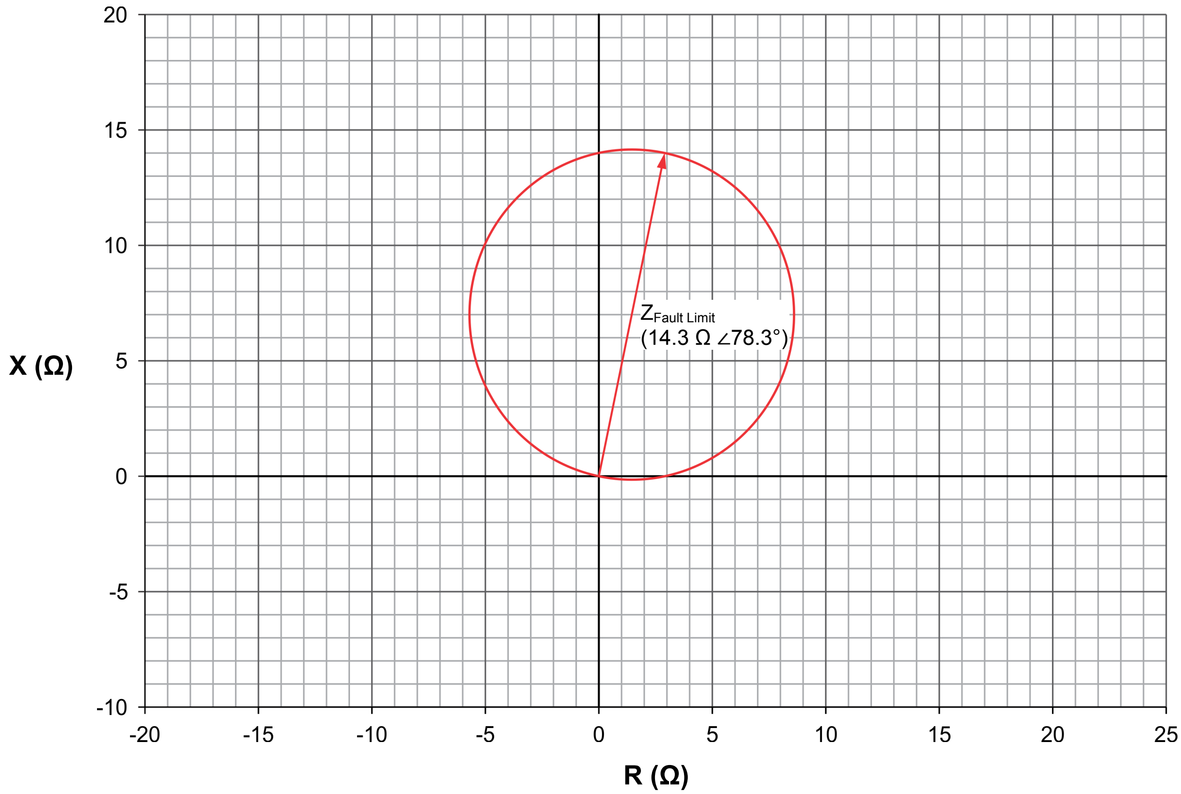


Figure 34. Self-polarized mho characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line).

15. Use the settings of the distance protection function contained in the project to determine the values of the resistance $R_{Fault\ Limit}$ and the inductive reactance $X_{L\ Fault\ Limit}$ measured by the relay for ground faults at the limits of the quadrilateral characteristic of the distance relay. Also calculate the phase angle $\theta_{Z\ Fault\ Ground}$. Assume that the fault resistance R_{Fault} is null and that there is no power source nor load at the remote end of the protected line.

$R_{Fault\ Limit} = (1+K_R)\ R\ reach = (1+3.14) \times 4.00\ \Omega = 16.6\ \Omega$

$X_{L\ Fault\ Limit} = (1+K_X)\ X\ reach = (1+0.75) \times 8.00\ \Omega = 14.0\ \Omega$

$\theta_{Z\ Fault\ Ground} = \tan^{-1}[1.75 \tan(85°)/4.14] = 78.3°$

16. Use the values of the resistance $R_{Fault\ Limit}$, the inductive reactance $X_{L\ Fault\ Limit}$, and the phase angle $\theta_{Z\ Fault\ Ground}$ determined in the previous step to draw (in Figure 35) the impedance characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults.

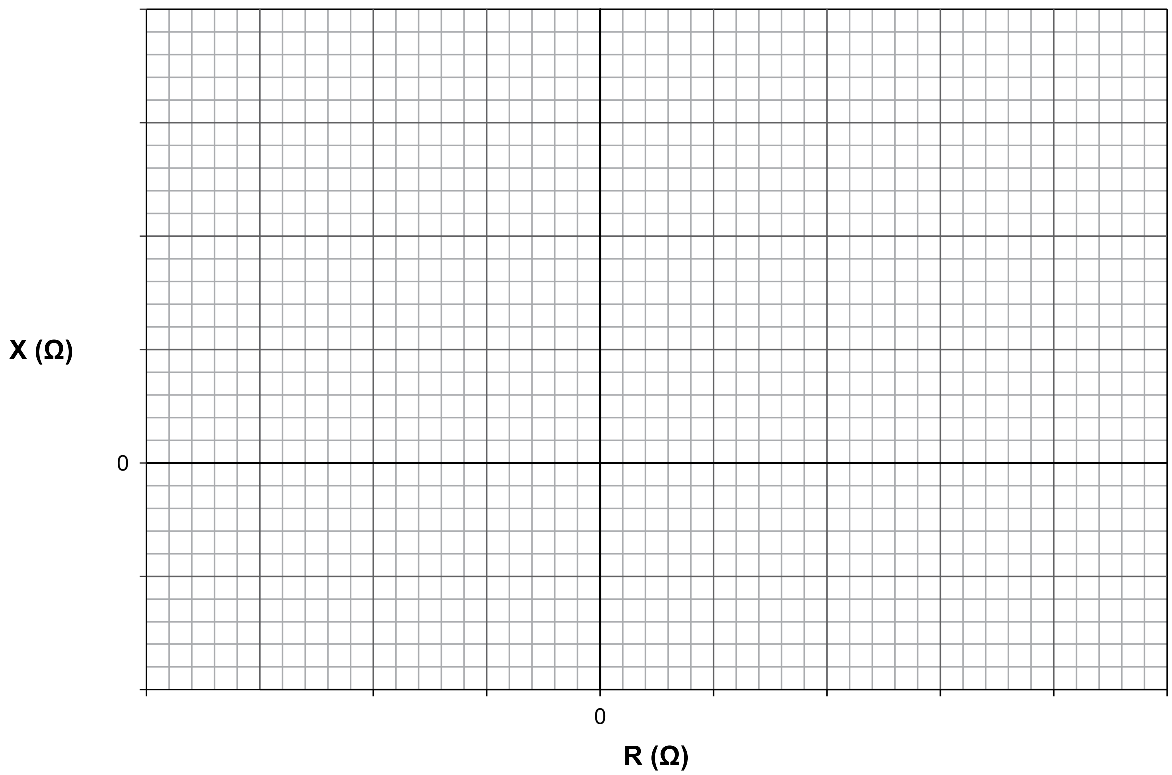


Figure 35. Quadrilateral characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line).

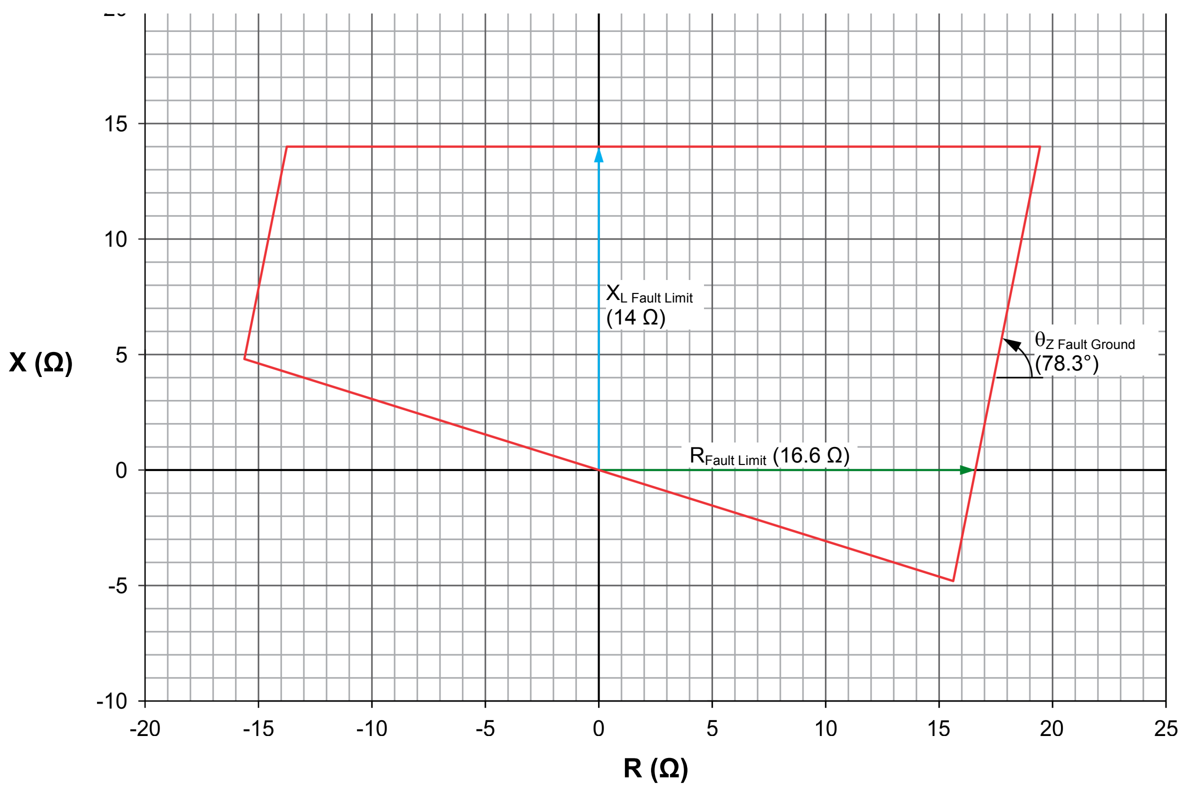


Figure 35. Quadrilateral characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line).

The bottom side of the quadrilateral characteristic in the figure above is assumed to be a straight line that is rotated about 20° with respect to the resistive (R) axis of the impedance diagram. In the Numerical Distance Relay, however, the bottom side of the quadrilateral impedance characteristic is slightly different. It consists of two straight lines, each being rotated a different angle with respect to the resistive (R) axis of the impedance diagram. This is due to the way quadrilateral characteristics are implemented in this particular type of distance relay.

Testing the impedance characteristic of the distance relay

In this section, you will test the impedance characteristic set in the protective relay using its internal relay test system.

17. In DIGSI 5, set the frequency of operation (*Rated frequency* parameter) of the protective relay to the frequency of your local ac power network.

Set the language used in the front panel display of the protective relay to the language used in DIGSI 5.

18. In DIGSI 5, access the settings of the distance protection function of the protective relay. In the *Project tree* area of DIGSI 5, the distance protection function is called *21 Distance prot. 1* and is located in protection function group *Line 1*.

Select the impedance characteristic you wish to test by enabling the self-polarized mho characteristic [*Z (MHO) 1*] or the quadrilateral characteristic (*Z 1*). Keep the *Mode* parameter of the other characteristic to *Off*.

19. In DIGSI 5, observe that a test sequence named *Gnd Fault Phase A* is available. This sequence emulates the voltages and currents which the distance relay measures when a ground fault occurs on phase A, assuming that there is no power source nor load at the other end of the protected line.

Access the parameters of test sequence *Gnd Fault Phase A*. Make the following observations:

- The test sequence consists of two steps.
- The first step (step 1) has a duration of 5.0 s.
- During the first step, the internal relay test system emulates the currents and voltages given in Table 4 at the inputs of the relay. Note that the phase angle of current I_A is arbitrarily set to 0°.

Table 4. Initial values of the currents and voltages applied to the inputs of a distance relay to emulate a ground fault on phase A.

Currents			Voltages		
I_A (A, ∠°)	I_B (A, ∠°)	I_C (A, ∠°)	E_A (V, ∠°)	E_B (V, ∠°)	E_C (V, ∠°)
0.5 ∠0°	0 ∠-120°	0 ∠120°	20 ∠0°	20 ∠-120°	20 ∠120°

- The second step (step 2) has a duration of 50.0 s.
- During the second step, the magnitude of the phase A current gradually increases up to 10.5 A.
- During the second step, the currents emulated for phase B and phase C, as well as all of the emulated voltages, are the same as those given in Table 4. The fault impedance measured on phase A by the distance relay thus decreases gradually.

By default, the frequency of the currents and voltages emulated by the internal relay test system during both steps of the sequence is set to 50 Hz.

Set the frequency of the currents and voltages emulated during both steps of test sequence *Gnd Fault Phase A* to the frequency of your local ac power network.

20. Load the configuration to the protective relay using DIGSI 5.

21. In DIGSI 5, restart the protective relay in the simulation mode to allow the distance protection function of the protective relay (i.e., protection function *21 Distance prot. 1* in protection function group *Line 1*) to be tested using the internal relay test system. Once the restart process is completed, the test environment should be displayed in DIGSI 5. Also, the front panel display of the protective relay should indicate that the unit is operating in the simulation mode (the words *Simulation mode* should appear briefly on the display at regular intervals).

The Error *LED on the front panel of the protective relay lights up when the unit is in simulation mode. This is normal. Do not be concerned about this error indication.*

During this procedure, if you notice that DIGSI 5 lags relay operation, press the Clear list *button at the top of the test environment. This should restore normal operation of DIGSI 5.*

22. In DIGSI 5, display the test environment of the protective relay. Start test sequence *Gnd Fault Phase A*, then observe the front panel of the protective relay to see how it responds to the currents and voltages emulated by its internal relay test system.

The relay display refreshes every 1 or 2 seconds.

Note that the protective relay displays the magnitude and phase of the measured currents and voltages. After 5 seconds, the magnitude of the current of phase A increases gradually. Eventually, LED indicators 1, 7 (or 8), and 16 should light up.

Table 5 provides the functions of the LED indicators of the protective relay (i.e., the column of 16 LEDs located on the left-hand side of the front panel). These functions are included in the configuration loaded to the protective relay.

Table 5. Functions of the LED indicators on the front panel of the protective relay.

LED indicator number	LED color	Function
1	Red	Pickup indication for a ground fault on phase A. The LED lights up when the distance protection function picks up.
2	Red	Same as LED indicator 1 for a ground fault on phase B.
3	Red	Same as LED indicator 1 for a ground fault on phase C.
4	Red	Same as LED indicator 1 for a phase-to-phase fault between phase A and phase B.
5	Red	Same as LED indicator 1 for a phase-to-phase fault between phase B and phase C.
6	Red	Same as LED indicator 1 for a phase-to-phase fault between phase C and phase A.
7	Red	Tripped indication for the self-polarized mho characteristic [*Z (MHO) 1*] of the distance protection function. The LED lights up when the self-polarized mho characteristic trips the protective relay.
8	Red	Tripped indication for the quadrilateral characteristic (*Z 1*) of the distance protection function. The LED lights up when the quadrilateral characteristic trips the protective relay.
16	Red	Relay tripped indication. The LED lights up when the protective relay trips.

The LED indicators are numbered 1 to 16 from the top to the bottom of the column, respectively.

23. Whenever the protective relay is tested using its internal relay test system, input signals (e.g., the currents at the three current inputs) as well as internal signals (e.g., relay pickup occurrences, the circuit breaker trip command, etc.) may be recorded in the relay. The signals recorded in the protective relay are referred to as a fault record. DIGSI 5 can be used to download a fault record from the protective relay and display the signals contained in the fault record in SIGRA. SIGRA is a Siemens application that displays the signals contained in a fault record on time charts. These time charts are useful to analyze the protective relay response to the fault.

A fault record has been created in the protective relay during the previous manipulation. Use DIGSI 5 to download the latest fault record from the protective relay and display the signals contained in this fault record in SIGRA. Figure 36 (self-polarized mho characteristic) and Figure 37 (quadrilateral characteristic) show two of the signals (the phase A current and the relay trip signal) that should be displayed in SIGRA.

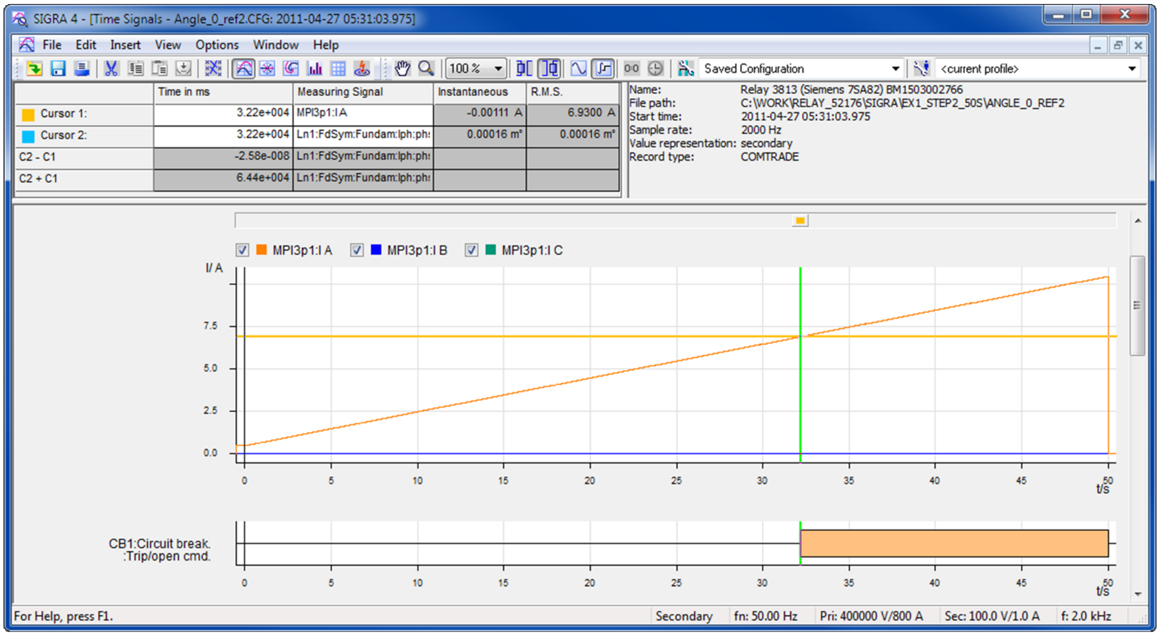


Figure 36. Signals contained in the fault record downloaded from the protective relay displayed in SIGRA (self-polarized mho characteristic).

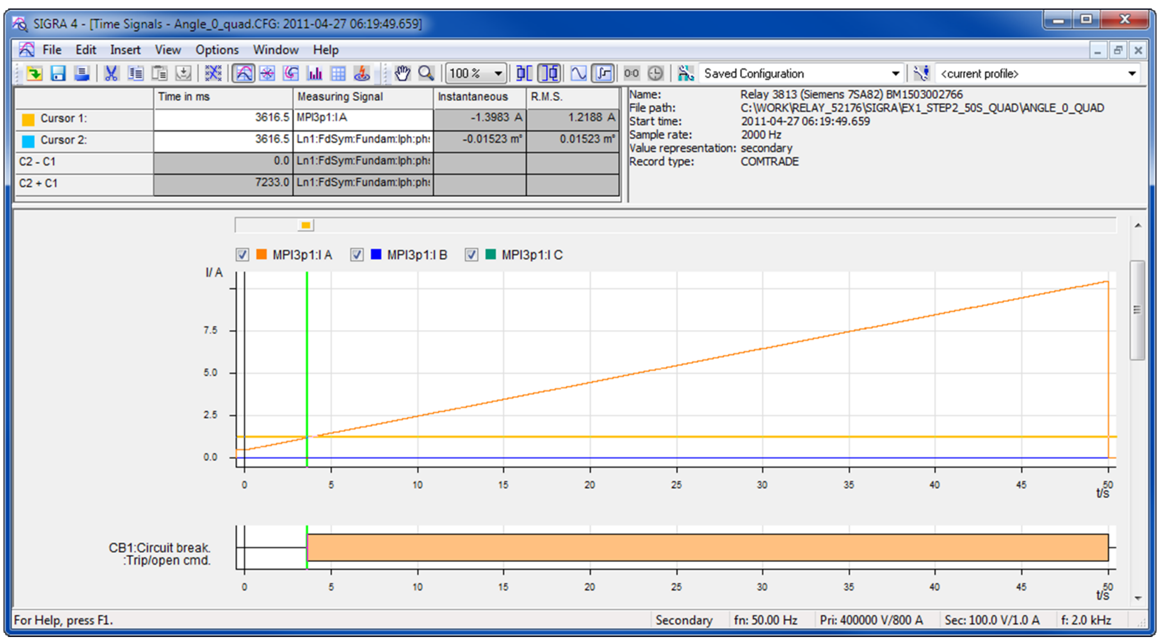


Figure 37. Signals contained in the fault record downloaded from the protective relay displayed in SIGRA (quadrilateral characteristic).

For optimal display of the signals, make the following settings:

- Select *R.M.S. Values* (and not *Instantaneous Values*).
- Select *Secondary Values* (and not *Primary Values*).
- Align both cursors at the beginning of the relay trip signal.
- Under the *Measuring Signal* column, select the magnitude of the phase A current (*MPI3p1:I A*) for Cursor 1 and the phase angle of the phase A current (*Ln1:FdSym:Fundam:Iph:phs A angle*) for Cursor 2. Record, in Table 6, the R.M.S. value of the magnitude of the phase A current and the instantaneous value of the phase angle of the phase A current.
- Under the *Measuring Signal* column, select the magnitude of the phase A voltage (*MPV3p1:V A*) for Cursor 1 and the phase angle of the phase A voltage (*Ln1:FdSym:Fundam:Vph:phs A angle*) for Cursor 2. Record, in Table 6, the R.M.S. value of the magnitude of the phase A voltage and the instantaneous value of the phase angle of the phase A voltage.

Table 6. Current I_A, voltage E_A, and impedance Z_{Fault} at which the relay tripped.

Current I_A		Voltage E_A		Impedance Z_{Fault} (polar coord.)		Impedance Z_{Fault} (rect. coord.)	
Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (Ω)	Phase angle (°)	$Z_{Fault,R}$ (Ω)	$Z_{Fault,X}$ (Ω)

24. Calculate the magnitude and phase angle of the fault impedance Z_{Fault} at which the relay tripped. Calculate also the resistive and reactive components of the fault impedance. Recall that:

$$Z_{Fault} = |Z_{Fault}| \angle\theta$$

$$Z_{Fault,R} = |Z_{Fault}| \cos(\theta) \text{ and } Z_{Fault,X} = |Z_{Fault}| \sin(\theta)$$

Record your results in Table 6.

25. Reset the protective relay by momentarily depressing the Reset button located just below the 16 LED indicators on the left-hand side of the relay front panel. The LED indicators should go out.

26. Access the parameters of test sequence *Gnd Fault Phase A*. Change the value of the phase angle of current I_A in step 2 of the test sequence, then repeat step 22 to step 25. Perform this step for each of the following values of the phase angle of current I_A:

-10°, -20°, -30°, -40°, -50°, -60°, -70°, -80°, -90°, -100°

Table 6. Current I_A, voltage E_A, and impedance Z_{Fault} at which the relay tripped. Results for the self-polarized mho characteristic of relay.

Current I_A		Voltage E_A		Impedance Z_{Fault} (polar coord.)		Impedance Z_{Fault} (rect. coord.)	
Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)
6.93	0	20	0	2.89	0	2.89	0
3.80	-10	20	0	5.26	10	5.18	0.91
2.67	-20	20	0	7.49	20	7.04	2.56
2.11	-30	20	0	9.48	30	8.21	4.74
1.79	-40	20	0	11.17	40	8.56	7.18
1.60	-50	20	0	12.50	50	8.03	9.58
1.48	-60	20	0	13.51	60	6.76	11.70
1.42	-70	20	0	14.08	70	4.82	13.24
1.41	-80	20	0	14.18	80	2.46	13.97
1.44	-90	20	0	13.89	90	0	13.89
1.52	-100	20	0	13.16	100	-2.28	12.96

Table 6. Current I_A, voltage E_A, and impedance Z_{Fault} at which the relay tripped. Results for the quadrilateral characteristic of relay.

Current I_A		Voltage E_A		Impedance Z_{Fault} (polar coord.)		Impedance Z_{Fault} (rect. coord.)	
Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)
1.22	0	20	0	16.39	0	16.39	0
1.16	-10	20	0	17.24	10	16.98	2.99
1.06	-20	20	0	18.87	20	17.73	6.45
0.93	-30	20	0	21.51	30	18.62	10.75
0.92	-40	20	0	21.74	40	16.65	13.97
1.10	-50	20	0	18.18	50	11.69	13.93
1.24	-60	20	0	16.13	60	8.06	13.97
1.34	-70	20	0	14.93	70	5.10	14.03
1.42	-80	20	0	14.08	80	2.45	13.87
1.44	-90	20	0	13.89	90	0	13.89
1.42	-100	20	0	14.08	100	-2.45	13.87

27. Place the measured values of the fault impedance Z_{Fault} at which the relay tripped on the impedance diagram you used earlier to draw the impedance characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (Figure 34 or Figure 35).

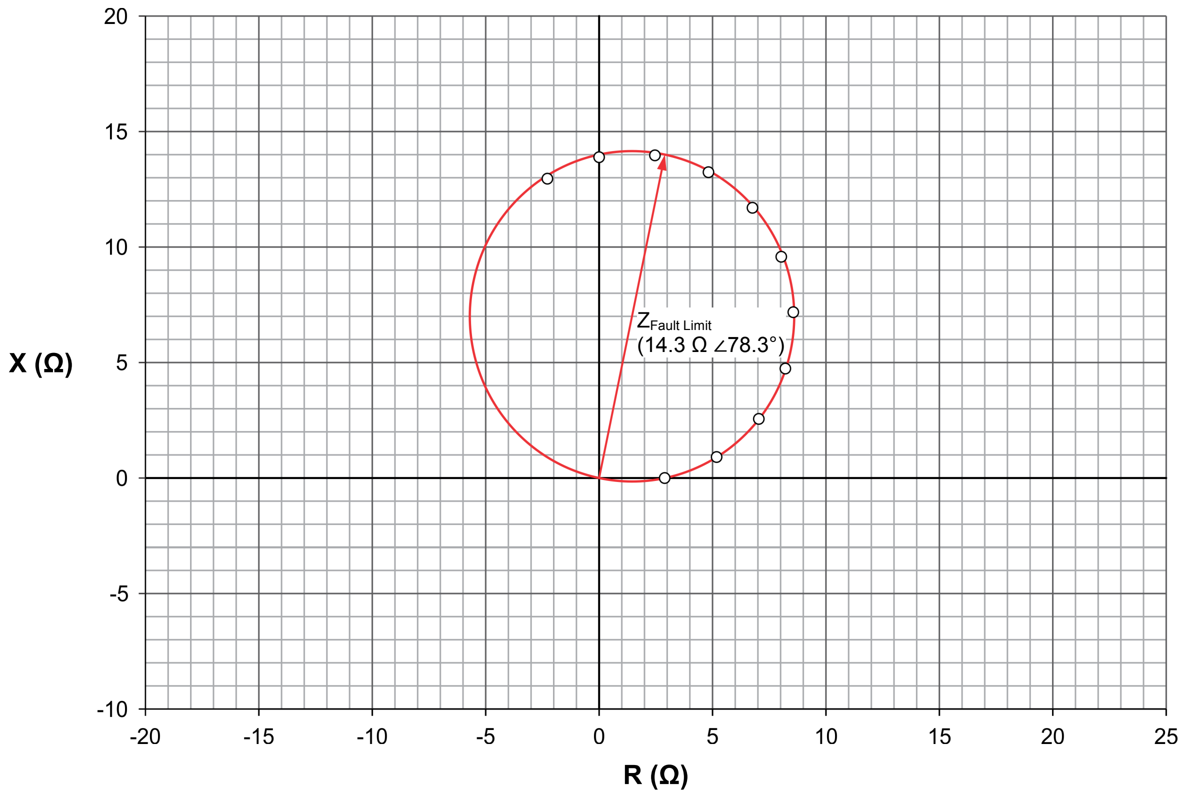


Figure 34. Self-polarized mho characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line). The measured values of the fault impedance Z_{Fault} at which the relay tripped are also shown.

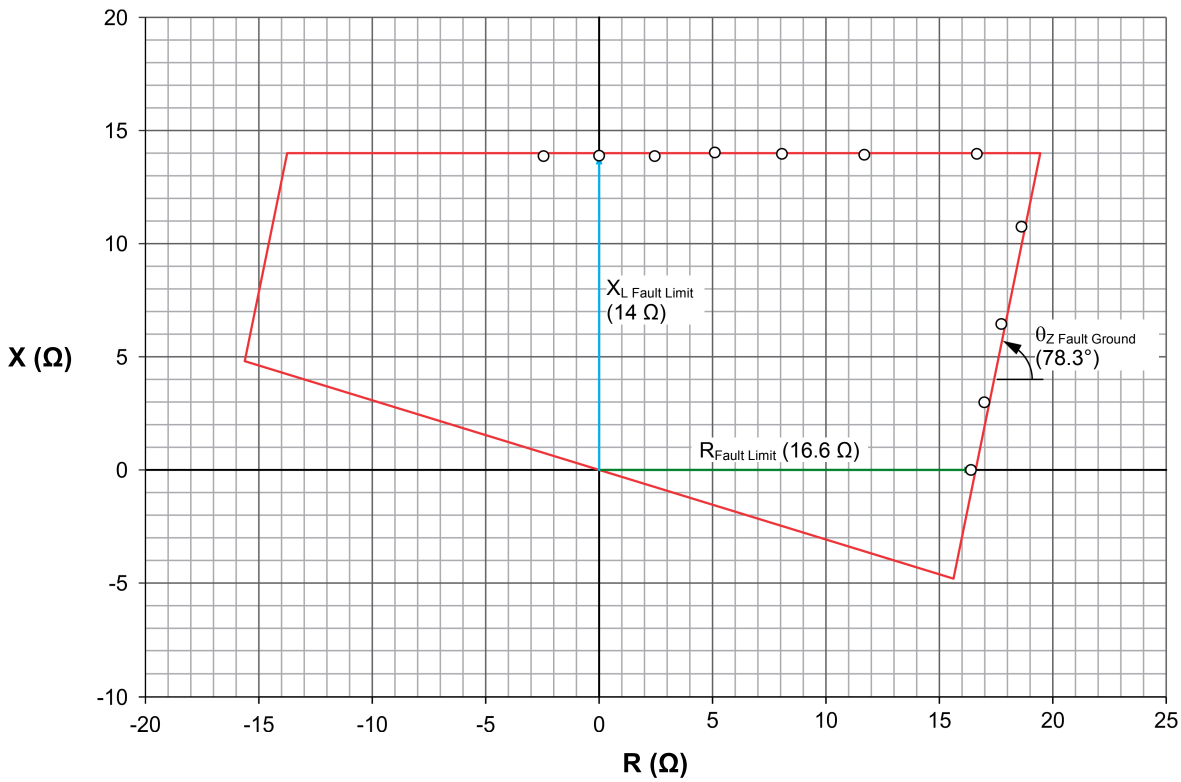


Figure 35. Quadrilateral characteristic of the distance relay based on the fault impedance Z_{Fault} measured by the relay during ground faults (no power source nor load at remote end of the line). The measured values of the fault impedance Z_{Fault} at which the relay tripped are also shown.

Do the measured values of the fault impedance Z_{Fault} at which the relay tripped match the impedance characteristic of the relay?

❑ Yes ❑ No

Yes

Optional manipulations

You may wish to test the other impedance characteristic set in the distance relay. If so, proceed as described below.

28. In DIGSI 5, access the settings of the distance protection function. Disable the impedance characteristic you tested, then enable the other impedance characteristic.

29. In DIGSI 5, access the parameters of test sequence *Gnd Fault Phase A*. Set the phase angle of current I_A back to 0° in step 2 of the test sequence.

30. Load the project into the distance relay.

31. Repeat step 22 to step 27. Record your results in Table 7.

Table 7. Current I_A, voltage E_A, and impedance Z_{fault} at which the relay tripped (optional testing of the second impedance characteristic).

Current I_A		Voltage E_A		Impedance Z_{Fault} (polar coord.)		Impedance Z_{Fault} (rect. coord.)	
Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)	Magnitude (A)	Phase angle (°)

Refer to Table 6 for answers.

Ending the exercise

32. In DIGSI 5, restart the protective relay in the process mode to allow normal operation of the unit. Once the restart process is completed, the display of the protective relay no longer indicates that the unit is operating in the simulation mode (the words *Simulation mode* no longer appear on the display).

33. Close the project open in DIGSI 5 without saving the changes you made to this project.

Close DIGSI 5.

Turn the protective relay off, then disconnect it from the host computer.

Delete the copy of the project file that you opened at the beginning of this exercise.

CONCLUSION

In this exercise, you became familiar with the self-polarized mho characteristic of distance relays and learned how to adjust it to protect a specific line segment. You saw the effect which the fault resistance has on the fault impedance. You understood the effect which the fault resistance has on the reach of a distance relay having a self-polarized mho characteristic. You became familiar with the quadrilateral characteristic of distance relays and learned how to adjust it to protect a specific line segment. You related the impedance characteristic of a distance relay to the measured fault impedance. You learned that distance relays take the ground impedance into account to properly interpret the impedance measured during ground faults. You learned the relationship between the measured circuit impedance (secondary impedance) and the actual circuit impedance (primary impedance). You tested the impedance characteristic implemented in a numerical distance relay.

REVIEW QUESTIONS

1. In a distance relay with a self-polarized mho characteristic, why is the impedance reach Z_R set to a value below the magnitude $|Z_{Line}|$ of the impedance of the protected line segment?

   The impedance reach Z_R is set to a value below the magnitude $|Z_{Line}|$ of the impedance of the protected line segment to create a safety margin ensuring that the distance relay cannot overreach, i.e., cannot detect faults located beyond the line segment that it protects (e.g., fault located on the adjacent line segment). This is required to achieve perfect selectivity.

   The safety margin is necessary because of the limited accuracy in the measurement of impedance by the distance relay as well as to inaccuracies in the line impedance (Z_{Line}) data.

2. State the importance of the fault resistance R_{Fault} for phase-to-phase faults and ground faults. Explain briefly.

   The fault resistance R_{Fault} for phase-to-phase faults is null in most cases, because such faults generally arise from direct accidental contact of two conductors of different phases in a power system.

   On the other hand, the fault resistance R_{Fault} is often not null during ground faults. Arcing, which is equivalent to pure resistance, can occur during a ground fault. Furthermore, the conductivity of the fault path to ground can also increase the fault resistance R_{Fault}.

3. Which type of characteristic should you use to protect a line segment for which the magnitude ($|Z_{Line}|$) of the line impedance is smaller than the projected fault resistance R_{Fault} during ground faults: the self-polarized mho characteristic or the quadrilateral characteristic? Explain.

The quadrilateral characteristic. This characteristic is perfectly suited to detect ground faults because the resistive (R) reach can be set independently of the reactive (X) reach. This allows the fault resistance to be accounted for without affecting the reach of the distance relay.

When the line segment to be protected is short, a self-polarized mho characteristic can fail to detect ground faults. Indeed, when the fault resistance R_{Fault} is larger than the magnitude ($|Z_{Line}|$) of the line impedance, the horizontal displacement of the fault impedance (Z_{Fault}) axis due to the fault resistance R_{Fault} is so important that the fault impedance Z_{Fault} for a ground fault located anywhere on the line segment lies outside the self-polarized mho characteristic of the distance relay.

4. Calculate the impedance of the ground return path if the line impedance is 25 Ω ∠75° and vector K_0 is equal to 0.70 ∠-8°.

$Z_{Ground} = K_0 Z_{Line}$ = (0.70 ∠-8°) (25 Ω ∠75°) = 17.5 Ω ∠67° = (6.84 + j16.1) Ω

5. Calculate the factors K_R and K_X for the case presented in the previous question.

Z_{Line} = (25 Ω ∠75°) = (6.47 + j24.1) Ω

$K_R = R_{Ground}/R_{Line}$ = 6.84/6.47 = 1.06

$K_X = X_{L\ Ground}/X_{L\ Line}$ = 16.1/24.1 = 0.67

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