Electricity and New Energy

Directional 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

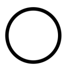
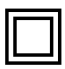
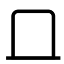
Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

Table of Contents

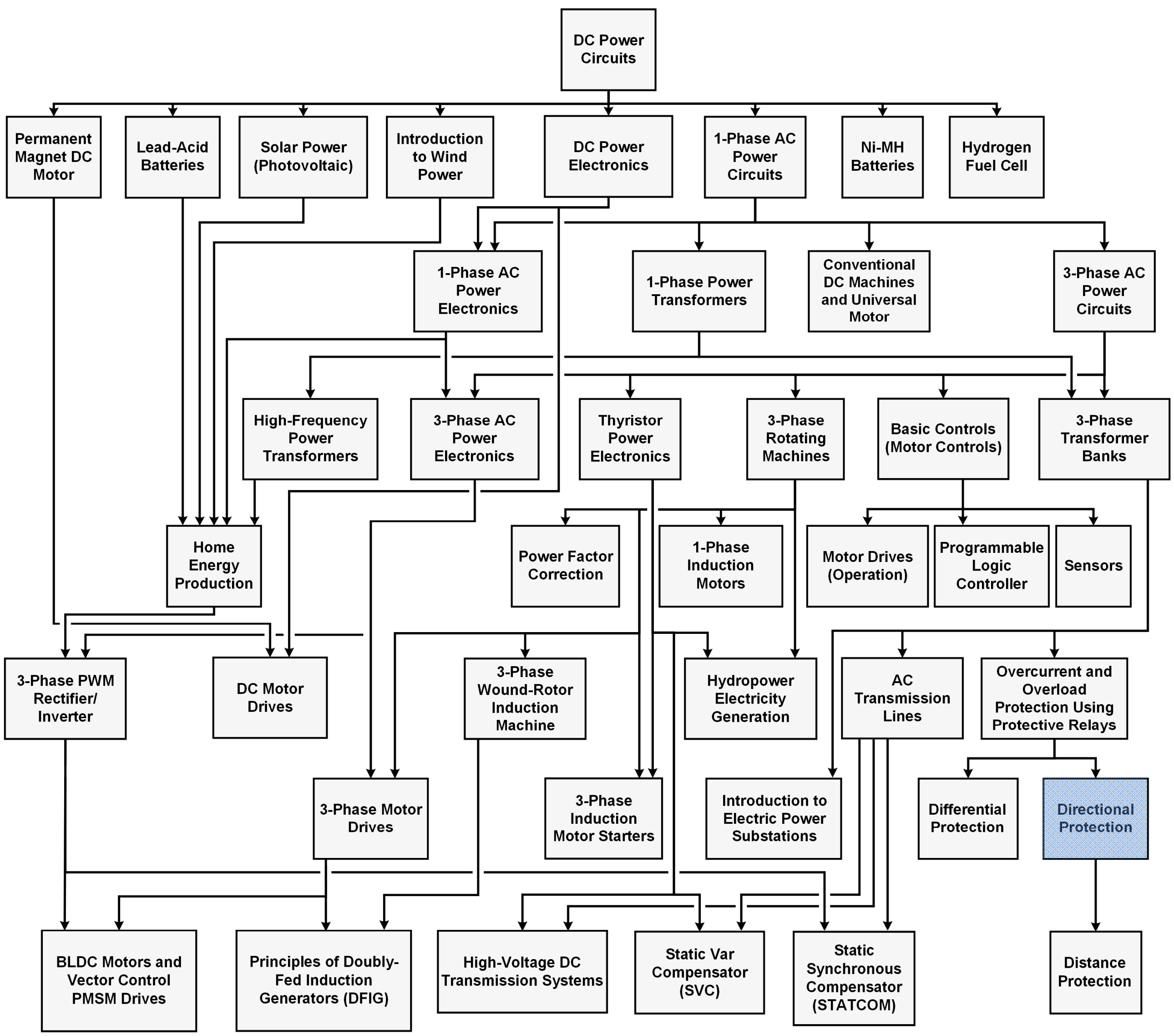
Table of Contents

Table of Contents

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 the operation and settings of the directional overcurrent relay (ANSI device no. 67). You will learn about directional overcurrent protection and directional comparison protection, which are two ways to protect power lines connected in parallel or forming a ring bus. You will understand how directional comparison protection uses a communication link between two directional overcurrent relays to allow fast clearing of faults. You will be familiar with the operation and settings of the directional power relay (ANSI device no. 32). You will learn how directional power protection can prevent damage to the prime mover of a synchronous generator when it stops driving the generator. You will also see how directional power protection can prevent damage to a synchronous generator resulting from sustained operation as an asynchronous generator following a loss of excitation.

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, and *Overcurrent and Overload Protection Using Protective Relays*, part number 52173.

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.

Detailed procedure in Exercise 1

It is recommended to perform the exercises in the order proposed in this manual, as Exercise 1 features more detailed explanations than the rest of the exercises.

Sample

Extracted from

Instructor Guide

Directional Overcurrent Protection

EXERCISE OBJECTIVE

In this exercise, you will learn how to determine the direction in which an alternating current flows. You will become familiar with the operation of a directional overcurrent relay, including its main settings. You will analyze the phasors of fault currents on a given phase to understand why the characteristic angle in a directional overcurrent relay is commonly set to 45°. You will verify the angular limits of the forward and backward direction zones of a directional overcurrent relay. You will learn how directional overcurrent protection achieves discriminative protection of two power lines connected in parallel.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Determining the direction in which an alternating current flows
- Operation of the directional overcurrent relay
- Typical value (45°) of the characteristic angle used in directional overcurrent relays

DISCUSSION

Determining the direction in which an alternating current flows

Current in any conductor of an electric circuit can flow from left to right or from right to left. This is commonly referred to as the direction of current flow. In dc power circuits, the polarity of the current indicates the direction of current flow. In ac power circuits, however, the polarity of the current alternates constantly. Consequently, polarity cannot be used to determine the direction of current flow.

In an ac power circuit, one determines the direction of current flow from the phase shift between the voltage E and the current I at any given point of the circuit (refer to Figure 6a).

> The term reverse direction is commonly used to refer to the backward direction. Both terms are used in this manual.

When the current flows from left to right in the circuit, the absolute value of the phase shift between the voltage and current is 90° or less (Figure 6b), the exact value of the phase shift being dependent on the value of the circuit impedance Z. This direction is generally considered as the forward direction. On the other hand, when the current flows from right to left in the circuit, the absolute value of the phase shift between the voltage and current is 90° or more (Figure 6c), the exact value of the phase shift being dependent on the value of the circuit impedance Z. This direction is generally considered as the reverse direction.

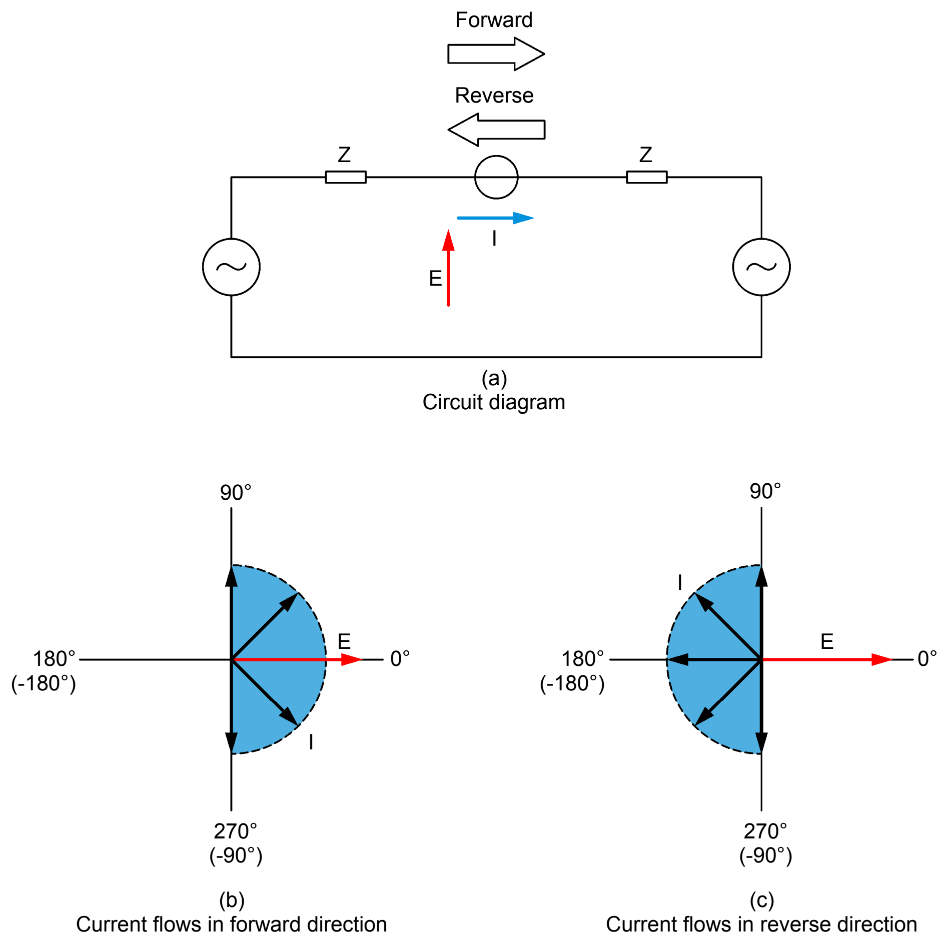


Figure 6. Determining the direction of current flow in an ac power circuit.

Phase angle values can be expressed over a range of 0° to 360° or over a range of -180° to 180°. In the phasor diagrams provided in this manual, phase angle values are expressed over a range of 0° to 360°. For practicality, however, phase angle values between -180° and 0° are also provided (shown in parentheses).

In most power networks, the impedance is of resistive-inductive nature. In this case, the expected range of phase angle values of the current is reduced to 90° for each direction of current flow, as shown in Figure 7.

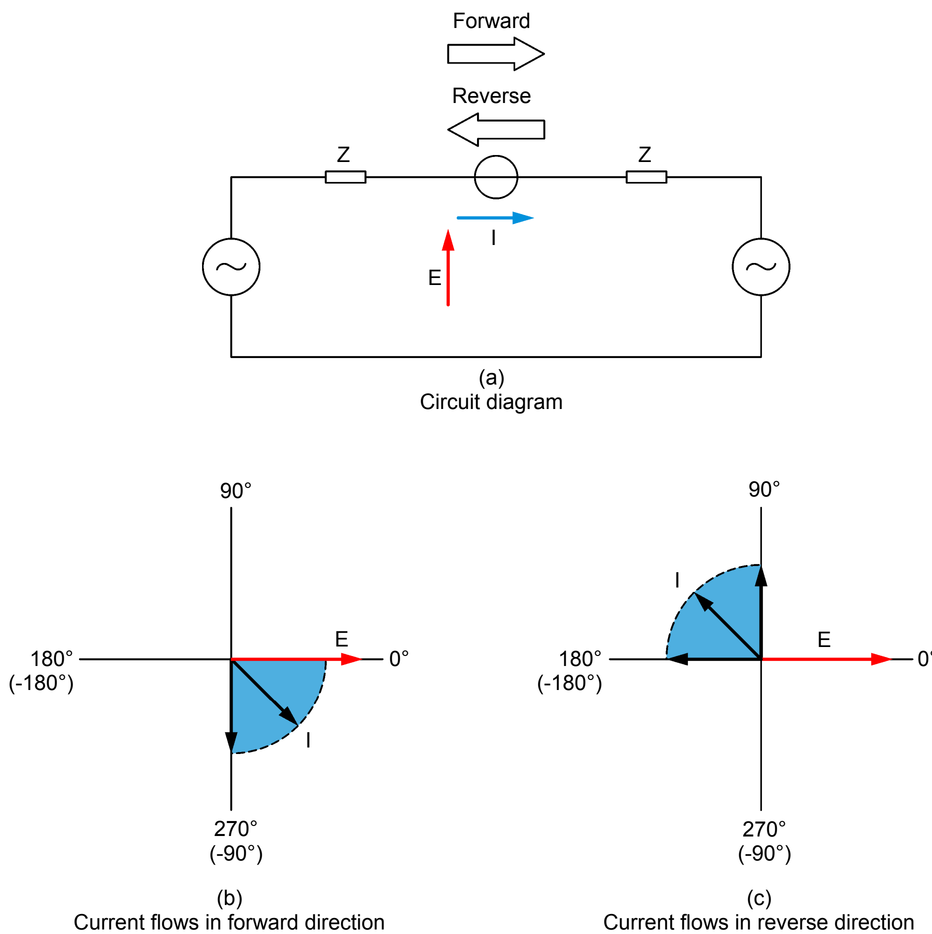


Figure 7. Determining the direction of current flow in an ac power circuit (resistive-inductive impedance only).

Operation of the directional overcurrent relay

The directional overcurrent relay is the key component to achieve directional overcurrent protection, as discussed in the Introduction of this manual. The operation of the directional overcurrent relay (ANSI device no. 67) along with its main parameters are explained below.

- A directional overcurrent relay (ANSI device no. 67) mainly consists of an overcurrent relay plus a directional element that determines the direction of current flow.
- A directional overcurrent relay measures current and voltage at a given point of the circuit, as shown in Figure 8. From these measurements, the directional element is able to determine the direction of current flow.

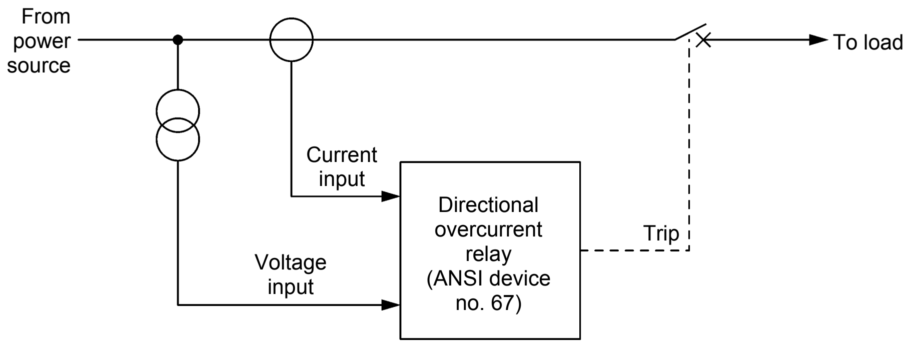


Figure 8. Connection of a directional overcurrent relay and HV circuit breaker to an electric power circuit.

- The directional element allows the operation (tripping) of the overcurrent relay within the directional overcurrent relay only when the measured current flows in the selected direction (forward or reverse) of current flow.
- A directional overcurrent relay can monitor line current on two phases, in which case it measures two currents and two voltages. This allows detection of any phase-to-phase fault. It can also monitor line current on all three phases, in which case it measures three currents and three voltages. This allows detection of any phase-to-phase fault as well as any phase-to-ground fault.
- In electromechanical and static directional overcurrent relays, the reference voltage for phase A is generally line voltage E_{BC}, not phase voltage E_A, as one could expect. This is because voltage E_{BC} is not affected when a ground fault occurs on phase A, thereby providing a more stable reference voltage (the same applies to phase B and phase C, i.e., line voltage E_{CA} is used as the reference voltage for phase B and line voltage E_{AB} is used as the reference voltage for phase C). On the other hand, modern directional overcurrent relays (digital and numerical units) generally use phase voltage E_A as the reference voltage for phase A and other techniques to obtain a reference voltage that is even more stable (these techniques are beyond the scope of this manual). However, note that the settings in certain modern directional overcurrent relays replicate the settings found in electromechanical and static directional overcurrent relays even if a phase voltage (e.g., voltage E_A for phase A) is used as the reference voltage instead of a phase-to-phase voltage (e.g., voltage E_{BC} for phase A).
- The reference voltage may be rotated to properly align the forward and reverse direction zones of the directional overcurrent relay. This rotation angle is referred to as the characteristic angle. Figure 9 shows the forward and reverse direction zones for two values of characteristic angle when line voltage E_{BC} is used as the reference voltage. The value at which the characteristic angle is set in most applications is discussed in the next section of this exercise.

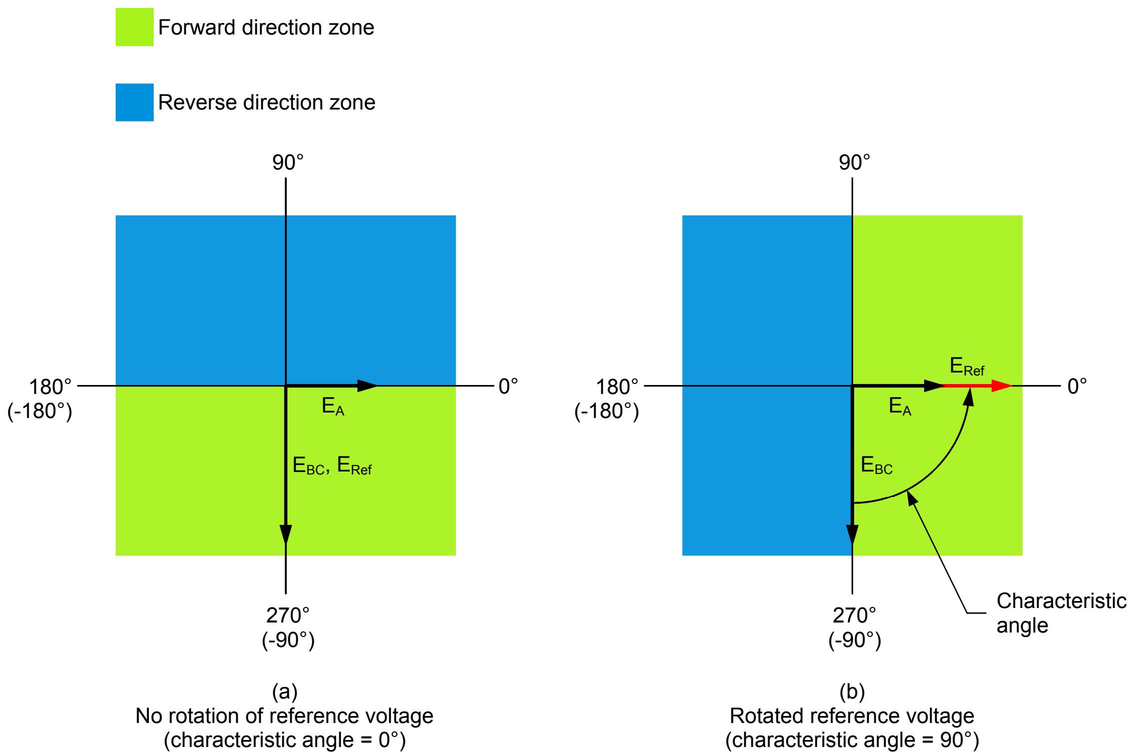


Figure 9. Selecting a characteristic angle to properly align the forward and reverse direction zones of the directional overcurrent relay.

- The main settings of a directional overcurrent relay are:
  - Direction of current flow (forward or reverse)
  - Current threshold, also referred to as the current setting. This is the minimum current for which the directional overcurrent relay may trip.
  - Time delay, also referred to as the time setting or the operate delay. This is the operating time of the relay when a definite-time overcurrent relay (ANSI device no. 51DT) is used in the directional overcurrent relay. When an inverse definite minimum time overcurrent relay (ANSI device no. 51I) is used, the operating time is calculated according to the chosen time-current characteristic.
  - Characteristic angle. Angle by which the reference voltage is rotated to allow proper operation of the directional overcurrent relay. This angle is generally set to 45°. This is explained in the following section.

Typical value (45°) of the characteristic angle used in directional overcurrent relays

The range of phase angle values of current expected for faults on phase A includes the ranges of phase angle values for a phase-to-ground fault, a phase-to-phase fault between phase A and phase B, and a phase-to-phase fault between phase A and phase C. These three cases are treated separately below to ease understanding. The circuit impedance considered is of resistive-inductive nature, as this is representative of actual circuit impedances.

When a phase-to-ground fault occurs on phase A, the range of phase angle values of current I_A that is expected is illustrated in Figure 10.

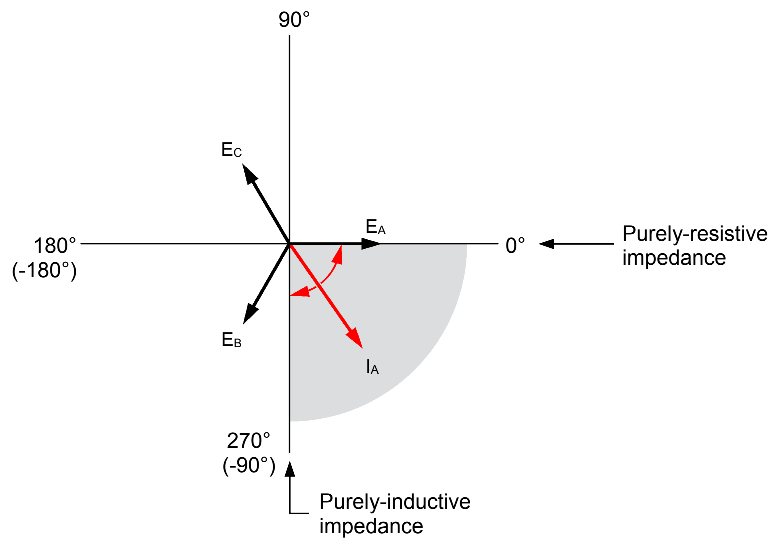


Figure 10. Range of phase angle values of current I_A expected for a phase-to-ground fault on phase A.

The ranges of phase angle values of current I_A expected for phase-to-phase faults between phase A and phase B and between phase A and phase C are shown in Figure 11.

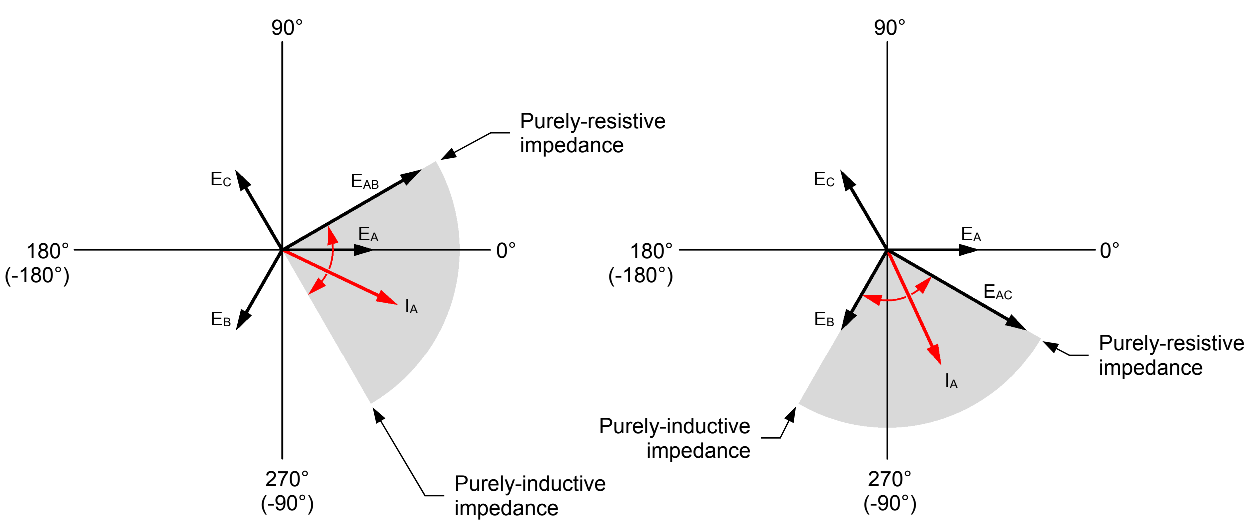


Figure 11. Ranges of phase angle values of current I_A expected for phase-to-phase faults between phase A and phase B (left) and between phase A and phase C (right).

The superposition of the ranges of phase angle values of current I_A involved in Figure 10 and Figure 11 is presented in Figure 12. The total range covers 150°. Similarly, the total range of phase angle values of the current is also 150° for faults on phase B or phase C.

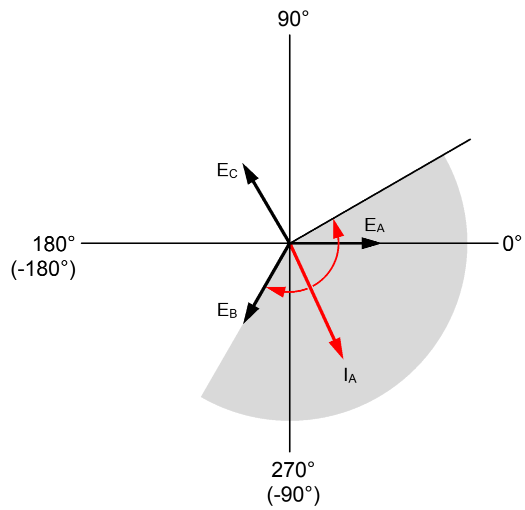


Figure 12. Range of phase angle values of current I_A expected for faults on phase A.

Setting the characteristic angle to 45° properly aligns the forward and reverse direction zones of the directional overcurrent relay with the vectors of fault current expected for phase A, as illustrated in Figure 13. Notice that the forward direction zone encloses every expected vector of fault current for phase A with a safety margin of 15° on each side of the expected range of phase angle values of current. This ensures optimal operation of the directional overcurrent relay.

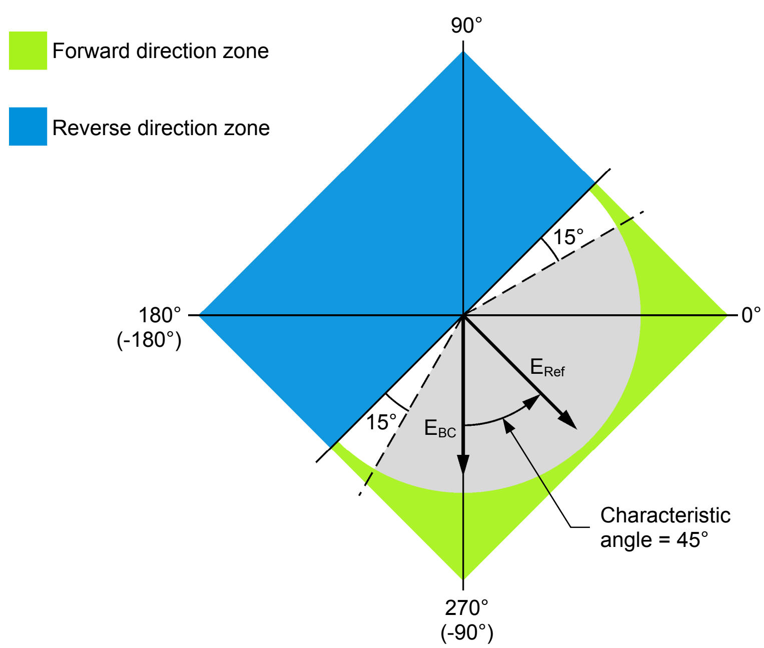


Figure 13. Setting the characteristic angle to 45° properly aligns the forward and reverse direction zones of the directional overcurrent relay with the range of phase angle values expected for the fault currents.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Operation of a directional overcurrent relay
  Forward direction zone. Backward (reverse) direction zone.
- Directional overcurrent protection of power lines connected in parallel
  Operation of the overcurrent relays at locations C and D. Operation of the directional overcurrent relays at locations E and F. Analysis of the relay responses.
- 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 Directional Overcurrent Relay (Model 3812) and the host computer on your work surface.

   This exercise can also be performed using the Numerical Distance Relay (Model 3813). The term protective relay is used throughout the remainder of this exercise procedure to refer to the protective relay used to perform the exercise.

   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.

Operation of a directional overcurrent relay

In this section, you will establish the phase angle limits of the forward and backward direction zones of a directional overcurrent relay (ANSI device no. 67).

Forward direction zone

5. In DIGSI 5, open project file *Directional Overcurrent Protection.dp5v6* created for the protective relay that you are using to perform the exercise. A project file contains the complete configuration of the protective relay for a particular application. 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 52174, Directional Protection\...*

   Refer to Appendix C to learn how to perform various tasks in software DIGSI 5.

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 a 200 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 100 kV/100 V ratio. For example, when the bus voltage is 120 kV, the voltage at the primary windings of the voltage transformers is 69.3 kV and the voltage at the secondary windings is 69.3 V.

   A ratio of 100 kV to 100 V eases calculations of voltage values at the secondary windings of the voltage transformers. This ratio is not commonly available in practice and is employed here strictly for educational purposes.

7. 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.

8. In DIGSI 5, access the settings of the directional overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the directional overcurrent protection function is called *67 Dir.OC-3ph-A1* and is located in protection function group *VI 3ph 1*.

   Make the following observations about the directional overcurrent protection function:

   - The characteristic angle (parameter *Rotation angle of ref. volt.* in the *General* section) is set to 45°.
   - The other parameters of the protection function are defined in time-current characteristic *Definite-T1*. Note that the *Mode* parameter is set to on, meaning that the protection function is activated.
   - The direction of current flow (parameter *Directional mode*) is set to forward.

- The protective relay has a definite-time characteristic, because the time delay (parameter *Operate delay*) is set to 0.1 s.
- The current threshold of the protective relay (parameter *Threshold*) is set to 400 A.
- Time-current characteristic *Definite-T1* is displayed in the right region of the working area of DIGSI 5.

The x-axis in the diagram showing the time-current characteristic of the protection function is graduated with values of current at the secondary windings of the current transformers. These values of current must be multiplied by the ratio of the current transformers (200 A/1 A in the currently-open project) to obtain values of current at the primary windings of the current transformers (i.e., values of current in the electric power circuit).

With voltage E_{BC} as the reference voltage and the value of the characteristic angle presented above, the forward and backward direction zones of the directional overcurrent relay are the same as those shown in Figure 13.

9. In DIGSI 5, access the settings of the overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the directional overcurrent protection function is called *50/51 OC-3ph-B1* or *50/51 OC-3ph-A* and is located in protection function group *VI 3ph 1*.

This function is inactive (*Mode* parameter is set to off) for now, but will be used later in this exercise procedure.

10. In DIGSI 5, access the parameters of test sequence *Directional OC Relay Operation*. This test sequence is part of the project file currently open in DIGSI 5 and can be used to test the directional overcurrent protection function of the protective relay using its internal relay test system.

In all test sequences, the magnitudes are expressed as secondary values, i.e., the values at the secondary windings of the current and voltage transformers.

Make the following observations about test sequence *Directional OC Relay Operation*.

- 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 balanced currents of 1.00 A at the current inputs of the relay. This is equivalent to balanced currents of 200 A in the electric power circuit, because 200 A/1 A current transformers are used in this project.
- During the first step, the internal relay test system emulates balanced voltages of 69.3 V at the voltage inputs of the relay. This is equivalent to balanced line-to-neutral voltages of 69.3 kV in the electric power circuit, because 100 kV/100 V voltage transformers (Y-connected) are used in this project.
- The second step (step 2) has a duration of 72.0 s.

- During the second step, the internal relay test system emulates a current of 2.50 A at the phase-A current input of the relay. This is equivalent to a current of 500 A in the electric power circuit. Also, the phase angle of this current increases linearly from -180° to 180°, as shown in Figure 14, thereby covering the entire range of possible phase angle values.

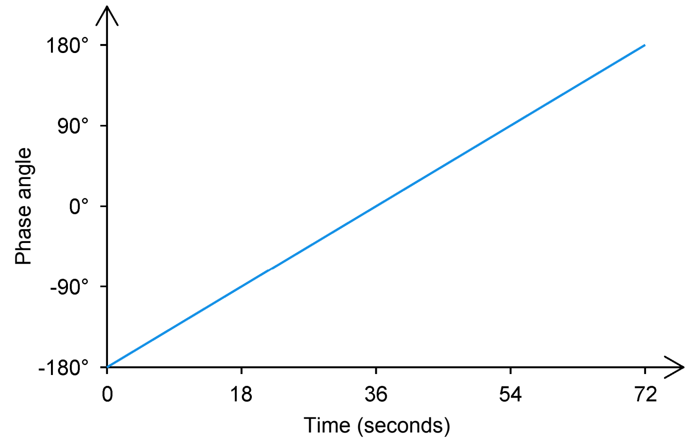


Figure 14. Phase angle of the current at phase A during step 2 of test sequence *Directional OC Relay Operation.*

- 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 emulated during step 1.
- 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 *Directional OC Relay Operation* to the frequency of your local ac power network.

11. Load the configuration (i.e., the content of the project file currently open) to the protective relay using DIGSI 5. This step generally takes some time.

12. In DIGSI 5, restart the protective relay in the simulation mode to allow the directional overcurrent protection function of the protective relay (i.e., protection function *67 Dir.OC-3ph-A1* in protection function group *VI 3ph 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.*

13. In DIGSI 5, start test sequence *Directional OC Relay Operation*, 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. For 5 seconds, the values of the balanced currents and voltages are displayed, then the magnitude of the current of phase A increases to 500 A and its phase angle decreases to -180°. The phase angle then slowly increases up to a value of 180°. Eventually, LED indicators 1, 9, and 16 light up.

Table 1 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 1. Functions of the LED indicators on the front panel of the protective relay.

LED indicator number	LED color	Function
1	Red	Pickup indication for phase A. The LED lights up when either the overcurrent protection function or the directional overcurrent protection function picks up.
2	Red	Same as LED indicator 1 for phase B.
3	Red	Same as LED indicator 1 for phase C.
7	Red	Overcurrent protection function tripped indication. The LED lights up when the overcurrent protection function trips the protective relay.
9	Red	Directional overcurrent protection function tripped indication. The LED lights up when the directional overcurrent protection function 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.

Explain why LED indicator 1 lit up during the simulation.

LED indicator 1 lit up because the relay picked up on phase A. This happened because, during a certain time (about 36 s), the magnitude (500 A) of the emulated current for phase A was higher than the current threshold (400 A) of the protective relay while this current flowed in the direction set in the relay (forward in this case).

Explain why LED indicators 9 and 16 lit up.

LED indicator 9 lit up to indicate that the directional overcurrent protection function tripped. This happened because the magnitude (500 A) of the emulated current for phase A was higher than the current threshold (400 A) of the protective relay while this current flowed in the direction set in the relay (forward in this case), for a time duration (about 36 s) much longer than the relay time delay (0.1 s).

LED indicator 16 lit up because the protective relay tripped.

14. 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 15 shows the signal representing the phase angle of the phase-A current and the pickup signal of the protective relay that should be displayed in SIGRA.

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

- Select *Instantaneous Values* (and not *R.M.S. Values*).
- Under the *Measuring Signal* column, select the phase angle of phase A (*VI3ph1:FdSym:Fundam:Iph:phs A angle*) for both cursors. The *Instantaneous* column then displays the phase angle values of the phase-A current at the time corresponding to cursors 1 and 2.
- Align the cursors with the beginning and end of the relay pickup signal.

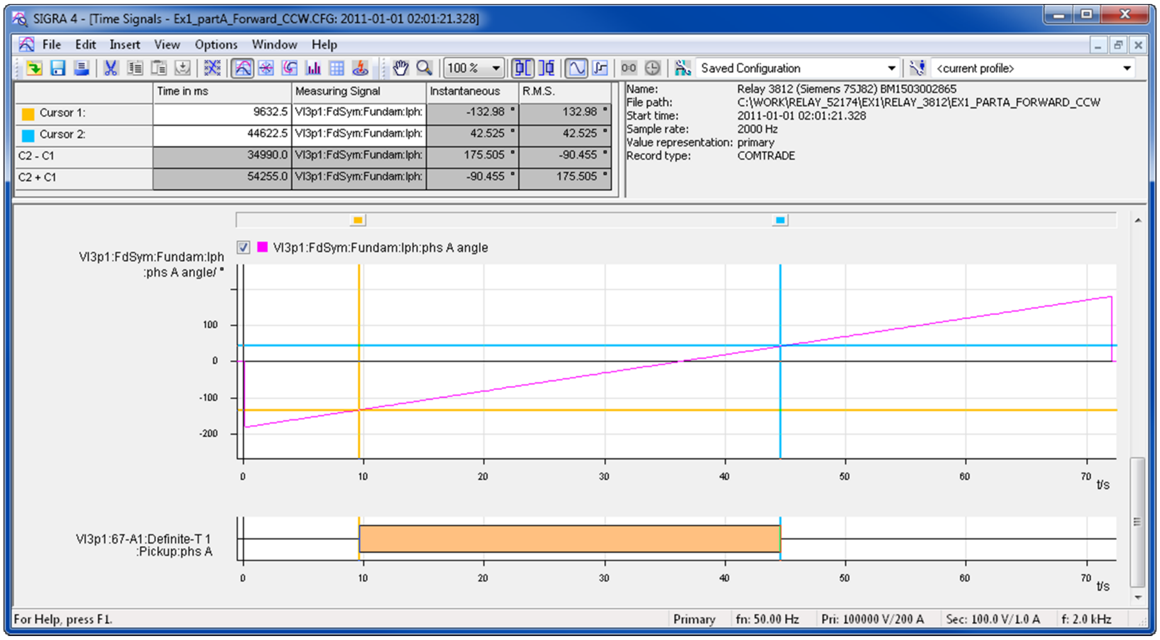


Figure 15. Signals contained in the fault record downloaded from the protective relay displayed in SIGRA.

For which range of phase angle values of the phase-A current did the relay pick up? Explain below and draw the forward direction zone of the relay in Figure 16.

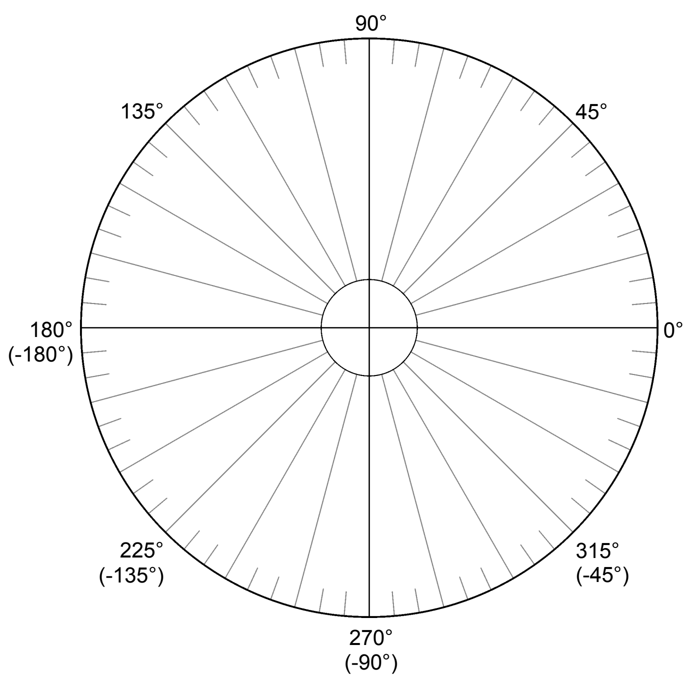


Figure 16. Experimental forward and backward direction zones of the directional overcurrent relay.

The relay picked up when the phase angle of the phase-A current was between about -133° (at t = 9.6 s) and 42.5° (at t = 44.6 s). This is a little less (175.5°) than the theoretical range of 180°, which spreads from phase angle values of -135° to 45° when the characteristic angle is set to 45°.

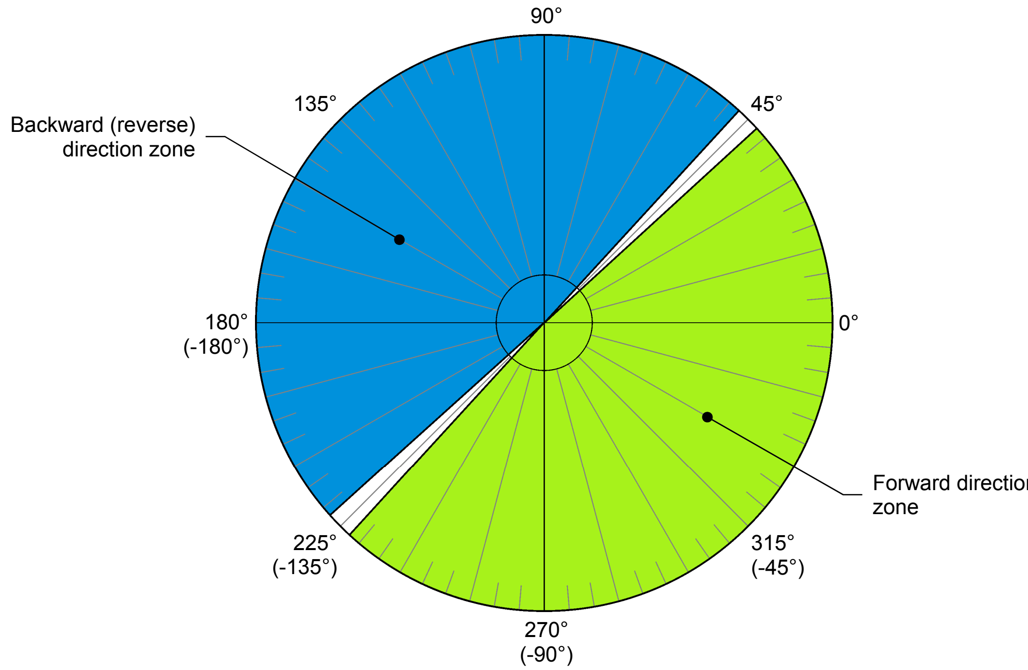


Figure 16. Experimental forward and backward direction zones of the directional overcurrent relay.

Similar results would be obtained if the phase angle of the phase-A current decreased linearly from 180° to -180° in the test sequence.

15. 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.

Backward (reverse) direction zone

16. In DIGSI 5, access the settings of the directional overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the directional overcurrent protection function is called *67 Dir.OC-3ph-A1* and is located in protection function group *VI 3ph 1*.

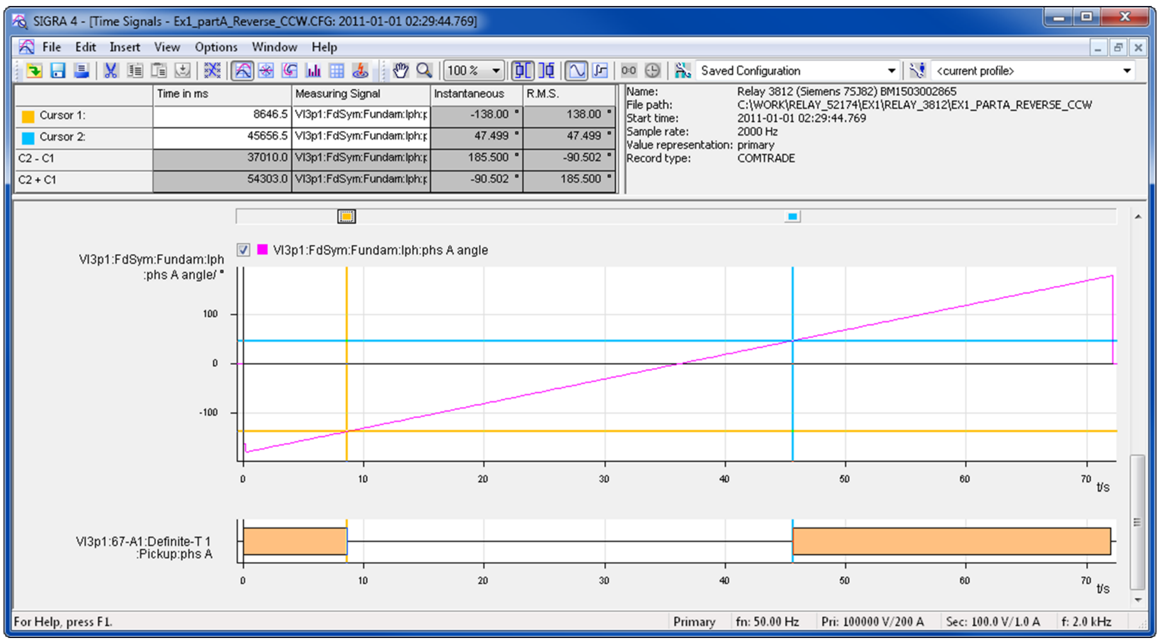
Change the direction of current flow (parameter *Directional mode*) to reverse.

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

18. In DIGSI 5, display the test environment of the protective relay. Start test sequence *Directional OC Relay Operation*, 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.

19. A fault record has been created in the protection 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.

The following figure shows the signals that should be displayed in SIGRA.



Signals contained in the fault record downloaded from the protective relay displayed in SIGRA.

For which range of phase angle values of the phase-A current did the relay pick up? Explain below and draw the <u>backward</u> direction zone of the relay in Figure 16.

The relay picked up when the phase angle of the phase-A current was between -180° and about -138° (at t = 8.6 s) and between about 47.5° (at t = 45.7 s) and 180°. Overall, the pickup range was approximately from phase angle values of 47.5° to 222° (-138°). This is a little less (174.5°) than the theoretical range of 180°, which spreads from phase angle values of 45° to 225° (-135°) when the characteristic angle is set to 45°.

20. Referring to Figure 13 and Figure 16, summarize the limitations of the directional overcurrent relay in determining the direction of current flow.

There are two small intervals (about 5° each) of phase angle of the measured current, located at the limit between the forward and backward direction zones, where the directional overcurrent relay considers that the direction of current flow is neither forward nor backward. This is because the relay is unable to determine the direction of current flow reliably when the value of the phase angle of the measured current is in either one of these two intervals of phase angle.

21. Reset the protective relay.

Directional overcurrent protection of power lines connected in parallel

In this section, you will assess how directional overcurrent protection can protect two power lines connected in parallel.

22. Look at the single line diagram shown in Figure 17. It illustrates two substations interconnected by two power lines connected in parallel. To protect the power lines, directional overcurrent protection is used. Each line is protected by an overcurrent relay close to substation A and a directional overcurrent relay close to substation B.

A directional overcurrent relay measures the circuit voltage via a voltage transformer. The voltage transformers have been omitted in Figure 17 for the sake of clarity. This applies to every other single line diagram in this exercise.

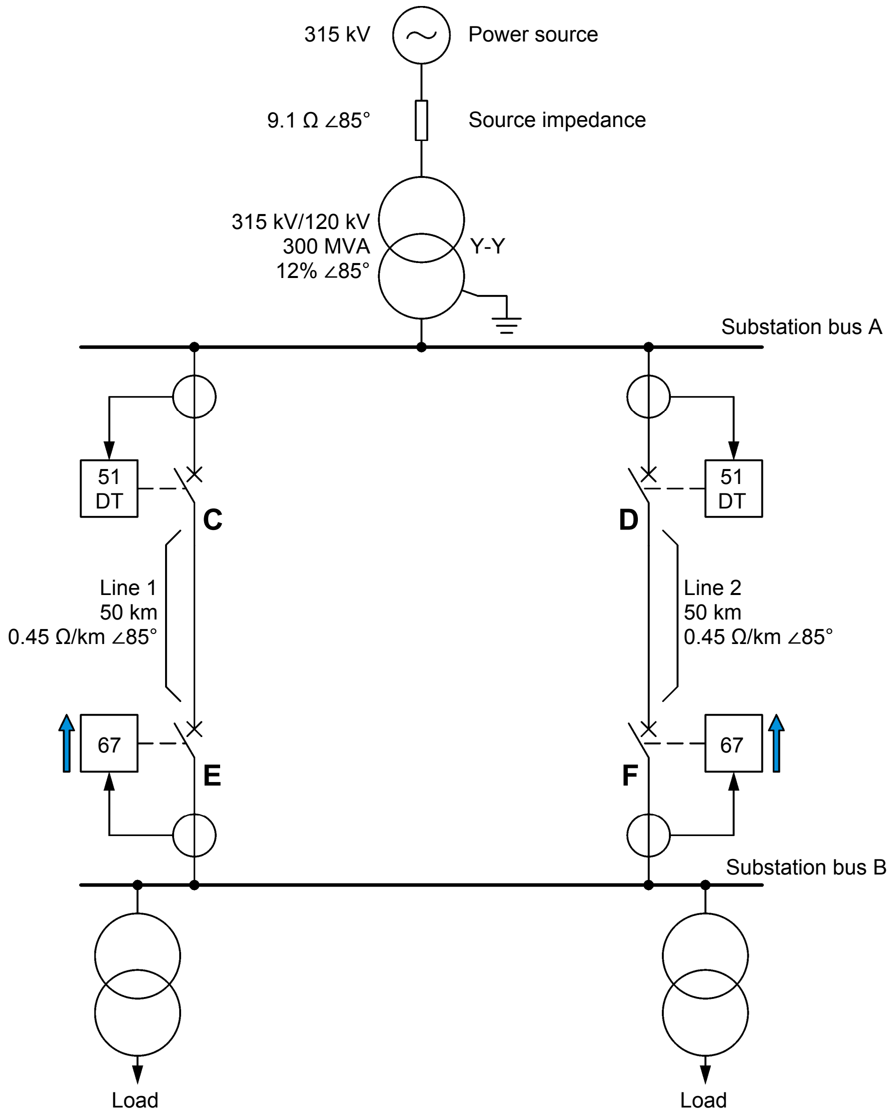


Figure 17. Substations interconnected by two power lines connected in parallel. Directional overcurrent protection is used to protect the power lines.

The magnitude and phase angle of the currents and voltages measured by the relays at locations C through F under normal operating conditions are given in Table 2.

All magnitudes are expressed as primary values, i.e., the values at the primary windings of the current and voltage transformers. Also, all phase angle values are referred to the phase angle of voltage E_{AN} at the power source (i.e., the phase angle of voltage E_{AN} at the power source is 0°).

Table 2. Currents and voltages in the circuit of Figure 17 under normal operating conditions.

	Relay C		Relay D	
	Magnitude	**Phase angle**	**Magnitude**	**Phase angle**
I_A (A, ∠°)	196	-6	196	-6
I_B (A, ∠°)	196	-126	196	-126
I_C (A, ∠°)	196	114	196	114
E_A (V, ∠°)	68809	-2	68809	-2
E_B (V, ∠°)	68809	-122	68809	-122
E_C (V, ∠°)	68809	118	68809	118
	Relay E ↑		**Relay F ↑**	
	Magnitude	**Phase angle**	**Magnitude**	**Phase angle**
I_A (A, ∠°)	196	174	196	174
I_B (A, ∠°)	196	54	196	54
I_C (A, ∠°)	196	-66	196	-66
E_A (V, ∠°)	68283	-6	68283	-6
E_B (V, ∠°)	68283	-126	68283	-126
E_C (V, ∠°)	68283	114	68283	114

Observe that the current at location E is phase shifted by 180° with respect to the current at location C. Also, the current at location F is phase shifted by 180° with respect to the current at location D. This is because the polarity of the current transformers at directional overcurrent relays E and F are reversed with respect to the polarity of the current transformers at overcurrent relays C and D. This practice is common when directional overcurrent relays are used to protect power lines connected in parallel, as explained later in this exercise.

Figure 18 shows the flow of the resulting fault currents for a ground fault on phase A located at 10 km from the load end of line 1.

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.

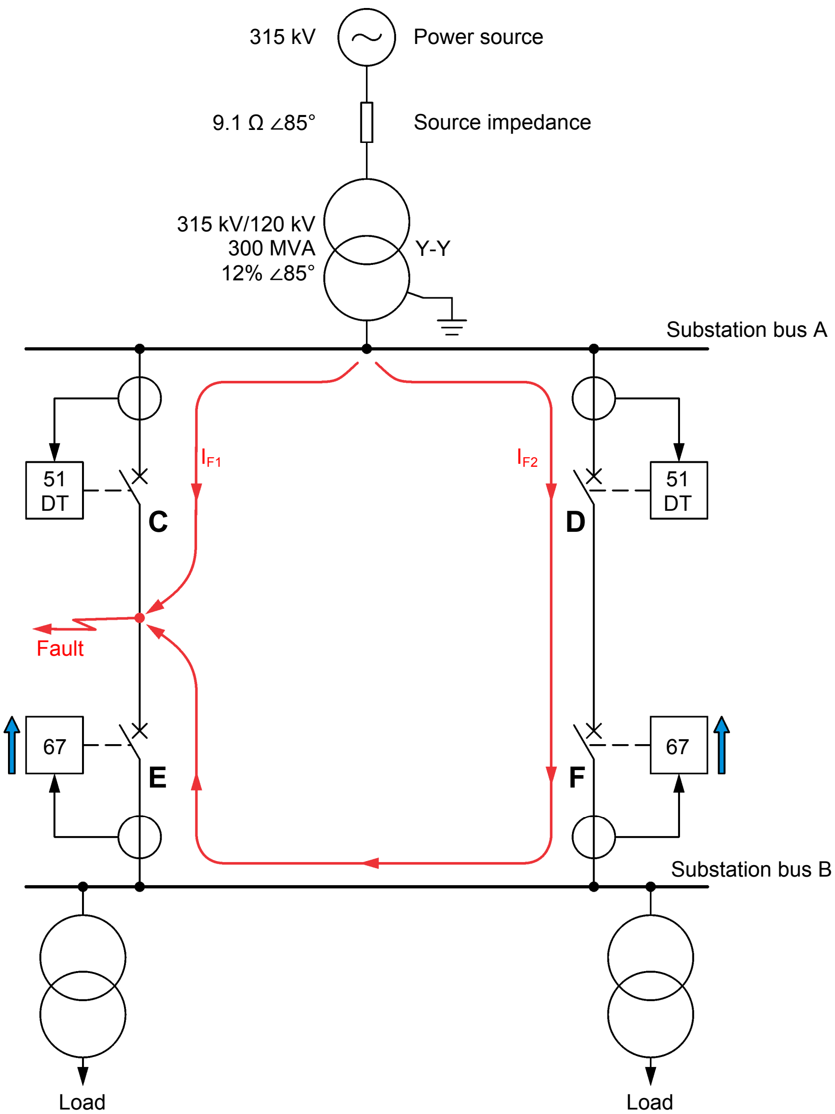


Figure 18. Flow of fault currents for a ground fault located at 10 km of the load end of line 1.

The magnitude and phase angle of the currents and voltages measured by the relays at locations C through F, assuming that the ground fault shown in Figure 18 occurs on phase A, are given in Table 3. Notice that a ground fault on phase A only affects the magnitude and phase angle of the current and voltage of phase A measured at locations C through F.

It is assumed here that the ground impedance (i.e., the impedance of the return path to the grounded terminal of the power transformer in Figure 18) is null.

Table 3. Currents and voltages in the circuit of Figure 17 under the ground fault condition (on phase A) shown in Figure 18.

	Relay C		Relay D	
	Magnitude	Phase angle	Magnitude	Phase angle
I_A (A, ∠°)	2324	-86	1550	-84
I_B (A, ∠°)	196	-126	196	-126
I_C (A, ∠°)	196	114	196	114
E_A (V, ∠°)	41833	0	41833	0
E_B (V, ∠°)	68809	-122	68809	-122
E_C (V, ∠°)	68809	118	68809	118
	Relay E ↑		**Relay F ↑**	
	Magnitude	**Phase angle**	**Magnitude**	**Phase angle**
I_A (A, ∠°)	1546	-86	1550	96
I_B (A, ∠°)	196	54	196	54
I_C (A, ∠°)	196	-66	196	-66
E_A (V, ∠°)	6958	-1	6958	-1
E_B (V, ∠°)	68283	-126	68283	-126
E_C (V, ∠°)	68283	114	68283	114

The settings of the definite-time overcurrent relays at locations C and D are given in Table 4, whereas the settings of the directional overcurrent relays at locations E and F are given in Table 5.

Table 4. Settings of the overcurrent relays at locations C and D.

Settings	Value
Current threshold	400 A
Time delay	0.4 s
CT ratio	200 A / 1 A

Table 5. Settings of the directional overcurrent relays at locations E and F.

Settings	Value
Characteristic angle	45°
Direction of current flow	Forward
Current threshold	400 A
Time delay	0.1 s
CT ratio	200 A / 1 A
VT ratio	100 kV / 100 V

23. In DIGSI 5, display the single-line diagram showing the connection of the protective relay to the electric power circuit.

Note the following very important point: the electric power circuit includes only one protective relay, whereas the protection system of the parallel power lines shown in Figure 17 includes four distinct protective relays.

To confirm that the protection system properly isolates the fault on line 1 (shown in Figure 18), you will:

- Program the protective relay in the DIGSI 5 project to act, in turn, as each of the four protective relays in the circuit of Figure 17.
- Obtain the response (i.e., whether or not the relay tripped, and if so, the trip time) of each relay under the ground fault condition shown in Figure 18.
- Analyze the response of each of the four relays to reconstitute the sequence of events that occurs when the relays at locations C through F in the circuit of Figure 17 are all in operation at the same time.

In this exercise, you will first obtain the response of the overcurrent relay at locations C and D. You will then obtain the response of the directional overcurrent relay at locations E and F.

For each of the four relays to be tested, a two-step test sequence bearing the name of the relay has been predefined in the DIGSI 5 project. The magnitude and phase angle of the currents and voltages in these sequences represent those given in Table 2 and Table 3.

24. In DIGSI 5, enable fault display on the relay.

The above setting allows the pickup and trip times of the relay to be read directly from the relay front panel display.

Operation of the overcurrent relays at locations C and D

25. In DIGSI 5, access the settings of the overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the overcurrent protection function is called *50/51 OC-3ph-B1* or *50/51 OC-3ph-A1* and is located in protection function group *VI 3ph 1*. Make sure the settings of the overcurrent protection function (current threshold and time delay) match those presented in Table 4.

Set the *Mode* parameter to on to activate the overcurrent protection function of the protective relay.

26. In DIGSI 5, access the settings of the directional overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the directional overcurrent protection function is called *67 Dir.OC-3ph-A1* and is located in protection function group *VI 3ph 1*.

Set the *Mode* parameter to off to deactivate the directional overcurrent protection function of the protective relay.

The protective relay is set to operate as the overcurrent relay at location C or D.

27. In DIGSI 5, access the parameters of test sequence *Testing of Relay C*. This test sequence is set so that the internal relay test system emulates the currents and voltages that the overcurrent relay at location C measures when the ground fault shown in Figure 18 occurs on phase A. The test sequence consists of two steps. The first step (step 1) has a duration of 10.0 s and the second step (step 2) has a duration of 2.0 s.

The magnitude and phase angle of the currents and voltages emulated during step 1 represent those given in Table 2 (normal operating conditions). The magnitude and phase angle of the currents and voltages emulated during step 2 represent those given in Table 3 (ground fault condition shown in Figure 18).

Note that 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 *Testing of Relay C* to the frequency of your local ac power network.

28. Load the configuration to the protective relay. This is necessary because the settings of the protection function have been modified to make the protective relay operate as an overcurrent relay having the settings shown in Table 4.

29. In DIGSI 5, display the test environment of the protective relay. Start test sequence *Testing of Relay C*, 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.

You may notice that the phase angle values displayed on the protective relay differ from those in the test sequence (presented in Table 2 and Table 3). This is because the protective relay assumes that the phase angle of voltage E_A is 0°, the phase angle values of all other currents and voltages being adjusted accordingly.

When the protective relay picks up or trips, information (protective function that picked up and tripped the relay, relay pickup time, relay trip time, etc.) about the response of the protective relay to the test sequence is displayed on the front panel display. Use the up and down arrow buttons on the relay front panel to scroll through this information.

Did the protective relay (i.e., the overcurrent relay at location C) operate? If so, record the trip time of the relay. Explain briefly.

Yes. The protective relay (i.e., the overcurrent relay at location C) tripped in about 400 ms because the magnitude of the emulated current for phase A (2324 A) was higher than the relay current threshold (400 A) for a time exceeding the relay time delay (0.4 s).

30. Reset the protective relay.

31. In DIGSI 5, access the parameters of test sequence *Testing of Relay D*. This test sequence is set so that the internal relay test system emulates the currents and voltages that the overcurrent relay at location D measures when the ground fault shown in Figure 18 occurs on phase A. Test sequence *Testing of Relay D* is built in the same manner as test sequence *Testing of Relay C*.

Set the frequency of the currents and voltages emulated during both steps of test sequence *Testing of Relay D* to the frequency of your local ac power network.

32. In DIGSI 5, display the test environment of the protective relay. Start test sequence *Testing of Relay D*, 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.

Did the protective relay (i.e., the overcurrent relay at location D) operate? If so, record the trip time of the relay. Explain briefly.

Yes. The protective relay (i.e., the overcurrent relay at location D) tripped in about 400 ms because the magnitude of the emulated current for phase A (1550 A) was higher than the relay current threshold (400 A) for a time exceeding the relay time delay (0.4 s).

33. Reset the protective relay.

Operation of the directional overcurrent relays at locations E and F

34. In DIGSI 5, access the settings of the directional overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the directional overcurrent protection function is called *67 Dir.OC-3ph-A1* and is located in protection function group *VI 3ph 1*. Make sure the settings of the directional overcurrent protection function (characteristic angle, direction of current flow, current threshold, and time delay) match those presented in Table 5.

Set the *Mode* parameter to on to activate the directional overcurrent protection function of the protective relay.

Observe that the direction of current flow (parameter *Directional mode*) is set to forward, whereas Figure 17 shows that the directional overcurrent relay at locations E and F look toward the power source, i.e., in the direction opposite to the expected direction of current flow under normal operating conditions (or reverse direction). This is because it is assumed that the polarity of the current transformers at the directional overcurrent relays is arranged in such a way that setting the direction of current flow to forward makes each relay look toward the line segment that it protects. This practice is common when directional overcurrent relays are used to protect power lines connected in parallel.

35. In DIGSI 5, access the settings of the overcurrent protection function of the protective relay. In the *Project tree* area of DIGSI 5, the overcurrent protection function is called *50/51 OC-3ph-B1* or *50/51 OC-3ph-A1* and is located in protection function group *VI 3ph 1*.

Set the *Mode* parameter to off to deactivate the overcurrent protection function of the protective relay.

The protective relay is now set to operate as the directional overcurrent relay at location E or F.

36. In DIGSI 5, access the parameters of test sequence *Testing of Relay E*. This test sequence is set so that the internal relay test system emulates the currents and voltages that the overcurrent relay at location E measures when the ground fault shown in Figure 18 occurs on phase A. Test sequence *Testing of Relay E* is built in the same manner as test sequence *Testing of Relay C*.

Set the frequency of the currents and voltages emulated during both steps of test sequence *Testing of Relay E* to the frequency of your local ac power network.

37. Load the configuration to the protective relay. This is necessary because the settings of the protection function have been modified to make the protective relay operate as a directional overcurrent relay having the settings shown in Table 5.

38. In DIGSI 5, display the test environment of the protective relay. Start test sequence *Testing of Relay E,* 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.

Did the protective relay (i.e., the directional overcurrent relay at location E) operate? If so, record the trip time of the relay. Explain briefly.

Yes. The protective relay (i.e., the directional overcurrent relay at location E) tripped in about 100 ms, because:

- the magnitude of the emulated current for phase A (1546 A) was higher than the relay current threshold (400 A).
- the emulated current for phase A was flowing in the same direction as the direction of current flow set in the relay (i.e., the phase angle [-86°] of the emulated current for phase A was in the forward direction zone of the relay).
- these two conditions lasted for a time exceeding the relay time delay (0.1 s).

39. Reset the protective relay.

40. In DIGSI 5, access the parameters of test sequence *Testing of Relay F*. This test sequence is set so that the internal relay test system emulates the currents and voltages that the overcurrent relay at location F measures when the ground fault shown in Figure 18 occurs on phase A. Test sequence *Testing of Relay F* is built in the same manner as test sequence *Testing of Relay C*.

Set the frequency of the currents and voltages emulated during both steps of test sequence *Testing of Relay F* to the frequency of your local ac power network.

41. In DIGSI 5, display the test environment of the protective relay. Start test sequence *Testing of Relay F*.

Did the protective relay (i.e., the directional overcurrent relay at location F) operate? If so, record the trip time of the relay. Explain briefly.

No. The protective relay (i.e., the directional overcurrent relay at location F) did not trip. Even if the magnitude of the emulated current for phase A (1550 A) was higher than the relay current threshold (400 A), the emulated current for phase A was flowing in the direction opposite to the direction of current flow set in the relay (i.e., the phase angle [96°] of the emulated current for phase A was not in the forward direction zone of the relay).

42. Reset the protective relay.

Analysis of the relay responses

43. Regroup the responses of the relays at locations C through F in Figure 19.

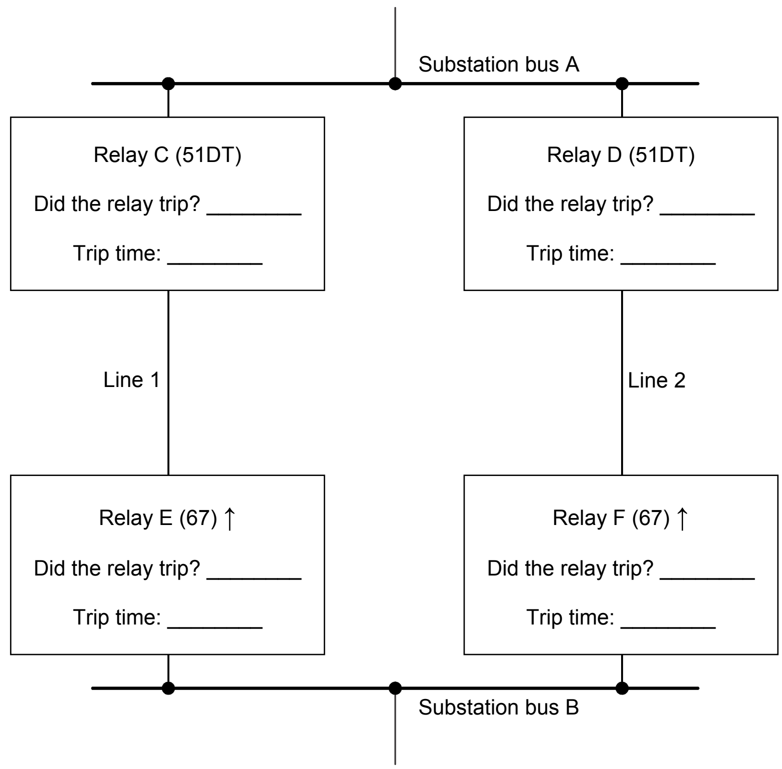


Figure 19. Responses of the relays.

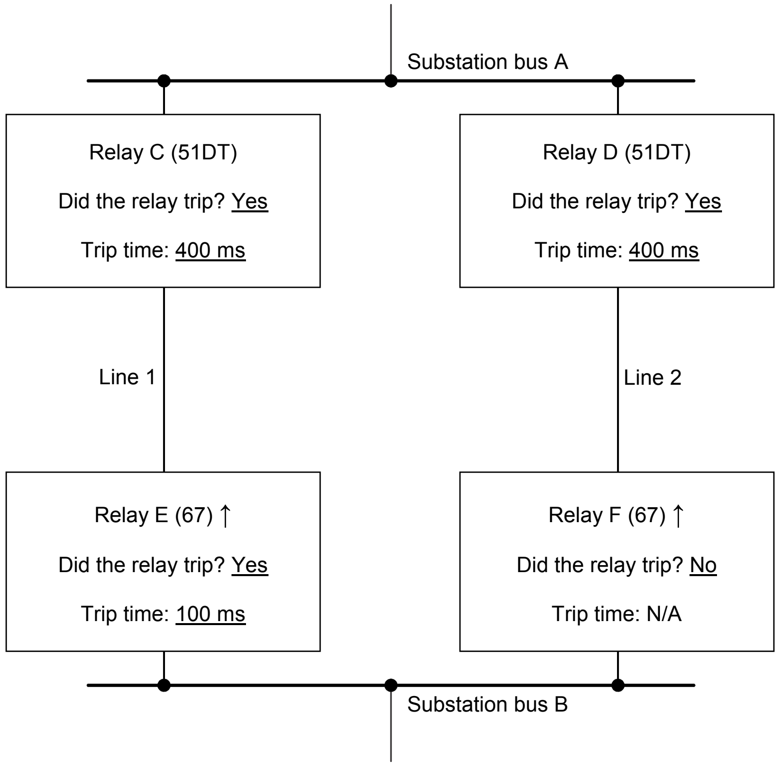


Figure 19. Responses of the relays.

Using the relay responses above, reconstitute the sequence of events that should occur when the relays at locations C through F are all in operation at the same time.

The directional overcurrent relay at location E trips about 100 ms after the ground fault occurred on phase A of line 1, because fault current I_{F2} (refer to Figure 18) flows in the same direction as the direction of current flow set in the relay. On the other hand, the directional overcurrent relay at location F does not trip, because fault current I_{F2} flows in the direction opposite to the direction of current flow set in the relay.

Tripping of the directional overcurrent relay at location E immediately opens the corresponding circuit breaker, thereby interrupting fault current I_{F2}. This, in turn, prevents the overcurrent relay at location D from tripping, because its time delay (0.4 s) largely exceeds the duration (about 100 ms) of fault current I_{F2}.

Finally, the overcurrent relay at location C trips about 400 ms after the fault occurred. This immediately opens the corresponding circuit breaker, thereby interrupting fault current I_{F1}.

How is the fault on line 1 isolated?

The fault on line 1 is isolated by the tripping of the relays at locations C and E.

How much time is required to clear the fault?

The directional overcurrent relay at location E operates in 100 ms, whereas the overcurrent relay at location C operates in 400 ms. It thus takes 400 ms to isolate the fault.

Does directional overcurrent protection isolate a fault on one of the two parallel connected lines while achieving proper discrimination? Explain briefly.

Yes. The protection isolates the fault while achieving proper discrimination. The faulty line (line 1) is disconnected and the healthy line (line 2) is left in service. Consequently, power is still available at substation bus B, thereby maintaining the availability of power at the load.

Ending the exercise

44. 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).

45. 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 learned how to determine the direction in which an alternating current flows. You became familiar with the operation of a directional overcurrent relay, including its main settings: direction of current flow, characteristic angle, current threshold, and time delay. You saw the range of phase angle that is expected for fault currents on a given phase. You also saw that setting the characteristic angle to 45° properly aligns the forward direction and backward direction zones of a directional overcurrent relay with the expected vectors of fault currents, thereby ensuring optimal detection of the direction of current flow. You experimentally verified the angular limits of the forward and backward direction zones of a directional overcurrent relay. You learned, and experimentally verified, how directional overcurrent protection achieves discriminative protection of two parallel-connected power lines.

REVIEW QUESTIONS

1. Why is the characteristic angle generally set to 45° in a directional overcurrent relay?

Setting the characteristic angle to 45° (typical value) properly aligns the forward and reverse direction zones of the directional overcurrent relay with the expected vectors of fault currents, thereby ensuring optimal detection of the direction of current flow.

2. Name the four main settings of a directional overcurrent relay.

The four main settings of a directional overcurrent relay are:

- Direction of current flow (forward or reverse)
- Current threshold
- Time delay
- Characteristic angle

3. How is the direction of current flow evaluated in an ac power circuit?

In an ac power circuit, one determines the direction of current flow from the phase shift between the voltage E and the current I at any given point of the circuit.

4. In a directional overcurrent relay, why is a voltage input required in addition to the current input?

In a directional overcurrent relay, a voltage input is required in addition to the current input to determine the direction of current flow via the phase shift between the voltage E and the current I.

5. Consider the two power lines connected in parallel as shown in Figure 17. Suppose that the polarity of the current transformers at each directional overcurrent relay is reversed, thereby causing each relay to look toward the load instead of toward the line segment that it protects. How could you fix this problem without changing the polarity of the current transformers?

This problem can be fixed by reversing the direction of current flow set in the directional overcurrent relay (i.e., set it to reverse).

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