Electricity and New Energy

Differential Protection

Course Sample

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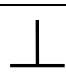
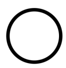
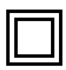
Safety and Common Symbols

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
	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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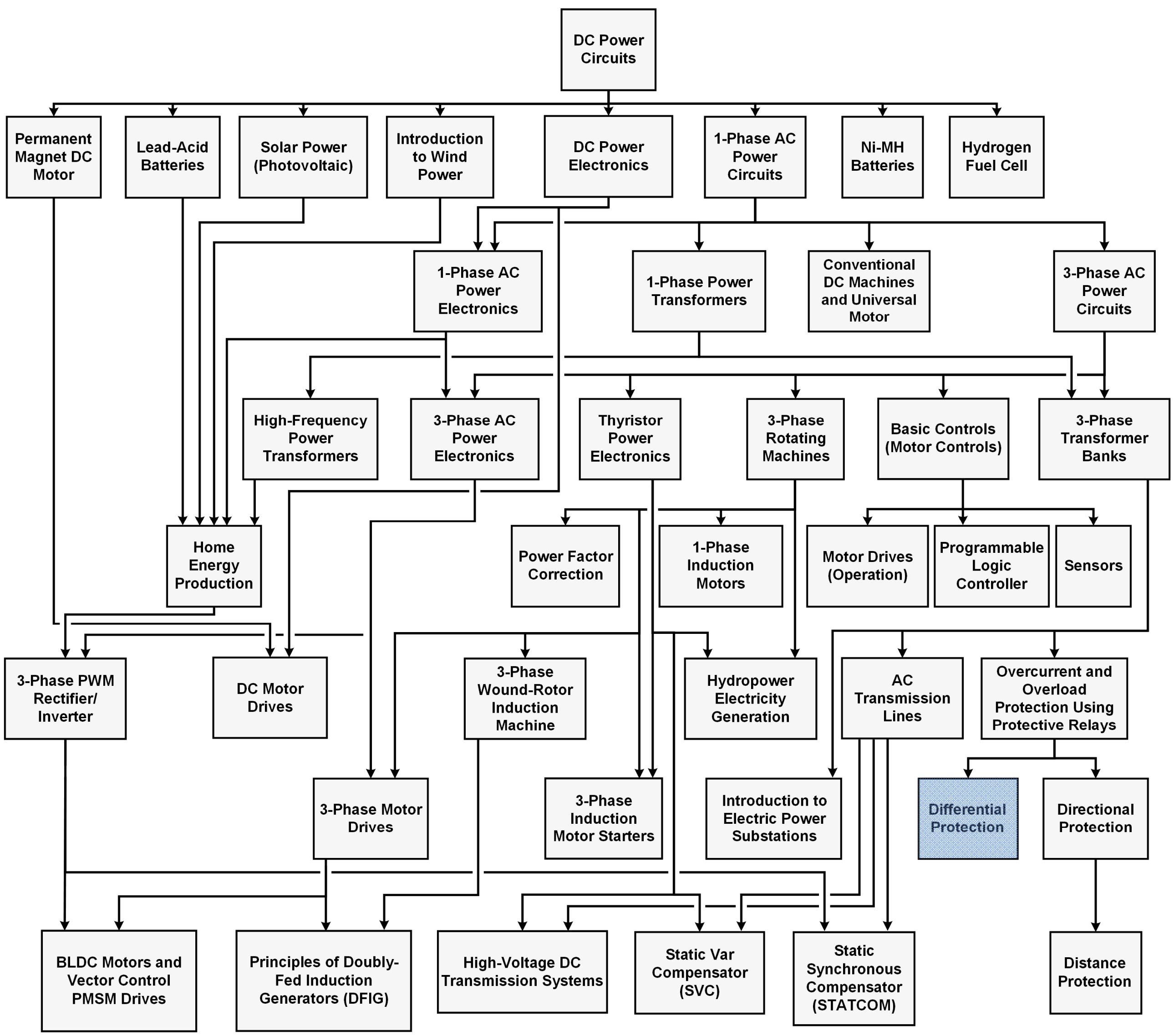
Preface

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 the principles of differential protection. You will know that differential protection is a type of unit protection that is used to protect costly and/or important equipment in electric power systems. You will be familiar with the operation and settings of the differential protective relay (ANSI device no. 87). You will know that differential protection using a fixed current threshold (current differential protection) has limited use because of its lack of sensitivity. You will be familiar with percentage restrained differential protection, a type of differential protection in which the current threshold is a percentage of the through current. You will be able to explain why percentage restrained differential protection provides equipment protection that is sensitive and stable. You will know how the characteristics of percentage restrained differential protection can be adjusted to take into account saturation of the current transformers. You will be familiar with common applications of differential 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, 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).

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

Fundamentals of Differential Protection

EXERCISE OBJECTIVE

In this exercise, you will learn the principle of differential protection, based on Kirchhoff's current law. You will see that current differential protection is implemented with an instantaneous overcurrent relay. You will learn about errors related to current measurement. You will understand the effect of these errors on the sensitivity of current differential protection.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Principle of differential protection
- Basic implementation of the differential protection (current differential protection)
- Current measuring errors in differential protection
- Effect of the current measuring error on the sensitivity of current differential protection

DISCUSSION

Principle of differential protection

Differential protection compares the magnitude and phase angle of the currents I_1 and I_2 (i.e., the current phasors I_1 and I_2) at both sides of the protected equipment to detect a fault in this equipment. The comparison of current phasors I_1 and I_2 is based on Kirchhoff's current law which states that the vector sum of the currents flowing through a node of an electric circuit is zero. This is written as a generic equation below.

$$\vec{I_1} + \vec{I_2} + \cdots + \vec{I_n} = 0 \text{ A} \quad (1)$$

Figure 2 illustrates Kirchhoff's current law for a three-branch node in an electric circuit.

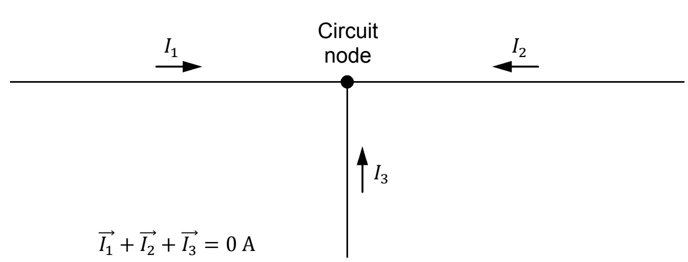


Figure 2. Kirchhoff's current law applied to a three-branch node in an electric circuit.

To respect Kirchhoff's current law, current phasors I_1 and I_2 at both sides of the protected equipment are generally defined as shown in Figure 3. With this convention, current entering the protected equipment is considered to be positive while current leaving the protected equipment is considered to be negative.

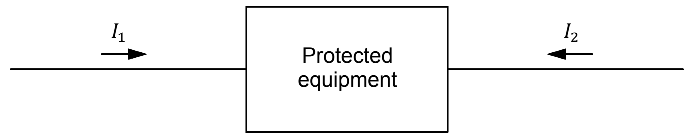
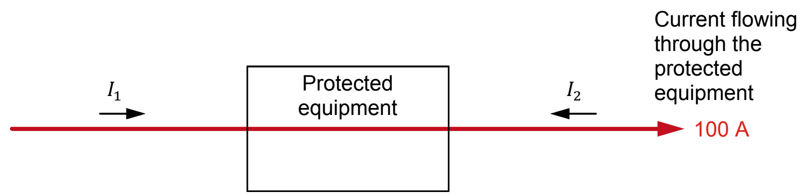


Figure 3. Definition of the current phasors at both sides of the protected equipment respecting Kirchhoff's current law.

When no fault is present in the protected equipment, the current entering the protected equipment has the same magnitude as the current leaving the protected equipment, but these currents are of opposite polarity (i.e., they are phase shifted by 180°). In this case, the sum of current phasors I_1 and I_2 at both sides of the protected equipment is null, as illustrated in Figure 4.



$$\vec{I_1} = 100\ \text{A}\ \angle 0° \qquad \vec{I_2} = -\vec{I_1} = 100\ \text{A}\ \angle 180°$$

$$\vec{I_1} + \vec{I_2} = \vec{I_1} + \left(-\vec{I_1}\right) = 100\ \text{A}\ \angle 0° + 100\ \text{A}\ \angle 180° = 0\ \text{A}$$

Figure 4. When no fault is present in the protected equipment, the sum of current phasors I_1 and I_2 at both sides of the protected equipment is zero.

On the other hand, when a fault occurs in the protected equipment and causes current to enter both sides of the protected equipment, the sum of current phasors I_1 and I_2 at both sides of the protected equipment is not zero. This is illustrated in Figure 5.

In the example given in Figure 5, the currents entering both sides of the protected equipment are considered perfectly in phase to ease calculation of the vector sum. When a fault occurs in actual equipment, however, the currents entering both sides of the protected equipment are rarely in phase. The phase relationship between these currents depends on the circuit parameters (fault location, source impedance, circuit impedance, etc.).

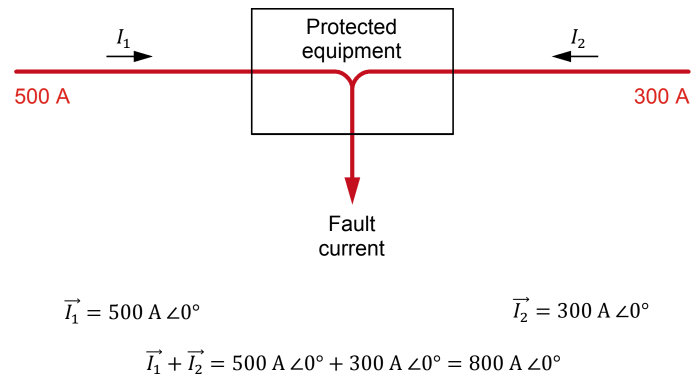


Figure 5. When a fault is present in the protected equipment, the sum of current phasors I_1 and I_2 at both sides of the protected equipment is no longer zero.

In conclusion, the sum of current phasors I_1 and I_2 is ideally suited to detect the presence of a fault in the protected equipment.

Basic implementation of the differential protection (current differential protection)

Figure 6 is a single-line diagram that shows the basic implementation of differential protection. Two current transformers are used to measure the currents I_1 and I_2 at both sides of the protected equipment. The current transformers are connected so as to respect the convention stated above (i.e., a current entering the protected equipment is considered to be positive and vice versa), as indicated by the arrows in Figure 6.

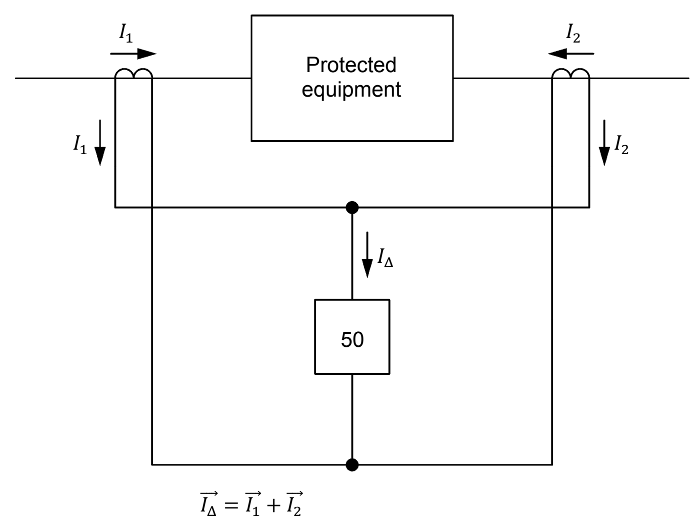


Figure 6. Single-line diagram showing the basic implementation of differential protection (current differential protection).

Figure 7 shows an alternate single-line diagram that uses the dot convention (small black circles) to indicate the polarity of the current transformers. The dot convention states that a current entering a dot-marked terminal at the primary winding of a current transformer results in a current leaving the similarly dot-marked terminal at the secondary winding of the current transformer, and vice versa.

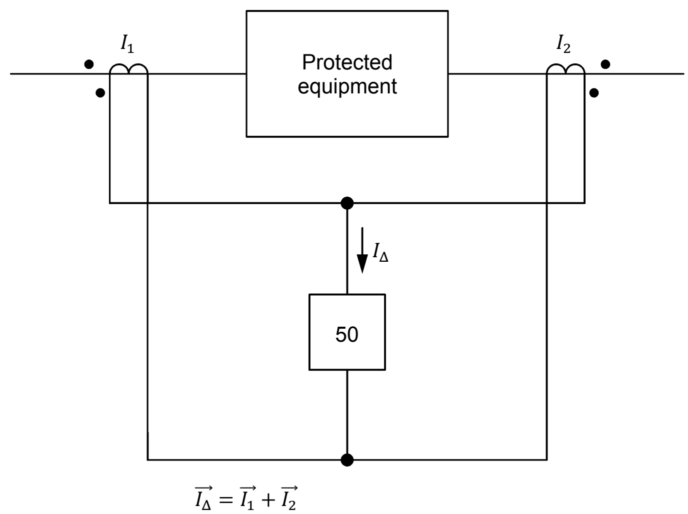


Figure 7. Single line diagram showing the basic implementation of differential protection (current differential protection). The dot convention is used to indicate the polarity of the current transformers.

The secondary windings of the current transformers in Figure 6 and Figure 7 are connected to an instantaneous overcurrent relay (ANSI device no. 50) in such a way that the differential current I_Δ flowing through this relay is equal to the sum of current phasors I_1 and I_2. This implementation of differential protection is commonly referred to as **current differential protection**.

Two current transformers and an instantaneous overcurrent relay connected as in Figure 7 are required to protect each phase of the power system.

When no fault is present in the protected equipment, the sum of current phasors I_1 and I_2 is null (i.e., differential current I_Δ is zero) and the instantaneous overcurrent relay takes no action. This is illustrated in Figure 8. Note that the red arrows in Figure 8 indicate the direction of the currents flowing in the circuit.

On the other hand, when a fault occurs in the protected equipment, the sum of current phasors I_1 and I_2 is no longer zero (i.e., differential current $I_\Delta \neq 0$). Consequently, the instantaneous overcurrent relay trips because the value of the differential current I_Δ exceeds the current setting of the relay. This is illustrated in Figure 9.

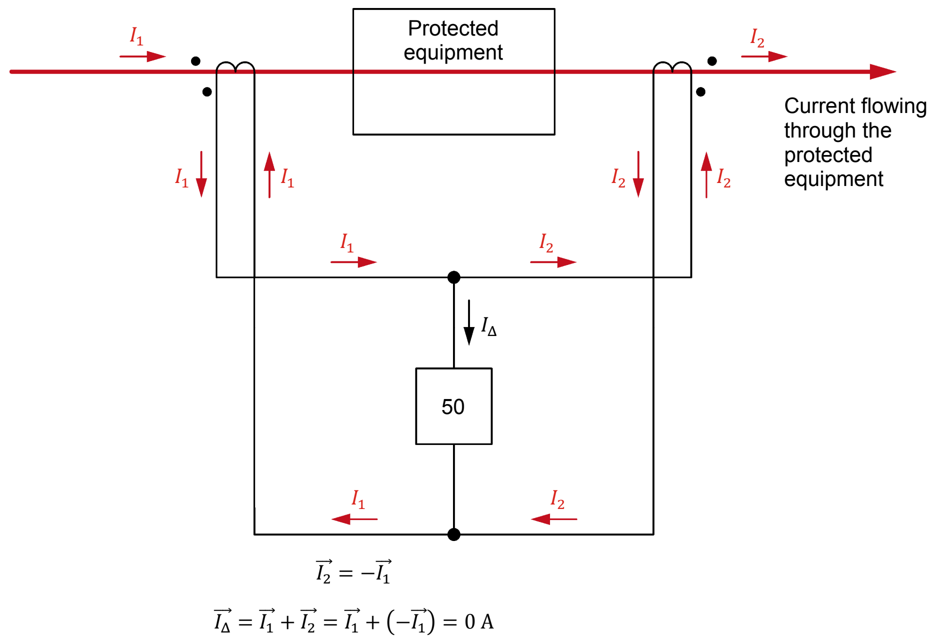


Figure 8. When no fault is present in the protected equipment, the differential current I_Δ is zero and the instantaneous overcurrent relay takes no action.

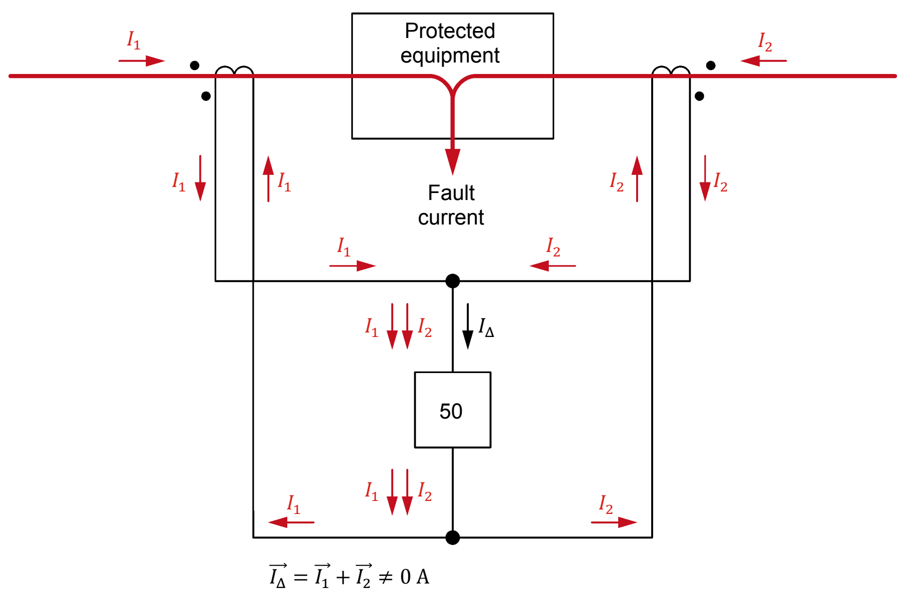


Figure 9. When a fault is present in the protected equipment, the instantaneous overcurrent relay trips because the value of the differential current I_Δ exceeds the current setting of the relay.

Tripping of the instantaneous overcurrent relay is used to trip circuit breakers located at both sides of the protected equipment (for the sake of clarity, these circuit breakers are not shown in the figures above). This immediately isolates the protected equipment from the power system, thereby preventing, or at least minimizing, damage to both the power system and the protected equipment.

The implementation of current differential protection shown so far applies when either an electromechanical relay or a static protective relay is used. Figure 10 is a single-line diagram that shows the implementation of differential protection using a **differential protective relay** (ANSI device no. 87) of numerical type. Notice that the numerical differential protective relay has two independent current inputs, each input being connected to the secondary winding of one of the two current transformers of the differential protection system. A computer algorithm running in the numerical differential protective relay calculates the sum of current phasors I_1 and I_2 (i.e., the value of the differential current I_Δ) from the currents measured at the two current inputs.

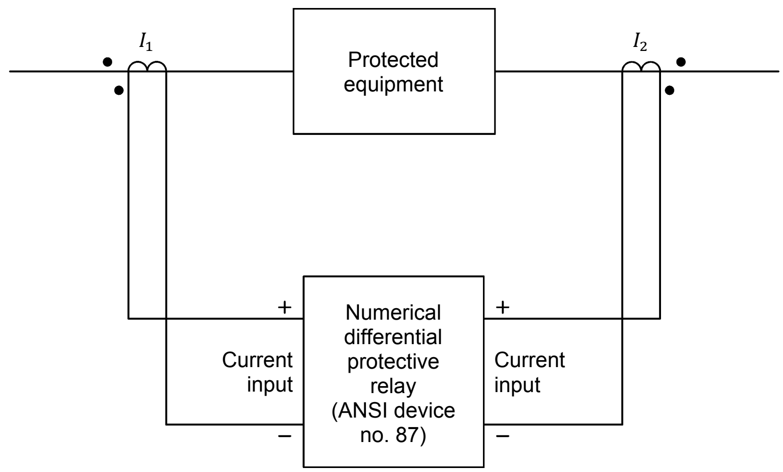


Figure 10. Single-line diagram showing differential protection implemented with a differential protective relay (ANSI device no. 87) of numerical type.

Current measuring errors in differential protection

Differential protection measures the currents I_1 and I_2 at both sides of the protected equipment to detect faults in the equipment. Like other measuring devices, current transformers have a limited accuracy which results in an error in the magnitude of the measured current. The accuracy of current transformers intended for protective relaying (e.g., C-class current transformers) is generally 10%, provided no saturation occurs in the current transformer. This means that the error on the magnitude of the measured current is guaranteed to be 10% or less up to a current of 20 times the rated current of the current transformer. In fact, the actual error on the magnitude of the measured current largely depends on the **burden** imposed to the current transformer. The higher the burden, the higher the error up to a value of 10%.

Similarly, protective relays (e.g., the instantaneous overcurrent relay used in current differential protection) also have a limited accuracy. The accuracy of the current inputs of protective relays is generally 5%. This means that the error on the magnitude of the current measured by the relay is guaranteed to be 5% or less.

The current measuring errors of the current transformers (10%) and the protective relay (5%) used in a differential protection system are combined, which results in a total error of 15%. This means that the error on the magnitude of the differential current I_Δ measured by the protective relay in a differential protection system is at most 15%.

Two current transformers having 10% accuracy introduce a current measuring error in a differential protection system which is at most 10%. This is because the current measuring error of a current transformer always has the same polarity, i.e., the magnitude of the current at the secondary winding of a current transformer is always a little less than the magnitude expected in theory. This is due to the fact that the magnetizing current producing the magnetic flux required for the current transformer operation subtracts from the current at the secondary winding.

Effect of the current measuring error on the sensitivity of current differential protection

The current measuring error due to the limited accuracy of the current transformers and current inputs of the protective relay used in a differential protection system introduces an error in the magnitude of the measured differential current I_Δ. More specifically, the current measuring error causes the magnitude of the measured differential current I_Δ to have a value other than zero even when no fault affects the protected equipment. Figure 11 is a graph of the magnitude of the differential current I_Δ that can be measured as a function of the magnitude of the current flowing through the protected device (i.e., the through current $I_{Through}$) when no fault affects the protected equipment and the current measuring error in the differential protection system is 15%. Notice that the magnitude of the differential current I_Δ and that of the through current $I_{Through}$ are expressed in multiples of the rated current (generally the rating of the current input of the protective relay). The graph shows that the magnitude of the measured differential current I_Δ increases proportionally with the through current $I_{Through}$. The magnitude of the differential current I_Δ can reach up to 3 I_{Rated} at a through current $I_{Through}$ of 20 I_{Rated}, even if no fault affects the protected equipment.

Figure 11 shows the maximum magnitude of the differential current I_Δ that can be measured when there is no fault in the protected equipment and the current measuring error in the differential protection system, determined from the rated accuracy of the current transformers and protective relay, is 15%. The actual magnitude of the differential current I_Δ measured can be less than what is shown in the graph depending on the actual current measuring error in the differential protection system.

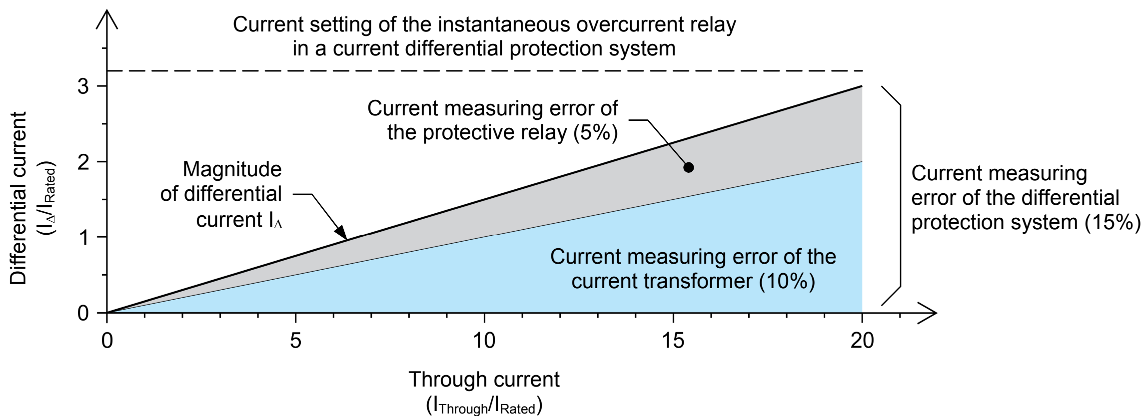


Figure 11. Magnitude of the measured differential current I_{Δ} as a function of the magnitude of the through current $I_{Through}$ when no fault affects the protected equipment and the current measuring error in the differential protection system is 15%.

When the measuring error is 15% as in the example above, the relay current setting has to be set a little above 3.0 I_{Rated} to ensure that the instantaneous overcurrent relay in a current differential protection system does not trip up to a maximum through current $I_{Through}$ of 20 I_{Rated}. For example, the relay current setting could be set to 3.2 I_{Rated}, as shown by the dotted line in Figure 11. Consequently, any fault affecting the protected equipment that results in a differential current I_{Δ} having a magnitude lower than this current setting remains undetected. This results in poor sensitivity of the current differential protection.

It is common to consider through currents with a magnitude up to 20 times the rated current, because currents of such magnitude can flow through the protected equipment when a fault occurs elsewhere in the power system. Also, the accuracy of current transformers is valid for currents with a magnitude up to 20 times the rated current of the current transformer.

Furthermore, other sources of errors (covered in the discussion of Exercise 2) increase the magnitude of the differential current I_{Δ} measured when no fault affects the protected equipment. Consequently, the current setting required to maintain the stability of the instantaneous overcurrent relay in a current differential protection system has to be increased, thereby further reducing the already-poor sensitivity of the protection. Because of its lack of sensitivity, current differential protection has limited use for equipment protection. However, studying current differential protection is useful as an introduction to **percentage restrained differential protection**, a form of differential protection that is commonly used for equipment protection. Percentage restrained differential protection, which has much better sensitivity than current differential protection, is discussed in the second exercise of this manual.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Analyzing an ideal current differential protection system
- Analyzing a current differential protection system with 15% current measuring error
- Testing the current differential protection system analyzed in the previous section
- 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.

Analyzing an ideal current differential protection system

In this section, you will analyze an ideal current differential protection system, i.e., a system in which the current measuring error is 0%.

1. Consider the single-line diagram of Figure 12. It shows a power transformer protected using current differential protection. For the sake of simplicity, the power transformer is considered to have a Y-Y configuration, unity turn ratio, negligible magnetizing current, and a nominal line current of 1000 A.

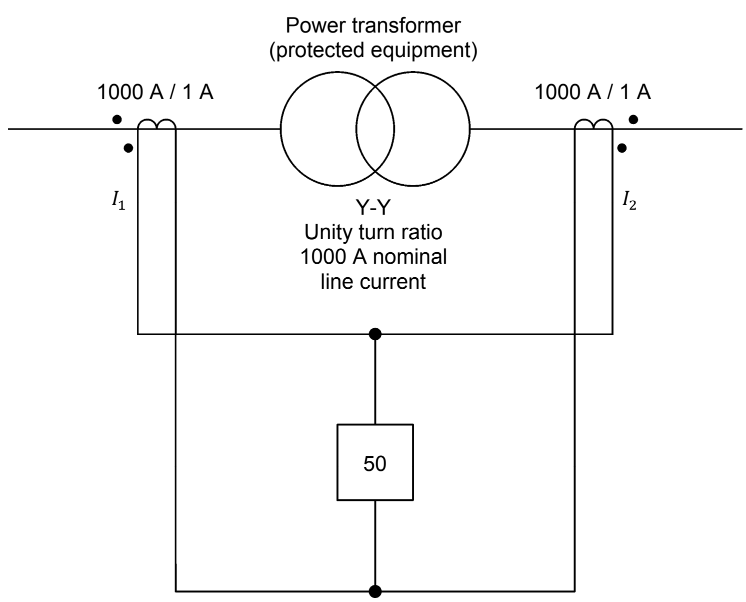


Figure 12. Single-line diagram showing a power transformer protected using current differential protection.

Two current transformers having a 1000 A / 1 A ratio and an instantaneous overcurrent relay having a 1 A current input are used to implement the current differential protection. Consequently, the rated current I_{Rated} is equal to 1 A.

The current setting of the instantaneous overcurrent relay is 0.25 I_{Rated}.

Also, it is assumed that the maximum value of current that can flow through the transformer during an external fault (i.e., the maximum through current) is equal to 12 I_{Rated}.

2. Table 1 shows the values (magnitude and phase angle) of current phasors I_1 and I_2 measured at both sides of the power transformer for through currents equal to I_{Rated}, 5 I_{Rated}, and 12 I_{Rated}. It also shows the values of current phasors I_1 and I_2 measured when a light fault affects the power transformer. In all cases, an ideal current differential protection system is assumed (i.e., the current measuring error is 0%).

The magnitude of current phasors I_1 and I_2 is expressed in multiples of current I_{Rated}.

Table 1. Evaluation of the current differential protection (current measuring error: 0%, relay current setting: 0.25 I_{Rated}).

Circuit condition	I_1 (I/I_{Rated} ∠°)	I_2 (I/I_{Rated} ∠°)	I_Δ (I/I_{Rated} ∠°)	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	1.0 ∠0°	1.0 ∠180°			
Through current (5 I_{Rated})	5.0 ∠0°	5.0 ∠180°			
Through current (12 I_{Rated})	12.0 ∠0°	12.0 ∠180°			
Faulty power transformer	2.0 ∠0°	0.0 ∠0°			

3. For each of the four circuit conditions in Table 1,

- calculate the value of the differential current I_Δ.
- determine whether or not the differential current I_Δ makes the instantaneous overcurrent relay trip, considering the relay current setting is 0.25 I_{Rated}.
- determine whether or not the current differential protection works properly.

Record your results in Table 1.

Table 1. Evaluation of the current differential protection (current measuring error: 0%, relay current setting: 0.25 I_{Rated}).

Circuit condition	I_1 (I/I_{Rated} ∠°)	I_2 (I/I_{Rated} ∠°)	I_Δ (I/I_{Rated} ∠°)	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	1.0 ∠0°	1.0 ∠180°	0.0	No	OK
Through current (5 I_{Rated})	5.0 ∠0°	5.0 ∠180°	0.0	No	OK
Through current (12 I_{Rated})	12.0 ∠0°	12.0 ∠180°	0.0	No	OK
Faulty power transformer	2.0 ∠0°	0.0 ∠0°	2.0 ∠0°	Yes	OK

4. From the data recorded in Table 1, can you conclude that current differential protection works perfectly when the current measuring error is 0%? Explain briefly.

Yes, current differential protection works perfectly when the current measuring error is 0%. The instantaneous overcurrent relay in the current differential protection does not trip when no fault affects the power transformer, no matter the magnitude of the current flowing through the power transformer. On the other hand, the relay trips when a fault affects the power transformer.

Analyzing a current differential protection system with 15% current measuring error

In this section, you will analyze a current differential protection system with a current measuring error of 15%.

5. Table 2 shows the values (magnitude and phase angle) of current phasors I_1 and I_2 measured at both sides of the power transformer for the same four circuit conditions considered earlier in the exercise. This time, however, the current measuring error in the current differential protection system is assumed to be 15%. Notice that the current measuring error of 15% is introduced by reducing the magnitude of current phasor I_1 by 15%.

Table 2. Evaluation of the current differential protection (current measuring error: 15%, relay current setting: 0.25 I_{Rated}).

Circuit condition	I_1 (I/I_{Rated} ∠°)	I_2 (I/I_{Rated} ∠°)	I_Δ (I/I_{Rated} ∠°)	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	0.85 ∠0°	1.0 ∠180°			
Through current (5 I_{Rated})	4.25 ∠0°	5.0 ∠180°			
Through current (12 I_{Rated})	10.2 ∠0°	12.0 ∠180°			
Faulty power transformer	1.70 ∠0°	0.0 ∠0°			

6. For each of the four circuit conditions in Table 2,
   - calculate the value of the differential current I_Δ.
   - determine whether or not the differential current I_Δ makes the instantaneous overcurrent relay trip, considering the relay current setting is still 0.25 I_{Rated}.
   - determine whether or not the current differential protection works properly.

   Record your results in Table 2.

Table 2. Evaluation of the current differential protection (current measuring error: 15%, relay current setting: 0.25 I_{Rated}).

Circuit condition	I_1 (I/I_{Rated} ∠°)	I_2 (I/I_{Rated} ∠°)	I_Δ (I/I_{Rated} ∠°)	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	0.85 ∠0°	1.0 ∠180°	0.15 ∠180°	No	OK
Through current (5 I_{Rated})	4.25 ∠0°	5.0 ∠180°	0.75 ∠180°	Yes	Unwanted tripping
Through current (12 I_{Rated})	10.2 ∠0°	12.0 ∠180°	1.80 ∠180°	Yes	Unwanted tripping
Faulty power transformer	1.70 ∠0°	0.0 ∠0°	1.70 ∠0°	Yes	OK

7. From the data recorded in Table 2, can you conclude that current differential protection works perfectly when the current measuring error is not null (15% in the present case). Explain briefly.

No, current differential protection does not work perfectly when the current measuring error is not null. With a current measuring error of 15%, the magnitude of the differential current I_{Δ} exceeds the current setting of the instantaneous overcurrent relay at through currents of 5 I_{Rated} and 12 I_{Rated}. Consequently, the relay trips while no fault affects the power transformer. Fortunately, the instantaneous overcurrent relay trips when a fault affects the power transformer.

8. In the previous step, you found that unwanted tripping of the current differential protection can occur when the current measuring error is not null (15% in the present case). What can then be done to prevent unwanted tripping?

Increase the current setting of the instantaneous overcurrent relay used in the current differential protection so that it slightly exceeds the maximum value which the differential current I_{Δ} can reach when no fault affects the protected transformer (i.e., the value which the differential current I_{Δ} reaches at the maximum through current). In the present case, the maximum through current is equal to 12 I_{Rated} (as stated in step 1). When the current measuring error is 15%, the maximum value of the differential current I_{Δ} is thus equal to 1.8 I_{Rated}.

Increased current threshold

9. Table 3 shows the values (magnitude and phase angle) of current phasors I1 and I2 measured at both sides of the power transformer for the same four circuit conditions considered earlier in the exercise and a current measuring error in the current differential protection system of 15%. This time, however, the system will be analyzed considering a relay current setting of 2.0 I_{Rated}.

Table 3. Evaluation of the current differential protection (current measuring error: 15%, relay current setting: 2.0 I_{Rated}).

Circuit condition	I_1 (I/I_{Rated} ∠°)	I_2 (I/I_{Rated} ∠°)	I_Δ (I/I_{Rated} ∠°)	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	0.85 ∠0°	1.0 ∠180°			
Through current (5 I_{Rated})	4.25 ∠0°	5.0 ∠180°			
Through current (12 I_{Rated})	10.2 ∠0°	12.0 ∠180°			
Faulty power transformer	1.70 ∠0°	0.0 ∠0°			

10. For each of the four circuit conditions in Table 3,

- calculate the value of the differential current I_Δ.
- determine whether or not the differential current I_Δ makes the instantaneous overcurrent relay trip, considering the relay current setting is now 2.0 I_{Rated}.
- determine whether or not the current differential protection works properly.

Record your results in Table 3.

Table 3. Evaluation of the current differential protection (current measuring error: 15%, relay current setting: 2.0 I_{Rated}).

Circuit condition	I_1 (I/I_{Rated} ∠°)	I_2 (I/I_{Rated} ∠°)	I_Δ (I/I_{Rated} ∠°)	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	0.85 ∠0°	1.0 ∠180°	0.15 ∠180°	No	OK
Through current (5 I_{Rated})	4.25 ∠0°	5.0 ∠180°	0.75 ∠180°	No	OK
Through current (12 I_{Rated})	10.2 ∠0°	12.0 ∠180°	1.80 ∠180°	No	OK
Faulty power transformer	1.70 ∠0°	0.0 ∠0°	1.70 ∠0°	No	Fault not detected

11. From the data recorded in Table 3, does increasing the current setting of the instantaneous overcurrent relay to 2.0 I_{Rated} prevent unwanted tripping of the current differential protection?

❑ Yes ❑ No

Yes

What is the adverse effect on the current differential protection of increasing the current setting of the instantaneous overcurrent relay to 2.0 I_{Rated}?

Increasing the current setting of the instantaneous overcurrent relay significantly reduces the sensitivity of the current differential protection. Any fault in the protected equipment resulting in a differential current I_{Δ} having a magnitude of less than 2.0 I_{Rated} is not detected by the current differential protection.

Testing the current differential protection system analyzed in the previous section

In this section, you will test a current differential protection system using a protective relay and a host computer.

12. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the next steps.

Install the Numerical Differential Protective Relay (Model 3819) 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.

13. 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).

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

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

16. In DIGSI 5, open project file *Current Differential 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 52175, Differential Protection\...*

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

17. In DIGSI 5, display the single-line diagram showing the connection of the protective relay to the electric power circuit. Observe that the diagram is similar to the single-line diagram of the power transformer protected by a current differential protection system shown in Figure 12.

Notice 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 1000 A/1 A ratio.

The differential protective relay used in this project is of numerical type, and thus, has two distinct current inputs for each phase of the power system. Consequently, the differential protective relay has a total of six current inputs. The secondary winding of each of the current transformers on both sides of the protected equipment (a power transformer in the present case) is connected to a distinct current input of the differential protective relay, as shown in Figure 13. The relay uses the currents it measures at its inputs to compute the sum of current phasors I_1 and I_2 (i.e., the value of the differential current I_Δ) for each of the three phases of the power system.

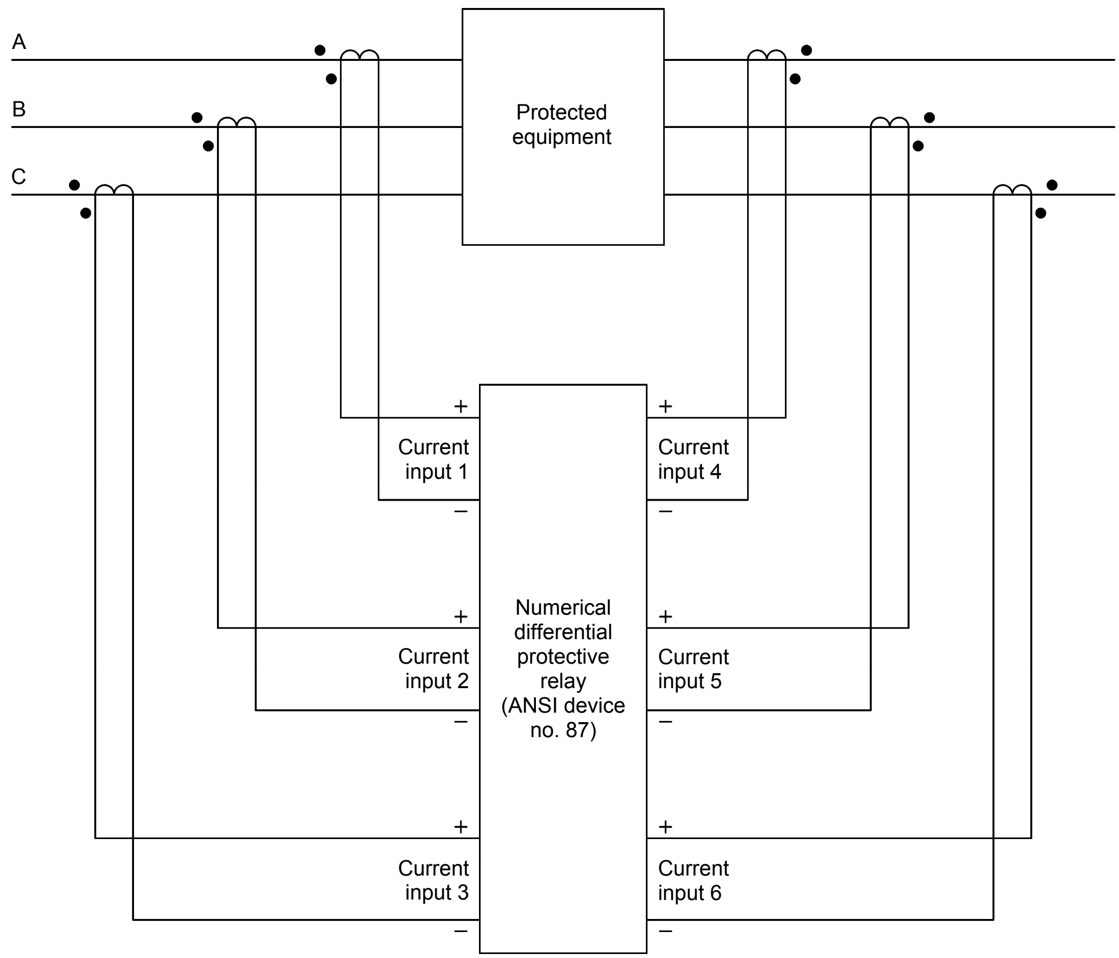


Figure 13. Connection of current transformers to a three-phase, differential protective relay of numerical type.

18. 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.

19. In DIGSI 5, access the settings of the differential protection function of the protective relay. In the *Project tree* area of DIGSI 5, the differential protection function is called *87T diff. prot. 1* and is located in protection function group *Transformer diff. 1*.

Make the following observations about the differential protection function:

- The time delay of the differential protection function (parameter *Operate delay* of function *I-DIFF*) is set to 0 s.

- The current threshold of the differential protection function (parameter *Threshold* of function *I-DIFF*) is set to 0.25 I_{Rated} (i.e., 0.25 A). This corresponds to the initial current threshold of the current differential protection system analyzed earlier in this exercise.

The parameters of the differential protection function have been set to provide a fixed current threshold of 0.25 I_{Rated} up to a current of 20 I_{Rated}. Other settings (parameters Slope 2 and Intersection 2 Irest of function I-DIFF) make the current threshold of the differential protection function increase for currents above 20 I_{Rated}. Do not be concerned about these parameters for now.

- The current threshold characteristic of the differential protection function is illustrated by curve *Tripping Stage1* in the working area of DIGSI 5. Uncheck curve *Tripping Stage2*; it is not used in this exercise.

20. In DIGSI 5, observe that four test sequences are available: *Through current IRated*, *Through current 5 IRated*, *Through current 12 IRated*, and *Internal Fault*. These four sequences emulate the currents measured at both sides of the power transformer (i.e., current phasors I_1 and I_2) for the four circuit conditions used earlier in this exercise to analyze a current differential protection system with 15% current measuring error.

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

Access the parameters of each of the test sequences, then make the following observations about these test sequences:

- The test sequences consist of two steps.
- The first step (step 1) has a duration of 10.0 s.
- During the first step, the internal relay test system emulates balanced currents of 0.85 A at the current inputs at side 1 of the power transformer and balanced currents of 1 A at the current inputs at side 2 of the power transformer. This is equivalent to balanced currents of 850 A and 1000 A, respectively, in the electric power circuit, because 1000 A/1 A current transformers are used in this project.
- The second step (step 2) has a duration of 10.0 s.
- During the second step, the internal relay test system emulates balanced currents having the magnitudes found in Table 2 at the current inputs at both sides of the power transformer, for test sequences *Through current IRated*, *Through current 5 IRated*, and *Through current 12 IRated*. For test sequence *Internal Fault*, the internal relay test system emulates currents having the magnitudes found in Table 2 at the current inputs at both sides of the power transformer for phase A only.
- By default, the frequency of the currents emulated by the internal relay test system during each step of the test sequences is set to 50 Hz.

Set the frequency of the currents emulated during each step of every test sequence to the frequency of your local ac power network.

21. 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.

22. In DIGSI 5, restart the protective relay in the simulation mode to allow the differential protection function of the protective relay (i.e., protection function *87T diff. prot. 1* in protection function group *Transformer diff. 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.

23. In DIGSI 5, start test sequence *Through current IRated*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system. Notice that the relay displays, for the three phases, the magnitude of the measured currents at both sides of the power transformer. It also displays, for the three phases, the magnitude of the measured differential current I_{Δ}, expressed in terms of I_{Rated}.

Table 4 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 4. 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 the differential 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	Differential protection function tripped indication. The LED lights up when the differential protection function trips the protective relay.
15	Red	Relay tripped indication. The LED lights up when the circuit breaker on side 1 of the power transformer receives a trip signal.
16	Red	Same as LED indicator 15 for the circuit breaker on side 2 of the power transformer.

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

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. When this happens, you may use the up, down, left, and right arrow buttons on the relay front panel to scroll through this information.

Did the protective relay trip for test sequence *Through current IRated*? Explain briefly and enter your results in Table 5.

No. The protective relay did not trip because the magnitude of the differential current I_{Δ} (0.15 I_{Rated}) did not exceed the relay current setting (0.25 I_{Rated}). The relay response is adequate: the relay does not trip at a through current of I_{Rated}.

Table 5. Testing of the current differential protection (current measuring error: 15%, relay current setting: 0.25 I_{Rated}).

Circuit condition	Test sequence	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	*Through current IRated*		
Through current (5 I_{Rated})	*Through current 5 IRated*		
Through current (12 I_{Rated})	*Through current 12 IRated*		
Faulty power transformer	*Internal Fault*		

Table 5. Testing of the current differential protection (current measuring error: 15%, relay current setting: 0.25 I_{Rated}).

Circuit condition	Test sequence	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	*Through current IRated*	No	OK
Through current (5 I_{Rated})	*Through current 5 IRated*	Yes	Unwanted tripping
Through current (12 I_{Rated})	*Through current 12 IRated*	Yes	Unwanted tripping
Faulty power transformer	*Internal Fault*	Yes	OK

24. 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.

25. In DIGSI 5, start test sequence *Through current 5 IRated*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Through current 5 IRated*? Explain briefly and enter your results in Table 5.

Yes. The protective relay tripped because the magnitude of the differential current I_Δ (0.75 I_{Rated}) exceeded the relay current setting (0.25 I_{Rated}). The relay response is inadequate: the relay trips, without an internal fault, at a through current of 5 I_{Rated}.

26. Reset the protective relay.

27. In DIGSI 5, start test sequence *Through current 12 IRated*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Through current 12 IRated*? Explain briefly and enter your results in Table 5.

Yes. The protective relay tripped because the magnitude of the differential current I_Δ (1.80 I_{Rated}) exceeded the relay current setting (0.25 I_{Rated}). The relay response is inadequate: the relay trips, without an internal fault, at a through current of 12 I_{Rated}.

28. Reset the protective relay.

29. In DIGSI 5, start test sequence *Internal Fault*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Internal Fault*? Explain briefly and enter your results in Table 5.

Yes. The protective relay tripped because the magnitude of the differential current I_Δ (1.70 I_{Rated}) for phase A exceeded the relay current setting (0.25 I_{Rated}). The relay trips as expected when an internal fault occurs.

30. Do the results compiled in Table 5 validate the conclusion of the analysis of the current differential protection with a current measuring error of 15% and a relay current setting of 0.25 I_{Rated} made earlier in the exercise (refer to Table 2)? Summarize briefly.

Yes, the same conclusions are reached. For a current differential protection with a current measuring error of 15% and a relay current setting of 0.25 I_{Rated}:

- the current differential protection trips as expected when an internal fault occurs.
- the current differential protection does not trip at a through current of I_{Rated}.
- unwanted tripping of the current differential protection occurs at through currents of 5 I_{Rated} and 12 I_{Rated}.

Increased current threshold

31. In DIGSI 5, access the settings of the differential protection function of the protective relay. In the *Project tree* area of DIGSI 5, the differential protection function is called *87T diff. prot. 1* and is located in protection function group *Transformer diff. 1*.

Increase the current threshold of the current differential protection to 2.0 I_{Rated} (i.e., 2.0 A). This corresponds to the increased current threshold of the current differential protection system analyzed earlier in this exercise.

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

33. In DIGSI 5, update the test environment of the protective relay. If required, refer to Appendix C to learn how to perform this task in DIGSI 5.

Start test sequence *Through current IRated*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Through current IRated*? Explain briefly and enter your results in Table 6.

No. The protective relay did not trip because the magnitude of the differential current I_{Δ} (0.15 I_{Rated}) did not exceed the relay current setting (2.0 I_{Rated}). The relay response is adequate: the relay does not trip at a through current of I_{Rated}.

Table 6. Testing of the current differential protection (current measuring error: 15%, relay current setting: 2.0 I_{Rated}).

Circuit condition	Test sequence	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	*Through current IRated*		
Through current (5 I_{Rated})	*Through current 5 IRated*		
Through current (12 I_{Rated})	*Through current 12 IRated*		
Faulty power transformer	*Internal Fault*		

Table 6. Testing of the current differential protection (current measuring error: 15%, relay current setting: 2.0 I_{Rated}).

Circuit condition	Test sequence	Relay trip?	Differential protection evaluation
Through current (I_{Rated})	*Through current IRated*	No	OK
Through current (5 I_{Rated})	*Through current 5 IRated*	No	OK
Through current (12 I_{Rated})	*Through current 12 IRated*	No	OK
Faulty power transformer	*Internal Fault*	No	Fault not detected

34. Reset the protective relay.

35. In DIGSI 5, start test sequence *Through current 5 IRated*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Through current 5 IRated*? Explain briefly and enter your results in Table 6.

No. The protective relay did not trip because the magnitude of the differential current I_{Δ} (0.75 I_{Rated}) did not exceed the relay current setting (2.0 I_{Rated}). The relay response is adequate: the relay does not trip at a through current of 5 I_{Rated}.

36. Reset the protective relay.

37. In DIGSI 5, start test sequence *Through current 12 IRated*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Through current 12 IRated*? Explain briefly and enter your results in Table 6.

No. The protective relay did not trip because the magnitude of the differential current I_{Δ} (1.8 I_{Rated}) did not exceed the relay current setting (2.0 I_{Rated}). The relay response is adequate: the relay does not trip at a through current of 12 I_{Rated}.

38. Reset the protective relay.

39. In DIGSI 5, start test sequence *Internal Fault*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system.

Did the protective relay trip for test sequence *Internal Fault*? Explain briefly and enter your results in Table 6.

No. The protective relay did not trip because the magnitude of the differential current I_{Δ} (1.70 I_{Rated} for phase A and 0.15 I_{Rated} for phase B and phase C) did not exceed the relay current setting (2.0 I_{Rated}). The relay response is inadequate: the relay does not trip for an internal fault on phase A.

40. Do the results compiled in Table 6 validate the conclusion of the analysis of the current differential protection with a current measuring error of 15% and a relay current setting of 2.0 I_{Rated} made earlier in the exercise (refer to Table 3)? Summarize briefly.

Yes, the same conclusions are reached. For a current differential protection with a current measuring error of 15% and a relay current setting of 0.25 I_{Rated}:

- the current differential protection does not trip at a through current of I_{Rated}.
- false tripping of the current differential protection no longer occurs at through currents of 5 I_{Rated} and 12 I_{Rated}.
- the current differential protection does not trip when an internal fault occurs.

Does increasing the current threshold of the relay significantly reduce the sensitivity of the current differential protection?

❑ Yes ❑ No

Yes

Ending the exercise

41. 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).

42. 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.

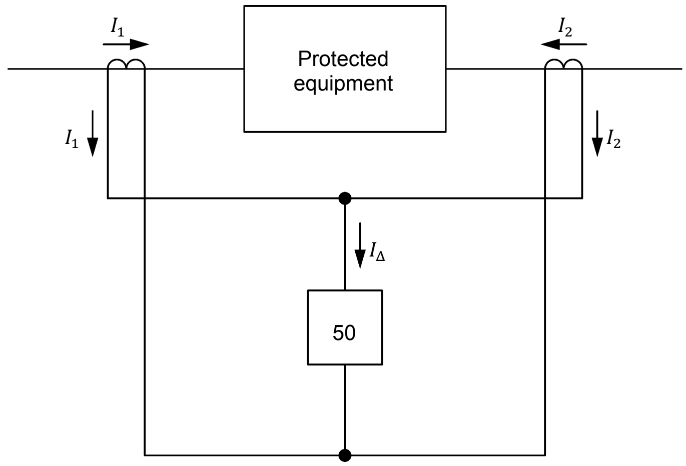
Delete the copy of the project file that you opened at the beginning of this exercise.

CONCLUSION

In this exercise, you learned that the principle of differential protection is based on Kirchhoff's current law. You saw that current differential protection is implemented with an instantaneous overcurrent relay. You learned about errors related to current measurement. You understood the effect of these errors on the sensitivity of current differential protection.

Review Questions

1. In the figure below, what is the differential current I_Δ if current phasor I_1 is 200 A ∠50° and current phasor I_2 is 250 A ∠-130°?



Evaluation of the differential current I_Δ.

a. 50 A ∠50°
b. 250 A ∠50°
c. 50 A ∠-130°
d. 200 A ∠-130°

c. 50 A ∠-130°

2. In a differential protection system, how does the sum of the current phasors at both sides of a piece of protected equipment relate to the presence of a fault within this equipment?

The current phasors at both sides of the protected equipment sum up to the differential current I_Δ. If no fault is present in the protected equipment, the differential current is null. When a fault occurs in the protected equipment, the differential current passing through the operating element is no longer null.

3. How many current inputs are needed to protect a three-phase power transformer?

Six current inputs are needed to protect a three-phase power transformer, which represent two current inputs for each phase of the power system.

4. Suppose that in a differential protection system, the current measuring error is 15% of the through current. What is the maximum differential current I_Δ measured under no fault condition when the through current is 3 A?

The maximum differential current I_Δ measured under no fault condition is 0.45 A (0.15·3 A).

5. Explain why current differential protection is not well suited to protect equipment when the current measuring error is not null?

When the current measuring error is not null, the differential current is not null, even when no fault affects the protected equipment. To improve the stability of the protection, the current threshold must be increased, which reduces the sensitivity of the protection to faults occurring within the equipment.

Bibliography

Blackburn, J. Lewis and Domin, Thomas J., *Protective Relaying, Principles and Applications*, 3rd ed., Taylor & Francis Group, 2007, ISBN 978-1-57444-716-3.

Westinghouse Electric Corporation, *Applied Protective Relaying*, 1976, Library of Congress Card Number 76-8060.

GEC Alsthom Measurements Limited, *Protective Relays – Application Guide*, 3rd ed., 1987.

Alstom Grid, *Network Protection & Automation Guide*, 1st ed., 2011, ISBN 978-0-9568678-0-3.

Reimert, D., *Protective Relaying for Power Generation Systems*, 1st ed., Taylor and Francis, 2006, ISBN 978-0-8247-0700-2.

Ziegler, Gerhard, *Numerical Differential Protection*, 2nd ed., Publicis Publishing, Erlangen, 2012, ISBN 978-3-89578-351-7.

Siemens, *SIPROTEC 5 – Transformer Differential Protection 7UT82/7UT85/ 7UT86/7UT87*, V6.00, 2014, C53000-G5040-C016-5.01.