Electricity and New Energy

Overcurrent and Overload Protection Using Protective Relays

Course Sample

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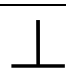
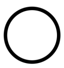
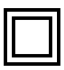
Safety and Common Symbols

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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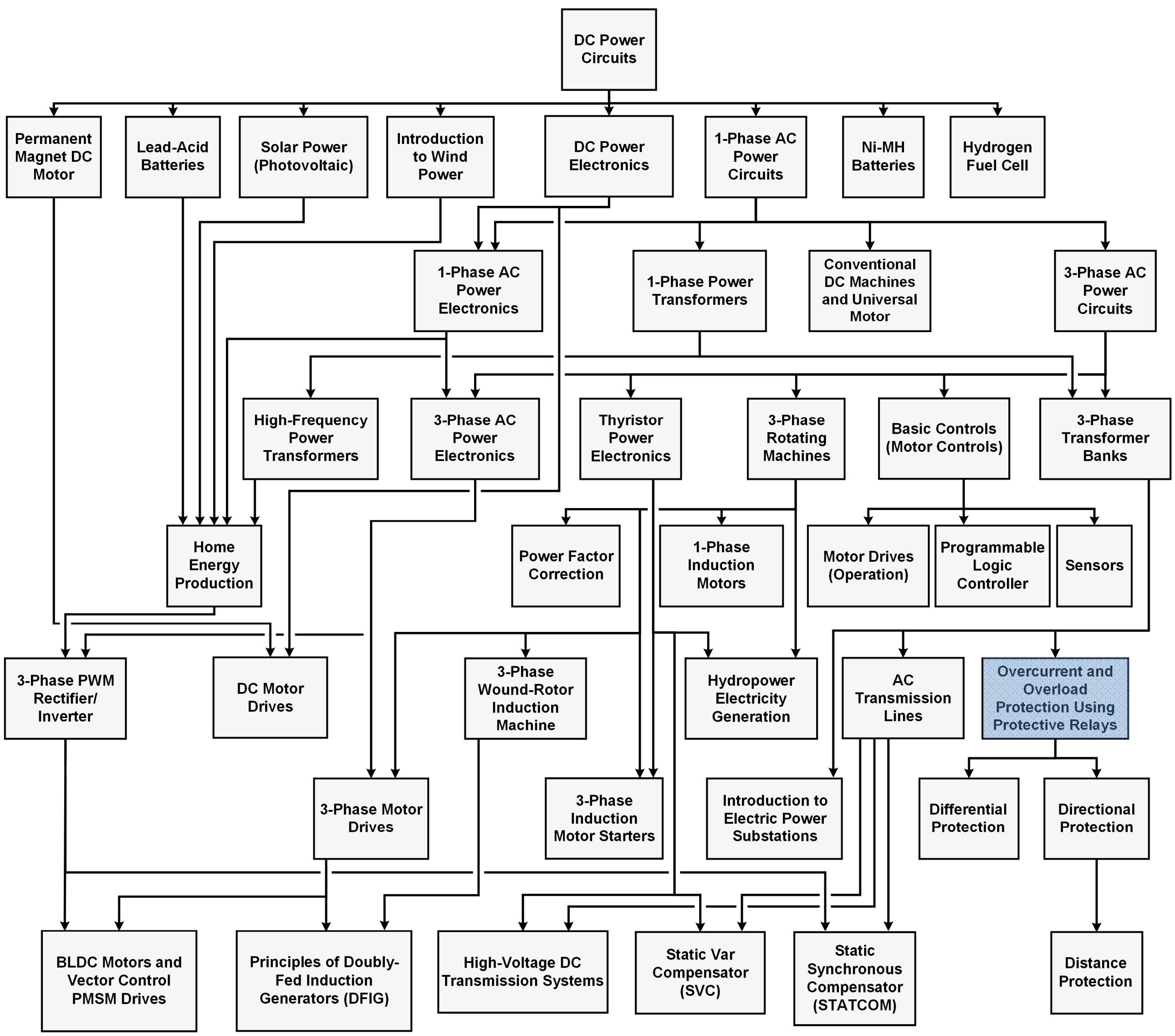
Preface

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 operation and settings of the instantaneous (ANSI device no. 50), definite-time (ANSI device no. 51DT), and inverse definite minimum time (ANSI device no. 51I) overcurrent relays. You will be able to adjust the settings of an overcurrent relay to obtain a specific time-current characteristic. You will know applications where it is common to use overcurrent relays and high-voltage circuit breakers in conjunction to achieve overcurrent protection of electrical equipment. You will be familiar with the operation and settings of the machine or transformer thermal relay (ANSI device no. 49) of the temperature-sensor type or the thermal-replica type. You will know how to combine protection functions in a numerical protective relay to achieve overcurrent and overload protection of an ac machine or a power transformer. You will also know how to implement overcurrent protection of a radial feeder using either definite-time overcurrent relays or inverse definite minimum time (IDMT) overcurrent relays. You will be able to use the internal relay test system of a numerical protective relay to assess that the relay operates as expected.

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, and *Three-Phase Transformer Banks*, part number 86379.

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.

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

Overcurrent and Overload Protection of AC Machines and Power Transformers

EXERCISE OBJECTIVE

When you have completed this exercise, you will understand the relationship between the power rating of an ac machine or a power transformer and its thermal capability. You will be familiar with the operation and settings of machine or transformer thermal relays (ANSI device no. 49) of the temperature-sensor type. You will also be familiar with the operation and settings of machine or transformer thermal relays of the thermal-replica type. You will be able to adjust the settings of a thermal relay of the thermal-replica type to obtain a specific inverse time-current characteristic. You will know how to use a numerical protective relay combining the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and a machine or transformer thermal relay (ANSI device no. 49) to achieve overcurrent and overload protection of an ac machine or a power transformer. You will also know that an IDMT overcurrent relay (ANSI device no. 51I) function can also be used to achieve overload protection of an ac machine or a power transformer. You will be able to use the internal relay test system of a numerical protective relay to assess that the machine or transformer thermal relay function operates as expected.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction
- Thermal capability and power rating of ac machines and power transformers
- Machine or transformer thermal relays of the temperature-sensor type
- Machine or transformer thermal relays of the thermal-replica type
- OC and OL protection of an ac machine or power transformer using a numerical protective relay combining the functions of ANSI devices no. 50 and no. 49
- Using the IDMT overcurrent relay (ANSI device no. 51I) function to achieve overload protection

DISCUSSION

Introduction

In the previous exercise, you saw that an instantaneous overcurrent relay (ANSI device no. 50) used in conjunction with a high-voltage circuit breaker is well suited to achieve overcurrent protection of an ac motor or a power transformer (up to about 5 to 10 MVA). In this situation, the current setting of the instantaneous overcurrent relay is set to several times the nominal current of the protected ac motor or power transformer. This, however, has the disadvantage that little or no protection against overload is provided because overload situations often result in currents that are generally less than about 3 to 4 times the nominal current of the protected ac motor or power transformer. Consequently, using an instantaneous overcurrent relay alone is not sufficient to protect an ac motor or a power transformer against both overcurrent and overload. It is thus common to use a numerical protective relay combining the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and a **machine or transformer thermal relay** (ANSI device no. 49) to achieve overcurrent and overload protection of an ac motor or a power transformer. It is also possible to combine the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and an IDMT overcurrent relay (ANSI device no. 51I) to achieve overcurrent and overload protection. These two alternatives to achieve overcurrent and overload protection are covered in this discussion.

Thermal capability and power rating of ac machines and power transformers

The current flowing in an ac machine (e.g., an induction motor or a synchronous generator) or a power transformer when it is loaded causes electric power to be dissipated as heat. This loss of electric power is due to the resistance of the wire used in the windings of the device (ac machine or power transformer) and is known as the copper loss (RI^2 loss). The heat caused by the flow of load current, in turn, causes the temperature of the device to increase until it stabilizes to a certain final value. The increase in the device's temperature, i.e., the difference between the final temperature (θ_{Final}) that is reached when it stabilizes and the ambient temperature ($\theta_{Amb.}$) is referred to as the **temperature rise** ($\Delta\theta$). The higher the value of the load current, the higher the temperature rise $\Delta\theta$. This is illustrated in Figure 32. Notice that the rate at which the temperature increases depends on the heating time constant τ_H of the device. The longer the heating time constant τ_H, the slower the device's temperature increases. In Figure 32, the heating time constant τ_H of the device is equal to 10 minutes, and thus, the device's temperature stabilizes after about 50 minutes (i.e., after about $5 \cdot \tau_H$).

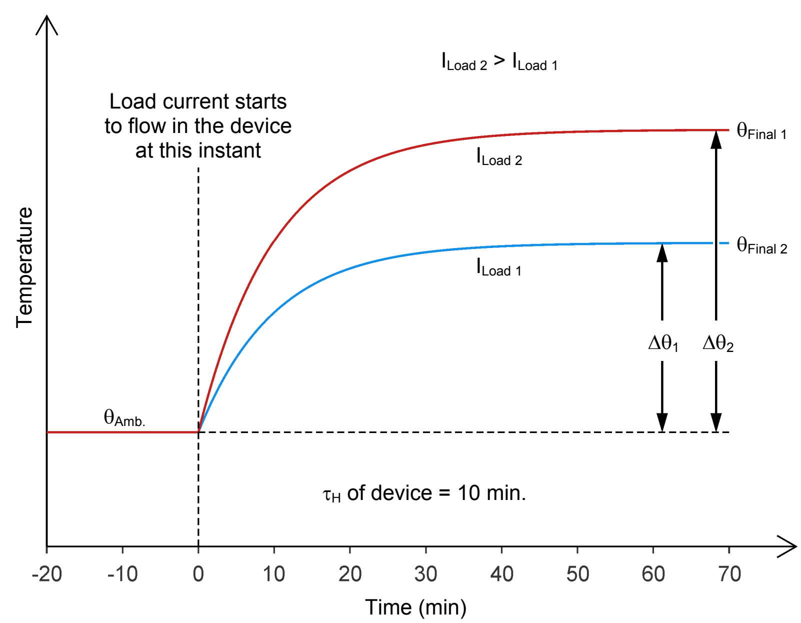


Figure 32. Temperature increase of an electric device such as an ac machine or power transformer as a function of time, caused by the flow of a load current of constant value.

The temperature rating of the insulation (often referred to as the insulation class) of the windings in an electric device such as an ac machine or a power transformer is generally the main factor limiting the maximum operating temperature of the device. This, in turn, limits the maximum temperature rise ($\Delta\theta_{Max.}$) that is possible, and thus, the maximum current that can flow in the device continuously without causing damage to the device. This ultimately determines the power rating of the device. The maximum current that can flow in the device continuously without causing damage is referred to as the maximum thermally-permissible current ($I_{Therm.\ Max.}$). For instance, when the temperature rating of the insulation of a particular device is 105°C (221°F) and a maximum ambient temperature of 40°C (104°F) is assumed, the maximum temperature rise $\Delta\theta_{Max.}$ that is allowed is 65°C (117°F), as shown in Figure 33. Any load current below current $I_{Therm.\ Max.}$ causes a temperature rise $\Delta\theta$ lower than the maximum temperature rise $\Delta\theta_{Max.}$, and thus, can flow in the device continuously without causing damage. However, any load current above current $I_{Therm.\ Max.}$ leads to a temperature rise $\Delta\theta$ higher than the maximum temperature rise $\Delta\theta_{Max.}$ and causes the maximum operating temperature of the device to be exceeded. Obviously, such a load current cannot flow in the device continuously as it will eventually cause damage to the device. Note that the higher the value of the load current, the shorter the time required to reach the maximum operating temperature of the device.

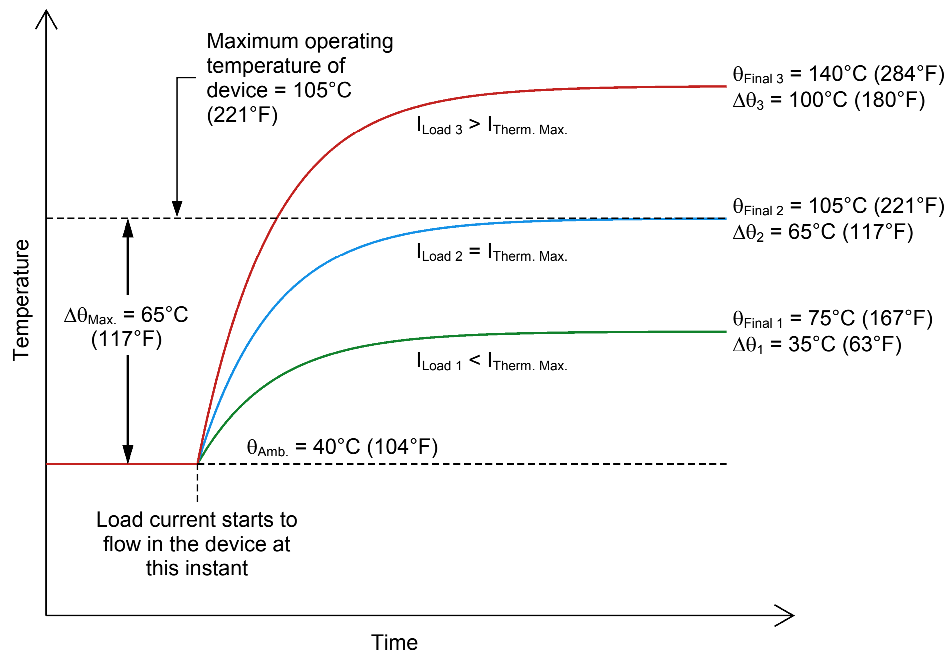


Figure 33. The temperature rise $\Delta\theta$ occurring in an electric power device such as an ac machine or power transformer exceeds the maximum temperature rise $\Delta\theta_{Max.}$ when the load current flowing through the device exceeds the maximum thermally-permissible current $I_{Therm.\ Max.}$.

The important fact to remember from Figure 33 is that the current flowing through an electric device such as an ac machine or a power transformer can be used to determine whether or not the device is overheating (i.e., to determine whether or not the temperature rise produced by a load current of a given value exceeds the maximum temperature rise $\Delta\theta_{Max.}$). This is the basic principle used in machine or transformer thermal relays of the thermal-replica type. The operation of these thermal relays is studied later in this discussion.

Machine or transformer thermal relays of the temperature-sensor type

Machine or transformer thermal relays are generally of the temperature-sensor type or of the thermal-replica type. Machine or transformer thermal relays of the temperature-sensor type are covered in this section of the discussion. Machine or transformer thermal relays of the thermal-replica type are covered in the next section of this discussion.

Figure 34 is a single-line diagram showing overload protection of an ac machine or a power transformer implemented with a thermal relay (ANSI device no. 49) of the temperature-sensor type used in conjunction with an HV circuit breaker.

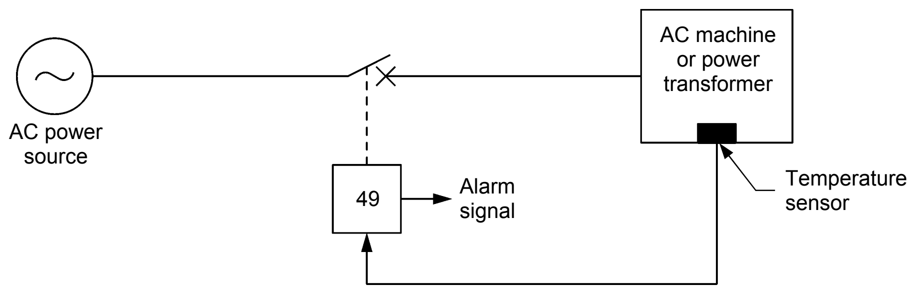


Figure 34. Overload protection of an ac machine or a power transformer implemented with a thermal relay (ANSI device no. 49) of the temperature-sensor type used in conjunction with an HV circuit breaker.

In a machine or transformer thermal relay of the temperature-sensor type, the temperature of the protected device is measured directly using a temperature sensor such as a resistive temperature detector (RTD) or a thermocouple. The thermal relay compares at regular time intervals the measured temperature of the device to a maximum temperature threshold set in the relay. When the measured temperature of the device reaches about 80% to 90% of the maximum temperature threshold (this percentage value is adjustable in the thermal relay), the thermal relay produces an alarm signal. This signal can be used to automatically initiate an action that will prevent the temperature of the protected device from further increasing or to warn an operator so that he or she can initiate the necessary action. Turning on cooling equipment (e.g., fans) on the protected device or reducing the load applied to the protected device (e.g., by shedding loads connected to a power transformer) are two examples of action that can prevent the device's temperature from increasing further. When the measured temperature of the device exceeds the maximum temperature threshold for a certain predetermined time set in the relay (this is likely to occur when no action is taken after the initial alarm signal), the thermal relay produces a trip command that can be used to open an HV circuit breaker connected in series with the device to be protected. This prevents prolonged overheating of the protected device, thereby avoiding damage to the device.

The value at which the maximum temperature threshold of a thermal relay is set depends on the nature of the device to be protected. For instance, the maximum temperature at which most oil-immersed power transformers can safely operate (i.e., without damage or reduction in life expectancy) is generally between 95°C (203°F) and 105°C (221°F). On the other hand, the maximum temperature at which ac machines such as induction motors and synchronous generators can safely operate generally ranges from 80°C (176°F) to about 200°C (392°F). The maximum operating temperature of any particular ac machine depends on its insulation class as defined in the IEC and NEMA standards. In all cases, the maximum temperature threshold set in a machine or transformer thermal relay must be carefully determined in accordance with the specifications of the particular device to be protected.

Note that in the case of overload protection of a power transformer, it is common not to use the trip command of the thermal relay to disconnect the protected transformer even when the maximum temperature threshold is exceeded. This is because damage, in general, does not occur immediately when a power transformer is overloaded. This is also motivated by the fact that the cause of a transformer overload is generally elsewhere in the power system, and consequently, disconnecting the overloaded power transformer is not the solution to the overload. In fact, disconnecting the overloaded power transformer simply aggravates the overload problematic since less power is available in the system to meet the demand. The consequence of disconnecting an overloaded power transformer is thus to move the overload problem to other power transformers in the power system. This can eventually lead to instability in the power system, which is highly undesirable. Using the trip command of a thermal relay to disconnect an overloaded power transformer is a design criterion that depends on the particular application in which the power transformer is used.

Machine or transformer thermal relays of the thermal-replica type

A machine or transformer thermal relay of the thermal-replica type operates the same way as a machine or transformer thermal relay of the temperature–sensor type, i.e., it first produces an alarm signal when the device's temperature nears the maximum temperature threshold. Then, it produces a trip command when the device's temperature exceeds the maximum temperature threshold for a certain predetermined time. However, in a machine or transformer thermal relay of the thermal-replica type, the device's temperature is estimated from the current flowing through the protected device instead of being measured directly using a temperature sensor. Figure 35 is a single-line diagram showing overload protection of an ac motor or a power transformer implemented with a thermal relay of the thermal-replica type used in conjunction with an HV circuit breaker.

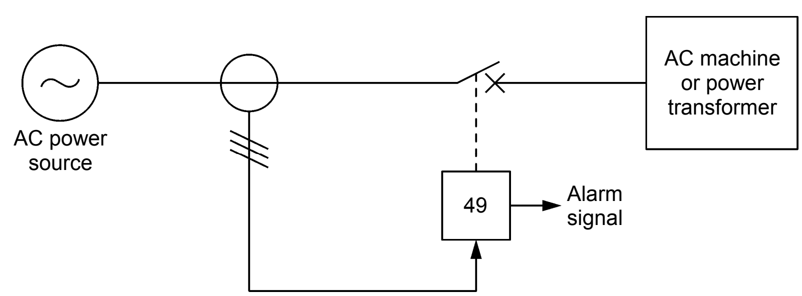


Figure 35. Overload protection of an ac machine or a power transformer implemented with a thermal relay of the thermal-replica type used in conjunction with an HV circuit breaker.

A thermal relay of the thermal-replica type uses a mathematical model to estimate the temperature of the protected device as accurately as possible from the measured value of the current flowing through the device. This mathematical model is based on the assumption that the protected device is a homogeneous body that produces and dissipates heat at a rate proportional to the temperature rise $\Delta\theta$.

When the protected device is loaded, current starts to flow in the device and its temperature begins to increase. When the value of the load current flowing through the device is constant, the device's temperature at any instant can be calculated using the following equation:

$$\theta(t) = \Delta\theta\left(1 - e^{-t/\tau_H}\right) + \theta_{Amb.} \tag{1}$$

where $\theta(t)$ is the device's temperature at time t, expressed in °C or °F

$\Delta\theta$ is the temperature rise caused by the flow of a current of constant value in the device, expressed in °C or °F

t is the time elapsed since current started to flow in the protected device, expressed in s or min

τ_H is the heating time constant of the protected device, expressed in s or min

$\theta_{Amb.}$ is the ambient temperature, expressed in °C or °F

A computational algorithm is performed repeatedly in the thermal relay to estimate the temperature from the value of the current flowing through the protected device. A long-term integration process takes place within this computational algorithm. This causes the estimated temperature to take into account the cumulative heating effect of the load current that flowed through the protected device since the thermal relay started to measure the value of the current flowing through the device. In other words, when a thermal relay of the thermal-replica type is put into service, it keeps track of the temperature rise caused by the current that flowed in the protected device up to the present time. Because of this feature, a thermal relay of the thermal-replica type is said to have memory of the temperature rise caused by the current that flowed in the protected device. This is true as long as the thermal relay is not reset.

Also, according to the mathematical model above, the value of the temperature rise $\Delta\theta$ resulting from the flow of a load current of constant value in the protected device is proportional to the value of the current squared, as illustrated in Figure 36.

This figure shows that the more the value of the load current flowing in the protected device exceeds the maximum thermally-permissible current $I_{Therm.\ Max.}$ of the protected device, the shorter the time required to reach the maximum temperature rise $\Delta\theta_{Max.}$ of the protected device.

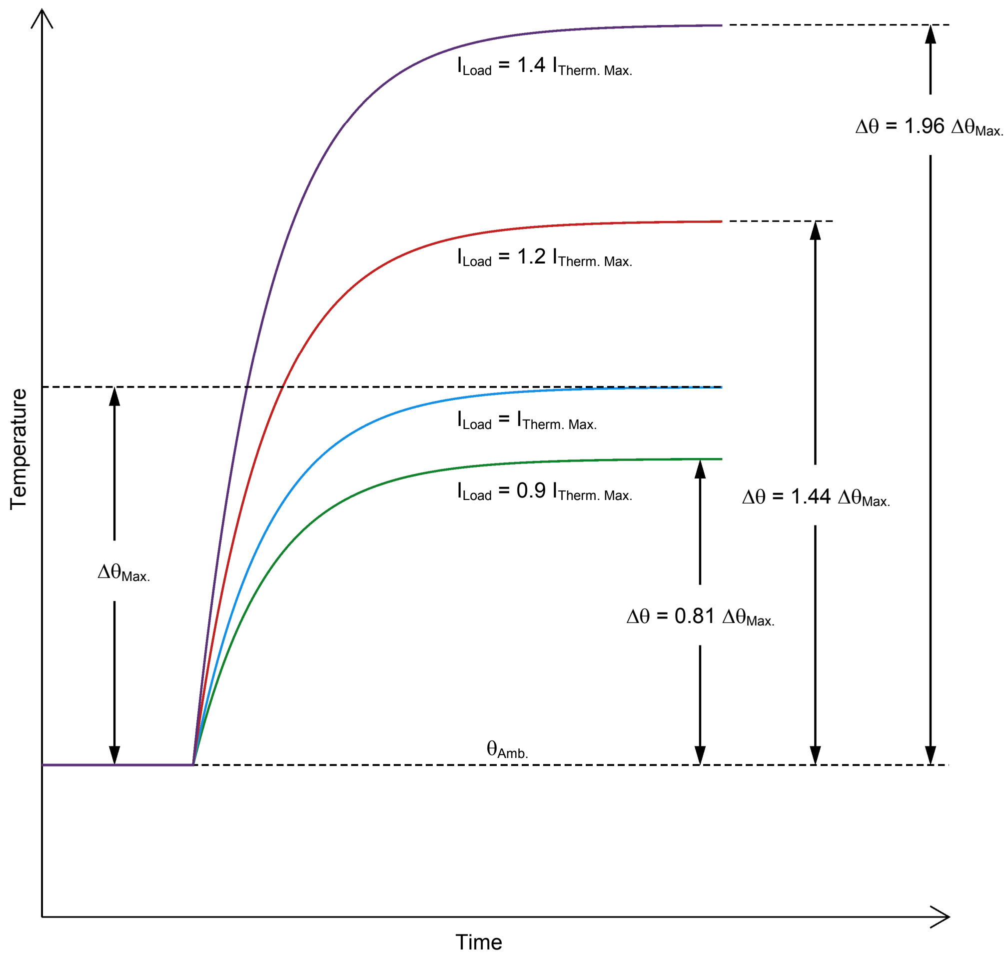


Figure 36. Temperature increase of an electric device such as an ac machine or a power transformer as a function of time, caused by the flow of load current of different values relative to the value of the current $I_{Therm.\ Max.}$ of the protected device.

The following equation allows calculation of the time required to reach the maximum temperature rise $\Delta\theta_{Max.}$ for any overload current of constant value:

$$t = \tau_H \ln \left[\frac{1}{1 - \left(\frac{I_{Therm.\ Max.}}{I} \right)^2} \right] \tag{2}$$

where t is the time required to reach the maximum temperature rise $\Delta\theta_{Max.}$, expressed in s or min

τ_H is the heating time constant of the protected device, expressed in s or min

$I_{Therm.\ Max.}$ is the maximum thermally-permissible current of the protected device

I is the value of the overload current flowing through the protected device

The operating time (i.e., the trip time) of a thermal relay of the thermal-replica type varies according to Equation (2). Consequently, the operating time of a machine or transformer thermal relay of the thermal-replica type decreases exponentially when the value of the current flowing through the protected device increases. This is illustrated in Figure 37, which shows the time-current characteristic of a machine or transformer thermal relay of the thermal-replica type. The characteristic is an inverse curve similar to the time-current characteristic of an IDMT overcurrent relay (ANSI device no. 51I).

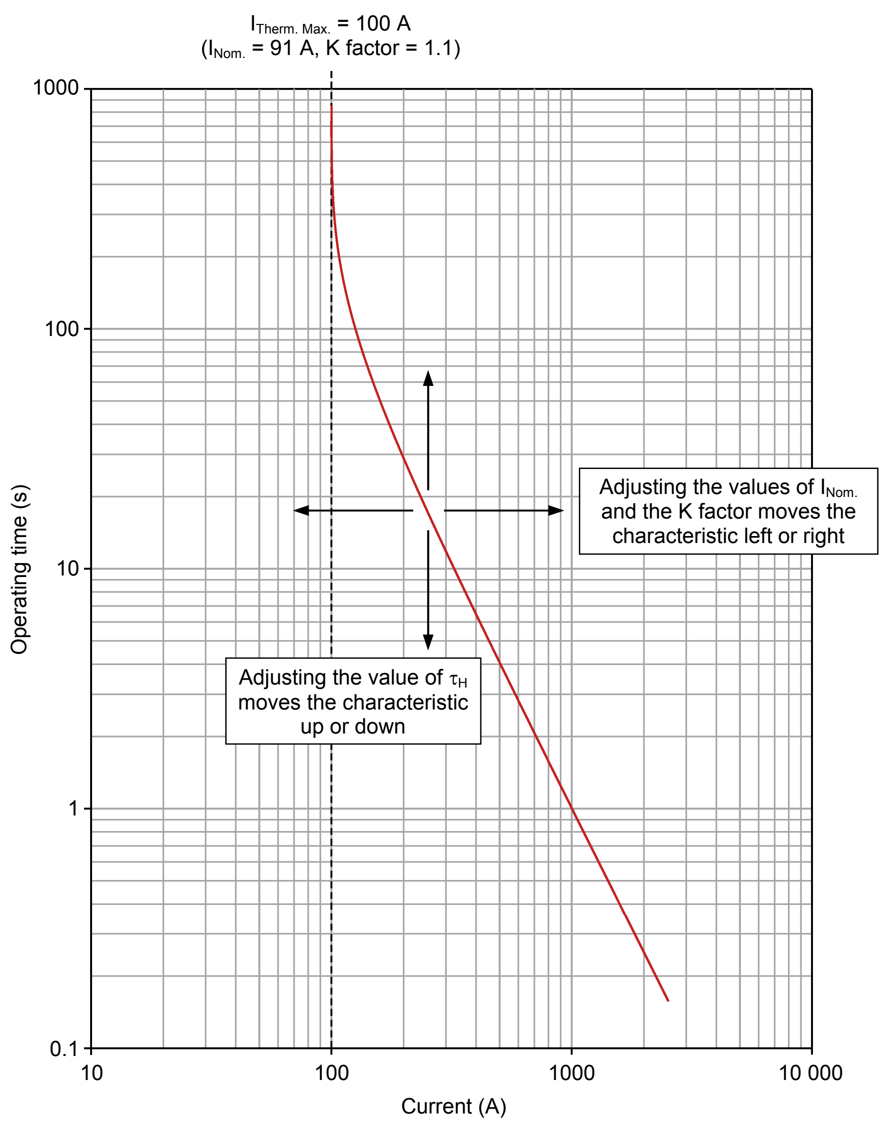


Figure 37. Time-current characteristic of a machine or transformer thermal relay (ANSI device no. 49) of the thermal-replica type ($I_{Nom.}$ = 91 A, K factor = 1.1, and τ_H = 100 s).

A thermal relay of the thermal-replica type requires the values of specific parameters related to the protected device in order to accurately estimate its temperature, and thus, provide effective overload protection of the device. The parameters that are generally required are listed below.

- Nominal current ($I_{Nom.}$)
- K factor
- Heating time constant (τ_H)
- Maximum temperature rise ($\Delta\theta_{Max.}$)
- Ambient temperature ($\theta_{Amb.}$)
- Cooling time constant (τ_C)
- Current $I_{Cooling}$

The nominal current $I_{Nom.}$ is the full-load current of the protected device specified by its manufacturer.

The K factor is a parameter of the protected device that is equal to the ratio of the maximum thermally-permissible current $I_{Therm.\ Max.}$ of the protected device to the nominal current $I_{Nom.}$ of the protected device (see equation below). The value of the K factor is generally between 1 and 2. The K factor indicates how much allowance for operation under overload condition the protected device has. The higher the value of the K factor, the more the protected device can be overloaded without exceeding the temperature rise $\Delta\theta_{Max.}$ of the device. The K factor is sometimes provided by the manufacturer of the protected device. It can also be determined from the values of the maximum thermally-permissible current $I_{Therm.\ Max.}$ and nominal current $I_{Nom.}$ of the protected device, using the equation below. When the K factor of the protected device is unknown, it should be set to 1 (i.e., to the most conservative value) in the thermal relay to ensure that the relay detects any device overload in time.

$$K = \frac{I_{Therm.\ Max.}}{I_{Nom.}} \tag{3}$$

The heating time constant τ_H is the heating time constant of the protected device. This time constant can generally be obtained from the manufacturer of the protected device.

The maximum temperature rise $\Delta\theta_{Max.}$ is the maximum rise in temperature allowed for the protected device, as specified by the manufacturer of the device.

The ambient temperature $\theta_{Amb.}$ is the temperature of the air surrounding the protected device. The ambient temperature is commonly set to a fixed value (generally the maximum ambient temperature specified for the protected device). In certain thermal relays of the thermal-replica type, the actual temperature of the air is measured at a location close to the protected device. This allows the thermal relay to estimate the actual temperature of the protected device more accurately.

The cooling time constant τ_C is the cooling time constant of the protected device. This time constant determines the rate at which the device's temperature decreases when the load current flowing through the device decreases below current $I_{Cooling}$ of the device. The value of the cooling time constant τ_C largely depends on the cooling system of the protected device. In general, the value of the cooling time constant τ_C of a device is equal to several times the value of the heating time constant τ_H of the device. The value of this multiple can generally be obtained from the manufacturer of the protected device. When no specific value is available, consider the cooling time constant τ_C to be about 7 times larger than the heating time constant τ_H.

The current $I_{Cooling}$ is the value of the load current below which it is considered that the temperature of the protected device decreases. A typical value for current $I_{Cooling}$ is about 5% of the nominal current $I_{Nom.}$ of the protected device.

Among the above parameters, the nominal current $I_{Nom.}$, the K factor, and the heating time constant τ_H directly affect the time-current characteristic of a thermal relay of the thermal-replica type. The values of the nominal current $I_{Nom.}$ and K factor determine the position of the vertical asymptotic line of the time-current characteristic. The time-current characteristic is moved right when the value of either one of these two parameters is increased and vice versa. For instance, the vertical asymptotic line in the time-current characteristic of a thermal relay shown in Figure 37 is located at a current of 100 A since the values of the nominal current $I_{Nom.}$ and K factor of the protected device are 91 A and 1.1, respectively ($I_{Therm.\ Max.} = K \cdot I_{Nom.}$). On the other hand, the value of the heating time constant τ_H determines the vertical position of the time-current characteristic. Increasing the heating time constant τ_H moves the time-current characteristic up and vice versa. The values of these parameters must be carefully set in the thermal relay to ensure effective overload protection of a specific device.

Note that the K factor of the device to be protected must be taken into account when setting the alarm threshold in a thermal relay of the thermal-replica type. For instance, when the K factor is 1.1, the temperature rise $\Delta\theta$ caused by a load current equal to the nominal current $I_{Nom.}$ is equal to 82.6% $[(1/1.1)^2]$ of the maximum temperature rise $\Delta\theta_{Max.}$. Consequently, the alarm threshold must be set to a value higher than 82.6% to prevent the thermal relay from producing an alarm when the protected device operates at the nominal current $I_{Nom.}$ for an extended period of time. The higher the K factor of the protected device, the lower the maximum value at which the alarm threshold can be set.

OC and OL protection of an ac machine or power transformer using a numerical protective relay combining the functions of ANSI devices no. 50 and no. 49

It is common to use a numerical protective relay combining the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and a machine or transformer thermal relay (ANSI device no. 49) to achieve overcurrent and overload protection of an ac machine (see Figure 38a) or a power transformer (see Figure 38b). In all cases, the current threshold of the instantaneous overcurrent relay function is set above the value of the maximum current that can flow in the protected device under normal operating conditions and below the value of expected fault currents. Also, the parameters of the thermal relay function are set so that the resulting inverse time-current characteristic is above the values of current that can flow in the protected device under normal operating conditions and below the values of current that cause damage to the protected device (e.g., the through-fault withstand duration curve of a power transformer, the thermal limit curves of an induction motor, etc.).

(a) Electrical motors in an industrial environment

(b) Power transformer in an electric substation

Figure 38. It is common to use a numerical protective relay combining the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and a machine or transformer thermal relay (ANSI device no. 49) to achieve overcurrent and overload protection of an ac machine (a) or a power transformer (b).

To make sure that the instantaneous overcurrent relay and thermal relay functions are set to protect a particular device properly, it is common to plot on a time-current graph the area corresponding to the normal operating currents of the protected device (the so-called device operating area) and the area corresponding to currents that cause damage to the protected device (the so-called device damage area). Then, the time-current characteristic of the numerical protective relay defined by the instantaneous overcurrent relay (ANSI device no. 50) and thermal relay (ANSI device no. 49) functions is also plotted on this graph. The numerical protective relay is properly set when its time-current characteristic is located between the device operating area and the device damage area. Figure 39 is an example of a time-current graph showing the operating area and damage area of a power transformer as well as the time-current characteristic of the numerical protective relay used to protect this transformer.

Figure 39 clearly shows that the protective relay will operate in time for any combination of current and time located in the device damage area but will not operate for any combination of current and time located in the device operating area. In the case of power transformers, the device operating area is determined using the nominal current $I_{Nom.}$ and peak magnetizing inrush current of the transformer. It is common to assume that the peak magnetizing inrush current has a magnitude of 12 times the nominal current $I_{Nom.}$ and lasts 0.1 s. On the other hand, the device damage area is determined from the applicable through-fault withstand duration curve (e.g., for liquid-immersed power transformers, this curve can be determined from the generic curves given in IEEE standard C57.109).

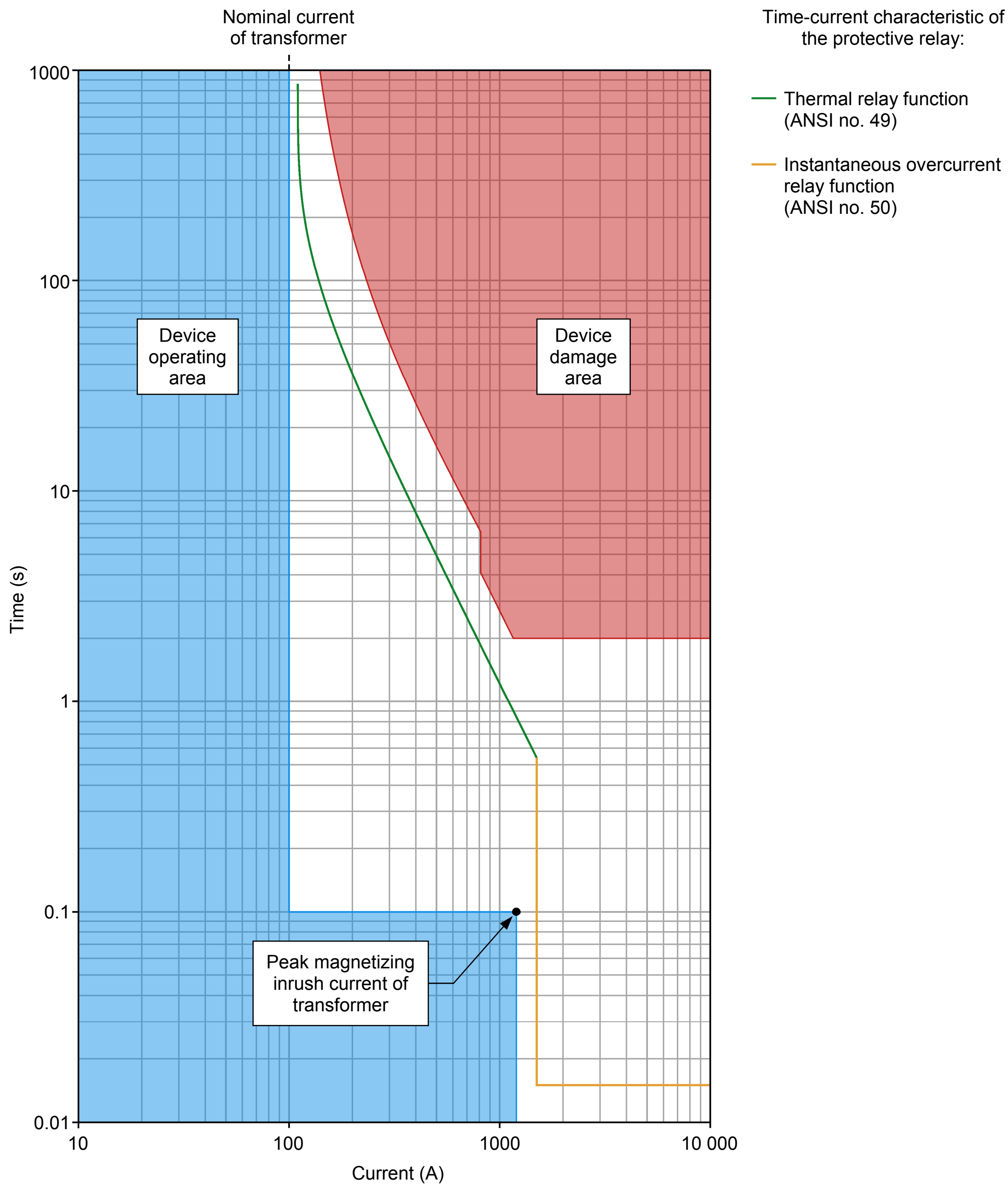


Figure 39. Operating area and damage area of a power transformer and time-current characteristic of the numerical protective relay used to protect this transformer.

Figure 40 is another example of a time-current graph that shows the operating area and damage area of an induction motor as well as the time-current characteristic of the numerical protective relay used to protect this motor. Once again, the graph clearly shows that the protective relay will operate in time for any combination of current and time located in the device damage area but will not operate for any combination of current and time located in the device operating area. In the case of ac induction motors, the device operating area is determined using the motor starting current curve for a specific starting condition. This curve provides important operating points of the motor such as its nominal current (commonly referred to as the full-load amperage or FLA), the starting time, and the locked rotor current (LRA). In Figure 40, the nominal current, starting time, and locked rotor current of the motor are equal to 200 A, 4 s, and 1000 A, respectively. On the other hand, the boundaries of the device damage area are determined using the motor safe stall point, a common specification of low-voltage (LV) induction motors. The motor safe stall point represents the maximum time a motor can operate with its rotor locked without damage. In Figure 40, the motor can run with its rotor locked, without damage, for a maximum time of 30 s. Note that in the case of medium-voltage (MV) induction motors, the motor running overload thermal limit curve and the motor locked rotor thermal limit curve provided by the motor's manufacturer are generally used to determine the boundaries of the device damage area.

Using the IDMT overcurrent relay (ANSI device no. 51I) function to achieve overload protection

So far, the thermal relay (ANSI device no. 49) function has been considered to achieve overload protection of ac machines and power transformers. However, an IDMT overcurrent relay (ANSI device no. 51I) can also be used to achieve overload protection of ac machines and power transformers. This is possible because thermal relays and IDMT overcurrent relays both have an inverse time-current characteristic that is adjustable. It is thus common to use a numerical protective relay combining the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and an IDMT overcurrent relay (ANSI device no. 51I) to achieve overcurrent and overload protection. The numerical protective relay is properly set when the time-current characteristic defined by the instantaneous overcurrent relay and IDMT overcurrent relay functions is located between the operating area and damage area of the protected device (i.e., the same as when the instantaneous overcurrent relay and thermal relay functions are used).

Note that contrary to the thermal relay function, the IDMT overcurrent relay function does not have memory of the temperature rise caused by the heating effect produced by the current that flowed in the protected device up to the present time. In brief, this is because an IDMT overcurrent relay starts to keep track of the heating effect due to current flowing through the protected device only when the value of the current exceeds the current threshold, and also because it resets the cumulated heating effect as soon as the value of the current decreases below the current threshold. For this reason, overload protection using a thermal relay function (ANSI device no. 49) is generally considered superior to overload protection using an IDMT overcurrent relay function (ANSI device no. 51I) in several applications.

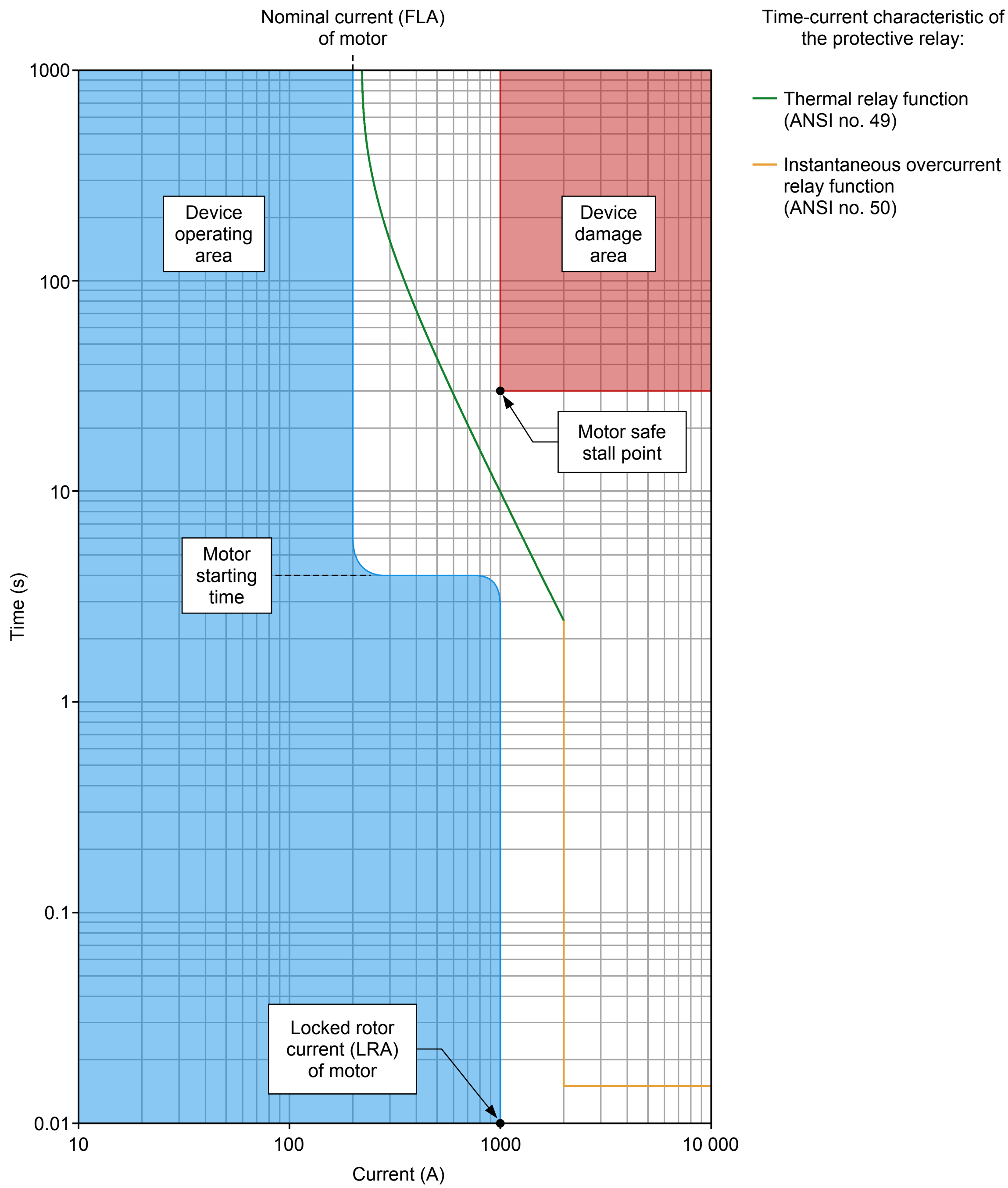


Figure 40. Operating area and damage area of an induction motor and time-current characteristic of the numerical protective relay used to protect this motor.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Settings of a machine or transformer thermal relay of the thermal-replica type
- Operation of a machine or transformer thermal relay of the thermal-replica type
- Time-current characteristic of a machine or transformer thermal relay of the thermal-replica type
- Overcurrent protection

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) or the Numerical Differential Protective Relay (Model 3819). The term protective relay is used throughout the remainder of this exercise procedure to refer to the protective relay that is used to perform the exercise.

Insert the LED identification label for Exercise 2 into the front panel of the protective relay. The identification labels can be found in Appendix D.

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

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

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

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

Settings of a machine or transformer thermal relay of the thermal-replica type

In this section, you will become familiar with the settings of a machine or transformer thermal relay (ANSI device no. 49) of the thermal-replica type. You will observe the operation of the thermal relay at various values of load current.

5. In DIGSI 5, open project file *Thermal Relay Settings and Operation.dp5v6* created for the protective relay that you are using to perform the exercise. By default, the project files required to perform the exercises in this manual should be located in the following folder: *C:\ProgramData\Festo Didactic\Manual 52173, OC and OL Protection\...*

6. In DIGSI 5, display the single-line diagram showing the connection of the protective relay to the electric power circuit. Observe that in this project, the current inputs of the protective relay are connected to a feeder in an electric power system via current transformers having a 1000 A/1 A ratio. The device to be protected could be an induction motor or a power transformer fed by this feeder.

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. Access the setting of the nominal current of the device to be protected by successively selecting (double clicking) the items below in the *Project tree* area of DIGSI 5.

Relay XXXX (Siemens YYYYY) ► *Settings* ► *VI 3ph 1* ► *General*

Characters XXXX in the items shown above correspond to the model number of the protective relay that is used in the project file that is currently open.

The parameter *Rated current* should be displayed in the working area of DIGSI 5. The value of this parameter is set to the value of the nominal current $I_{Nom.}$ of the device to be protected. The *Rated current* parameter is currently set to 1000 A.

9. In DIGSI 5, access the settings of the thermal relay (ANSI device no. 49) function of the protective relay. In the *Project tree* area of DIGSI 5, the thermal relay function is called *49 Th.overl. 1* and is located in protection function group *VI 3ph 1*. Figure 41 shows the settings of the thermal relay function that should be displayed in the working area of DIGSI 5.

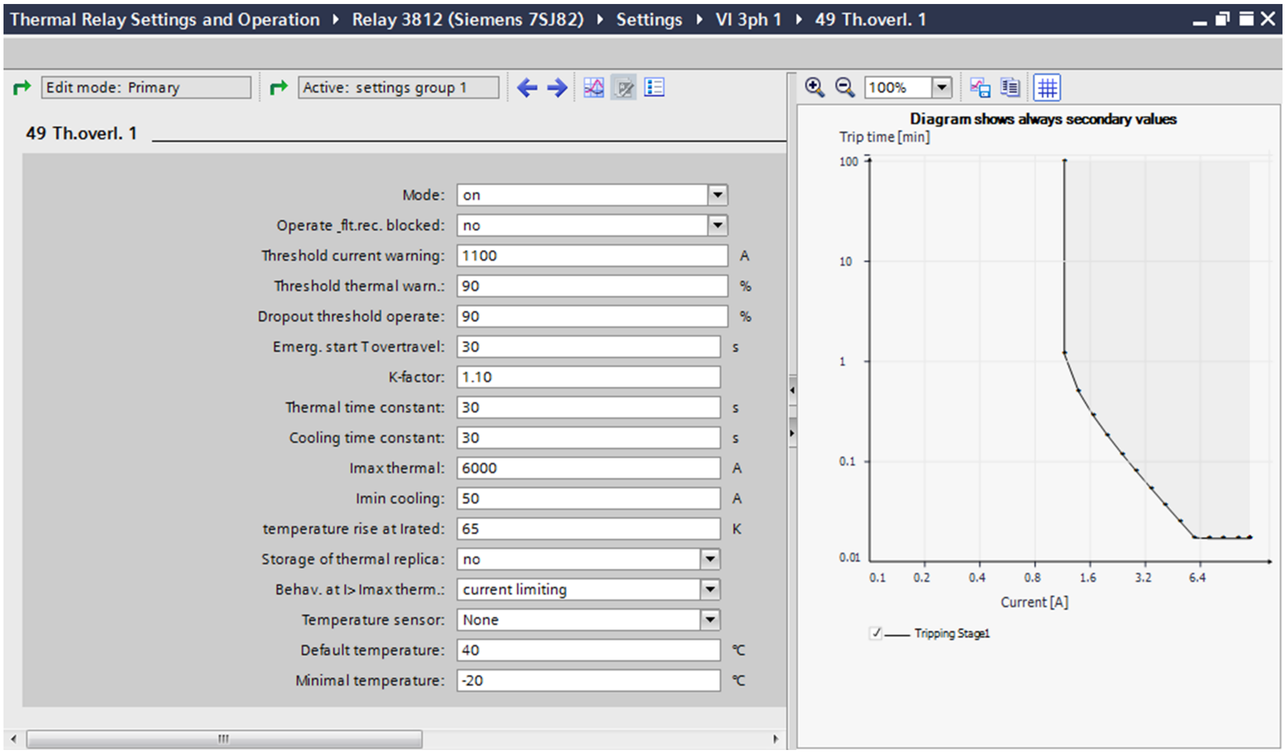


Figure 41. Settings of the thermal relay (ANSI device no. 49) function of the protective relay displayed in the working area of DIGSI 5.

10. Observe that the thermal relay function is defined by several parameters. The key parameters are described in the following table.

Table 4. Key parameters of the thermal relay function of the protective relay.

Name of parameter in DIGSI 5	Description
Mode	Turns the thermal relay (ANSI device no. 49) function on or off.
Threshold current warning	Current at which the thermal relay function produces an alarm signal to indicate that the current flowing through the protected device exceeds the maximum value permitted. This parameter should be set to the value of the maximum thermally permissible current $I_{Therm.\ Max.}$ $(K \cdot I_{Nom.})$ of the protected device. The alarm signal takes the form of an LED that lights up on the protective relay front panel.
Threshold thermal warn.	Temperature at which the thermal relay function produces an alarm signal to indicate that the temperature of the protected device nears the maximum operating temperature. The value of this parameter is expressed as a percentage of the maximum temperature rise $\Delta\theta_{Max.}$ of the protected device. The alarm signal takes the form of an LED that lights up on the protective relay front panel.
K-factor	K factor of the protected device.

Name of parameter in DIGSI 5	Description
Thermal time constant	Heating time constant τ_H of the protected device, expressed in seconds (s).
Cooling time constant	Cooling time constant τ_C of the protected device, expressed in seconds (s).
Imax thermal	Maximum value at which the current flowing through the protected device is limited in the thermal relay function. The goal of this parameter is to limit the effect which high current levels have on the operation of the thermal relay function. Parameter Imax thermal should not be confused with the maximum thermally-permissible current ($I_{Therm.\ Max.}$) of the protected device.
Imin cooling	Value of the current flowing through the protected device at which the thermal relay function considers that the protected device starts to cool down. This current is referred to as current $I_{Cooling}$ in the discussion.
Temperature rise at Irated	Maximum rise in temperature allowed for the protected device, i.e., maximum temperature rise $\Delta\theta_{Max.}$, as specified by the manufacturer of the device. Note that the maximum temperature rise is expressed in Kelvin (K). When expressing temperature differences, 1 K equals 1°C.
Default temperature	Maximum ambient temperature at which the protected device can operate, as specified by the manufacturer of the device. The ambient temperature is expressed in degrees Celsius (°C).

With the values of the parameters in the currently-open project file, the nominal current $I_{Nom.}$, the K factor, current $I_{Therm.\ Max.}$ ($K \cdot I_{Nom.}$), and the heating time constant τ_H of the protected device are equal to 1000 A, 1.1, 1100 A, and 30 s, respectively. The values of these parameters determine the time-current characteristic of the thermal relay function, which is shown in the working area of DIGSI 5. Notice that the time-current characteristic converges toward a vertical asymptotic line located at the value (1100 A) of current $I_{Therm.\ Max.}$ ($K \cdot I_{Nom.}$).

The x-axis in the diagram showing the time-current characteristic of the thermal relay 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 (1000 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 protected device).

Observe that the value of parameter *Threshold current warning* is 1100 A, which corresponds to the value of current $I_{Therm.\ Max.}$ of the protected device. This sets the thermal relay function so that it produces an alarm signal when the current flowing through the protected device exceeds 1100 A.

Also observe that the value of parameter *Threshold thermal warn.* is 90%. This sets the thermal relay function so that it produces an alarm signal when the temperature of the protected device reaches 90% of the maximum temperature rise $\Delta\theta_{Max.}$ of the protected device.

11. In DIGSI 5, increase the value of the heating time constant τ_H to 600 s. Observe that the time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 moves up.

Set the value of the heating time constant τ_H back to its initial value (30 s). Observe that the time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 moves down.

A short heating time constant (30 s) is used in this exercise to speed up observations that will be performed later in this exercise. A common value of heating time constant for induction motors and power transformers is about 900 s.

12. In DIGSI 5, increase the value of the K factor to 1.5. Observe that the time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 moves right.

Set the value of the K factor back to its initial value (1.1). Observe that the time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 moves left.

13. In DIGSI 5, access the setting of the nominal current of the device to be protected (if necessary, refer to step 8). Increase the value of the nominal current $I_{Nom.}$ of the device to be protected to 1500 A.

Access the settings of the thermal relay (ANSI device no. 49) function of the protective relay. Notice that time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 has not been updated to reflect the increase of the nominal current $I_{Nom.}$ of the device to be protected. To update the time-current characteristic displayed, simply set the value of parameter *Imin cooling* to 51 A instead of 50 A. Observe that the time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 moves right because the value of the nominal current $I_{Nom.}$ of the device to be protected is now 1500 A (instead of 1000 A).

14. In DIGSI 5, access the setting of the nominal current of the device to be protected. Set the value of the nominal current $I_{Nom.}$ of the device to be protected back to its initial value (1000 A).

Access the settings of the thermal relay (ANSI device no. 49) function of the protective relay. To update the time-current characteristic displayed, simply set the value of parameter *Imin cooling* back to its initial value (50 A). Observe that the time-current characteristic of the thermal relay function shown in the working area of DIGSI 5 moves left because the value of the nominal current $I_{Nom.}$ of the device to be protected is now 1000 A (instead of 1500 A).

15. 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*.

Observe that the overcurrent protection function is enabled in the protective relay (parameter *Mode* in time-current characteristic *Definite-T1* is set to *On*). Also observe that the overcurrent protection function in the protective relay is set to operate as an instantaneous overcurrent relay (ANSI device no. 50 function) because the time setting (parameter *Operate delay* in time-current characteristic *Definite-T1*) is set to 0.00 s. Also observe that the current setting of the overcurrent protection function (parameter *Threshold* in time-current characteristic *Definite-T1*) is currently set to 6000 A.

In this project, the protective relay is thus programmed to combine the thermal relay (ANSI device no. 49) and instantaneous overcurrent relay (ANSI device no. 50) functions.

Operation of a machine or transformer thermal relay of the thermal-replica type

In this section, you will observe the operation of a thermal relay (ANSI device no. 49) of the thermal-replica type.

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

17. On the protective relay, observe that the front panel display indicates the values of the line currents (I_A, I_B, I_C) flowing through the protected device and the relative temperature of the protected device (expressed as a percentage of the maximum temperature rise $\Delta\theta_{Max.}$ of the protected device).

The front panel display also indicates the time until the thermal relay function trips the protective relay. The time indicated remains infinite (∞) as long as the value of the line currents flowing through the protected device is below the value (1100 A) of current $I_{Therm.\ Max.}$ ($K \cdot I_{Nom.}$), and decreases progressively when the value of the line currents flowing through the protected device exceeds the value of current $I_{Therm.\ Max.}$.

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

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

LED indicator number	LED color	Function
1	Red	Pickup indication for phase A of the instantaneous overcurrent relay (ANSI device no. 50) function. The LED lights up when line current A flowing through the protected device exceeds the current setting of the instantaneous overcurrent relay function.

LED indicator number	LED color	Function
2	Red	Pickup indication for phase B of the instantaneous overcurrent relay (ANSI device no. 50) function. The LED lights up when line current B flowing through the protected device exceeds the current setting of the instantaneous overcurrent relay function.
3	Red	Pickup indication for phase C of the instantaneous overcurrent relay (ANSI device no. 50) function. The LED lights up when line current C flowing through the protected device exceeds the current setting of the instantaneous overcurrent relay function.
5	Green	Current alarm signal. The LED lights up when the value of the current flowing through the protected device exceeds the value (1100 A in the present case) of the maximum thermally-permissible current $I_{Therm.\ Max.}$ ($K \cdot I_{Nom.}$).
6	Green	Thermal alarm signal. The LED lights up when the relative temperature of the protected device exceeds a certain percentage (90% in the present case) of the maximum temperature rise $\Delta\theta_{Max.}$ of the protected device.
7	Red	Thermal relay function tripped indication. The LED lights up when the thermal relay function trips the protective relay.
8	Red	Instantaneous overcurrent relay function tripped indication. The LED lights up when the instantaneous overcurrent relay 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.

19. In DIGSI 5, access the parameters of test sequence *800 A load – 200 s*. This test sequence is part of the project file currently open in DIGSI 5 and can be used to test the thermal relay 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 transformers.

Test sequence *800 A load – 200 s* makes the internal relay test system emulate balanced currents of 0.800 A at the current inputs of the relay during a period of 200 s. This is equivalent to balanced currents of 800 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *800 A load – 200 s* to the frequency of your local ac power network.

20. In DIGSI 5, restart the protective relay in the simulation mode to allow the thermal relay function of the protective relay (i.e., protection function *49 Th.overl. 1* 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 for the protective relay that you are using 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.*

21. In DIGSI 5, start test sequence *800 A load – 200 s*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system. Observe that the value of the line currents flowing through the protected device is 800 A.

Notice that the relative temperature indicated on the relay front panel increases progressively when current flows through the protected device. Record the relative temperature of the protected device when it stabilizes (i.e., at least 150 s after current began to flow through the protected device).

Max. relative temperature @ 800 A: __________ %

Max. relative temperature @ 800 A: 53%

Wait until the test sequence terminates. Did the protective relay trip or produce an alarm signal? Explain briefly.

No, because the current flowing through the protected device was lower than the current $I_{Therm. Max.}$ (1100 A) and the max. relative temperature reached about 53%.

22. Notice that after the test sequence terminated, the relative temperature indicated on the relay front panel decreases slowly because current no longer flows through the protected device. It takes significant time for the relative temperature to decrease down to 0%.

To avoid waiting for the relative temperature to decrease to 0%, start test sequence *Reset thermal protection* in DIGSI 5. This test sequence resets the value of the relative temperature computed by the thermal relay function.

23. In DIGSI 5, access the parameters of test sequence *1000 A load – 200 s*.

Test sequence *1000 A load – 200 s* makes the internal relay test system emulate balanced currents of 1.000 A at the current inputs of the relay during a period of 200 s. This is equivalent to balanced currents of 1000 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *1000 A load – 200 s* to the frequency of your local ac power network.

24. In DIGSI 5, start test sequence *1000 A load – 200 s*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system. Observe that the value of the line currents flowing through the protected device is 1000 A.

Notice that the relative temperature indicated on the relay front panel increases progressively when current flows through the protected device. Record the relative temperature of the protected device when it stabilizes (i.e., at least 150 s after current began to flow through the protected device).

Max. relative temperature @ 1000 A: __________ %

Max. relative temperature @ 1000 A: 83%

Wait until the test sequence terminates. Did the protective relay trip or produce an alarm signal? Explain briefly.

No, because the current flowing through the protected device was lower than the current $I_{Therm.\ Max.}$ (1100 A) and the max. relative temperature reached about 83%.

25. In DIGSI 5, start test sequence *Reset thermal protection* to reset the value of the relative temperature computed by the thermal relay function.

26. In DIGSI 5, access the parameters of test sequence *1090 A load – 200 s*.

Test sequence *1090 A load – 200 s* makes the internal relay test system emulate balanced currents of 1.090 A at the current inputs of the relay during a period of 200 s. This is equivalent to balanced currents of 1090 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *1090 A load – 200 s* to the frequency of your local ac power network.

27. In DIGSI 5, start test sequence *1090 A load – 200 s*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system. Observe that the value of the line currents flowing through the protected device is 1090 A.

Record the relative temperature of the protected device when it stabilizes (i.e., at least 150 s after current began to flow through the protected device).

Max. relative temperature @ 1090 A: __________ %

Max. relative temperature @ 1090 A: 98%

Wait until the test sequence terminates. Did the protective relay trip or produce an alarm signal? Explain briefly.

The protective relay did not trip because the current flowing through the protected device was lower than the current $I_{Therm.\ Max.}$ (1100 A). However, the protective relay produced a thermal alarm signal (LED indicator 6 lit up) when the relative temperature of the protected device reached 90%.

28. In DIGSI 5, start test sequence *Reset thermal protection* to reset the value of the relative temperature computed by the thermal relay function.

29. Do the values of maximum relative temperature measured so far confirm that the temperature rise estimated by the thermal relay function is proportional to the square of the current flowing through the protected device? Explain briefly.

Yes. When the value of the current flowing through the protected device is 800 A, the estimated temperature rise should be 52.9% [$(800\ A/1100\ A)^2 \cdot 100\% = 52.9\%$] of the maximum temperature rise $\Delta\theta_{Max.}$ of the protected device. Similarly, when the values of the current flowing through the protected device are 1000 A and 1090 A, the values of the estimated temperature rise should be 82.6% and 98.2%, respectively. All these values of temperature rise closely match the values of maximum relative temperature measured so far in this exercise.

30. In DIGSI 5, access the parameters of test sequence *1110 A load – 150 s*.

Test sequence *1110 A load – 150 s* makes the internal relay test system emulate balanced currents of 1.110 A at the current inputs of the relay during a period of 150 s. This is equivalent to balanced currents of 1110 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *1110 A load – 150 s* to the frequency of your local ac power network.

31. In DIGSI 5, start test sequence *1110 A load – 150 s*, then observe the front panel of the protective relay to see how it responds to the currents emulated by its internal relay test system. Observe that the value of the line currents flowing through the protected device is 1110 A, which very slightly exceeds the value (1100 A) of current $I_{Therm.\ Max.}$.

Does the protective relay produce a current alarm signal?

Yes, LED indicator 5 lights up as soon as current starts to flow through the protected device.

Wait until the test sequence terminates. Did the protective relay trip or produce an alarm signal?

The protective relay produced a thermal alarm signal (LED indicator 6 lit up) when the relative temperature of the protected device reached 90%. The thermal relay function tripped when the relative temperature reached 100% (LED indicator 7 lit up), thereby tripping the protective relay (LED indicator 16 lit up).

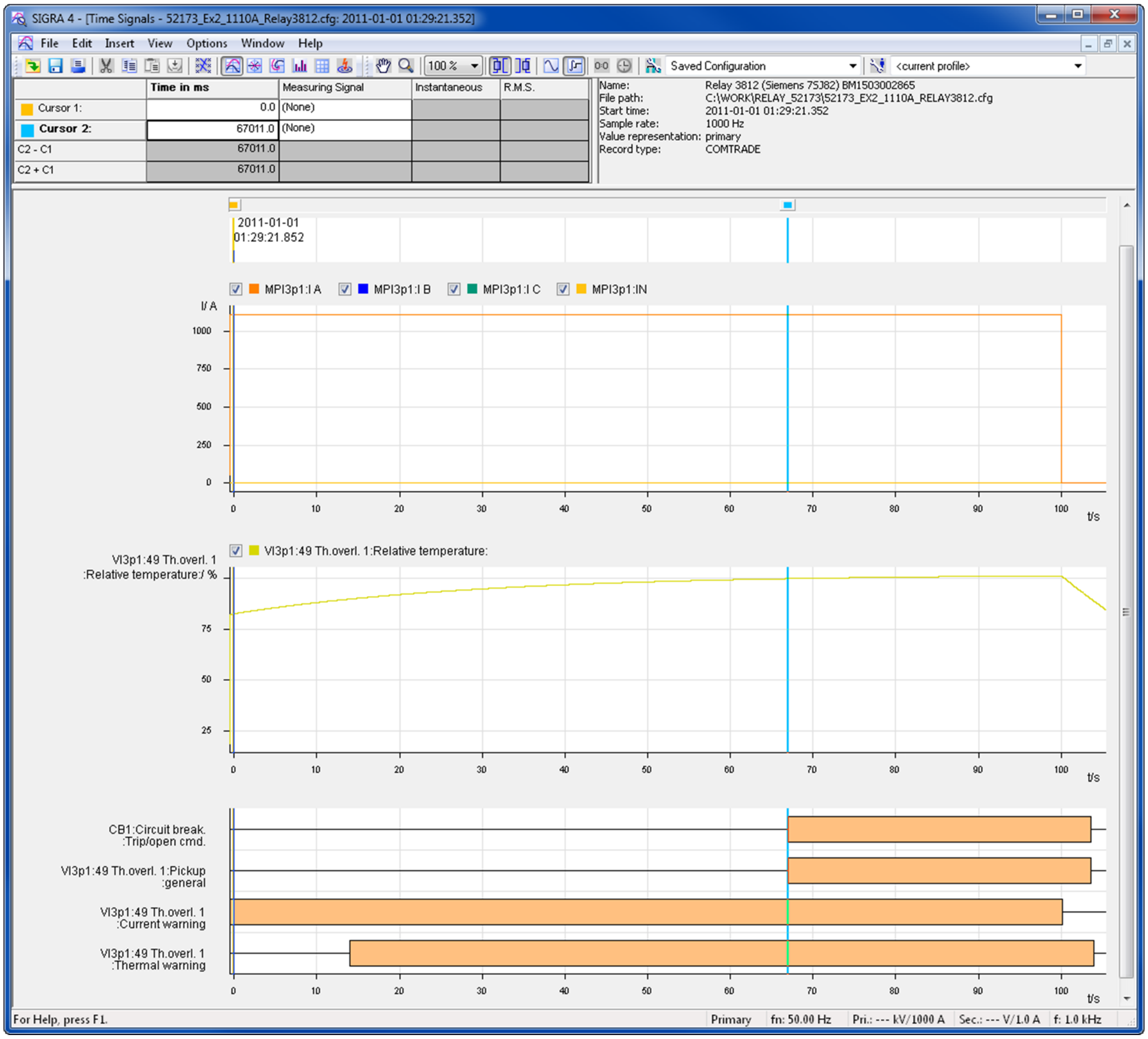
Did the protective relay operate as expected? Explain briefly.

Yes. The protective relay had to trip after a certain time because the protected device was under prolonged overload conditions, i.e., the value of the current flowing through the protected device exceeded the value of current $I_{Therm.\ Max.}$ long enough to cause the relative temperature of the protected device to reach 100%.

32. A fault record has been created in the protective relay when it tripped. Use DIGSI 5 to download the latest fault record from the protective relay and display the signals contained in this fault record in SIGRA. Determine the trip time of the protective relay from these signals. Note that signal recording begun 50 s after current started to flow in the protected device. Therefore, add 50 s to the trip time determined from the signals contained in the fault record.

Relay trip time @ 1110 A: __________ s

Relay trip time @ 1110 A: 67 s + 50 s = 117 s



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

33. In DIGSI 5, start test sequence *Reset thermal protection* to reset the value of the relative temperature computed by the thermal relay function.

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.

Time-current characteristic of a machine or transformer thermal relay of the thermal-replica type

In this section, you will measure the trip time of the protective relay at different values of current to confirm that the thermal relay function operates as expected.

34. In DIGSI 5, access the parameters of test sequence *1200 A load – 90 s*.

Test sequence *1200 A load – 90 s* makes the internal relay test system emulate balanced currents of 1.200 A at the current inputs of the relay during a period of 90 s. This is equivalent to balanced currents of 1200 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *1200 A load – 90 s* to the frequency of your local ac power network.

35. In DIGSI 5, start the test sequence (i.e., the last sequence that you accessed the parameters), then observe the front panel of the protective relay. Observe that the value of the line currents flowing through the protected device exceeds the value (1100 A) of current $I_{\text{Therm. Max.}}$.

Wait until the test sequence terminates. The protective relay should trip before the end of the test sequence.

Use DIGSI 5 to download the latest fault record from the protective relay and display the signals contained in this fault record in SIGRA. Determine the trip time of the protective relay from these signals.

Relay trip time @ 1200 A: __________ s

Relay trip time @ 1200 A: 54.6 s

36. In DIGSI 5, start test sequence *Reset thermal protection* to reset the value of the relative temperature computed by the thermal relay function.

Reset the protective relay.

37. In DIGSI 5, access the parameters of test sequence *1400 A load – 60 s*.

Test sequence *1400 A load – 60 s* makes the internal relay test system emulate balanced currents of 1.400 A at the current inputs of the relay during a period of 60 s. This is equivalent to balanced currents of 1400 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *1400 A load – 60 s* to the frequency of your local ac power network.

Repeat step 35 to obtain the trip time of the protective relay.

Relay trip time @ 1400 A: __________ s

Relay trip time @ 1400 A: 28.7 s

Repeat step 36 to reset the thermal relay function and the protective relay.

38. In DIGSI 5, access the parameters of test sequence *2200 A load – 30 s*.

Test sequence *2200 A load – 30 s* makes the internal relay test system emulate balanced currents of 2.200 A at the current inputs of the relay during a period of 30 s. This is equivalent to balanced currents of 2200 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *2200 A load – 30 s* to the frequency of your local ac power network.

Repeat step 35 to obtain the trip time of the protective relay.

Relay trip time @ 2200 A: __________ s

Relay trip time @ 2200 A: 8.54 s

Repeat step 36 to reset the thermal relay function and the protective relay.

39. In DIGSI 5, access the parameters of test sequence *4400 A load – 15 s*.

Test sequence *4400 A load – 15 s* makes the internal relay test system emulate balanced currents of 4.400 A at the current inputs of the relay during a period of 15 s. This is equivalent to balanced currents of 4400 A flowing through the protected device because 1000 A/1 A current transformers are used in this project.

Set the frequency of the balanced currents emulated during each step of test sequence *4400 A load – 15 s* to the frequency of your local ac power network.

Repeat step 35 to obtain the trip time of the protective relay.

Relay trip time @ 4400 A: __________ s

Relay trip time @ 4400 A: 1.99 s

Repeat step 36 to reset the thermal relay function and the protective relay.

40. Use the equation given in the discussion to compute the expected trip time of the thermal relay function in the protective relay at values of current of 1110 A, 1200 A, 1400 A, 2200 A, and 4400 A.

$$t = \tau_H \ln\left[\frac{1}{1-\left(\frac{I_{Therm.\ Max.}}{I}\right)^2}\right]$$

$I_{Therm.\ Max.}$ = 1100 A
τ_H = 30 s

@ I = 1110 A $\quad t = 30\ s \ln\left[\frac{1}{1-\left(\frac{1100\ A}{1110\ A}\right)^2}\right] = 120.6\ s$

@ I = 1200 A $\quad t = 30\ s \ln\left[\frac{1}{1-\left(\frac{1100\ A}{1200\ A}\right)^2}\right] = 55.0\ s$

@ I = 1400 A $\quad t = 30\ s \ln\left[\frac{1}{1-\left(\frac{1100\ A}{1400\ A}\right)^2}\right] = 28.8\ s$

@ I = 2200 A $\quad t = 30\ s \ln\left[\frac{1}{1-\left(\frac{1100\ A}{2200\ A}\right)^2}\right] = 8.6\ s$

@ I = 4400 A $\quad t = 30\ s \ln\left[\frac{1}{1-\left(\frac{1100\ A}{4400\ A}\right)^2}\right] = 1.9\ s$

41. Are the trip times of the protective relay obtained in steps 32, 35, 37, 38, and 39 as expected?

Yes, the trip times of the protective relay obtained in steps 32, 35, 37, 38, and 39 are very close to the expected trip times of the thermal relay function calculated in step 40.

Does the trip time of the protective relay decrease with the value of the overload current?

❑ Yes ❑ No

Yes

Overcurrent protection

In this section, you will observe the operation of the protective relay when the current flowing through the protected device exceeds the current setting of the instantaneous overcurrent relay (ANSI device no. 50) function.

42. In DIGSI 5, access the parameters of test sequence *6600 A load – 2 s*.

Test sequence *6600 A load – 2 s* makes the internal relay test system emulate balanced currents of 6.600 A at the current inputs of the relay during a period of 2 s. This is equivalent to balanced currents of 6600 A flowing through the protected device because 1000 A/1 A current transformers are used in this project. The magnitude of these currents is sufficient to trip the instantaneous overcurrent relay function in the protective relay. Also, the magnitude and duration of these currents are sufficient to trip the thermal relay function in the protective relay.

Set the frequency of the balanced currents emulated during each step of test sequence *6600 A load – 2 s* to the frequency of your local ac power network.

43. In DIGSI 5, start test sequence *6600 A load – 2 s*, then observe the front panel of the protective relay. Wait until the test sequence terminates. The protective relay should trip before the end of the test sequence.

Did both the instantaneous overcurrent relay and thermal relay functions in the protective relay trip?

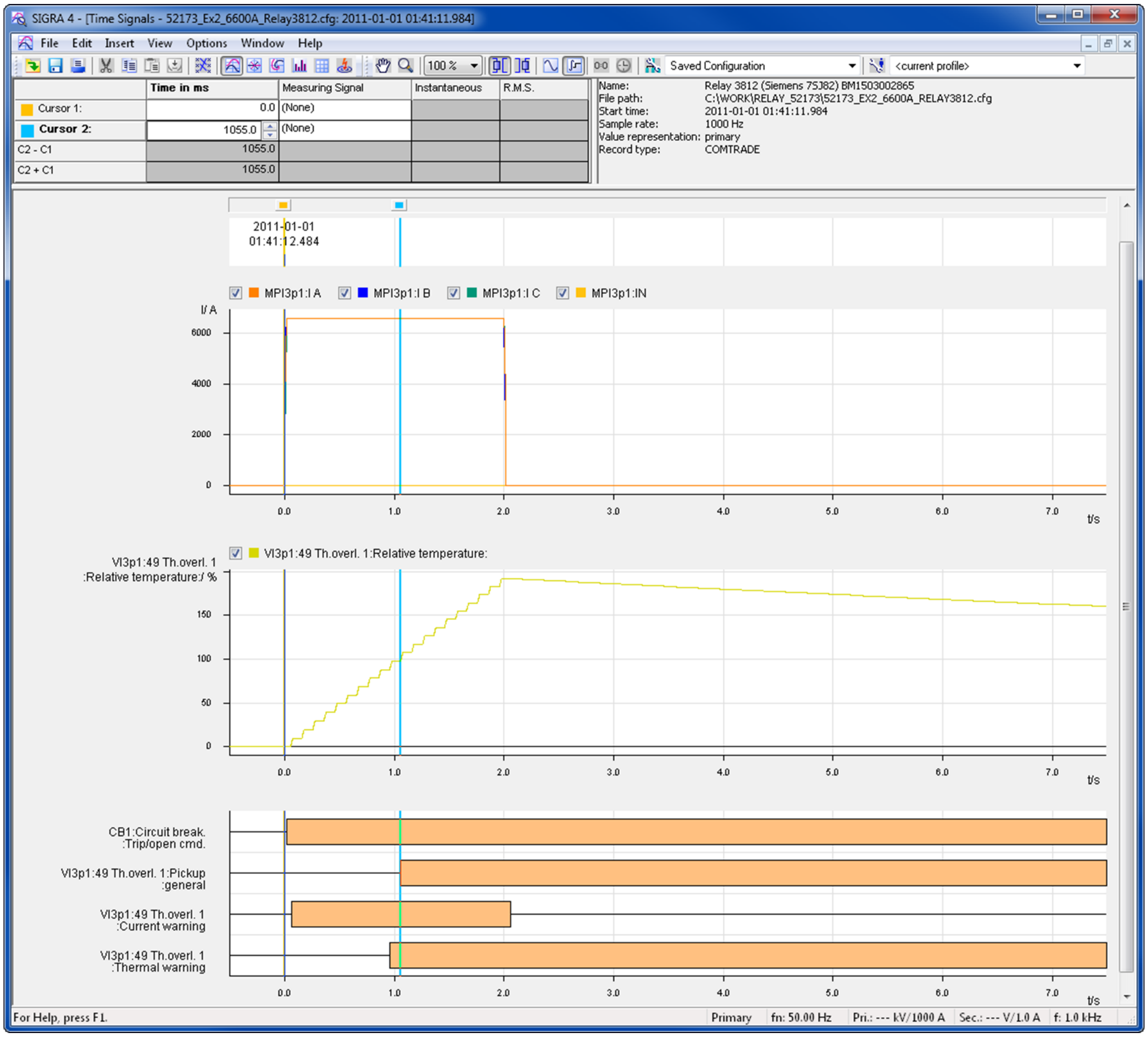
Yes. This is indicated by both LED indicator 7 (thermal relay function tripped indication) and LED indicator 8 (instantaneous overcurrent relay function tripped indication) being lit.

44. Use DIGSI 5 to download the latest fault record from the protective relay and display the signals contained in this fault record in SIGRA.

Observe the signals displayed in SIGRA. Which function tripped the protective relay? Explain briefly.

The instantaneous overcurrent relay function, because the operating time of the thermal relay function, about 1 s, is definitely longer than the operating time (virtually 0 s) of the instantaneous overcurrent relay function.

In actual protection systems, i.e., when the protective relay controls the opening of a circuit breaker connected in the series with the protected device, line currents are interrupted a few tenths of a second after the instantaneous overcurrent relay function tripped the protective relay. Consequently, this greatly limits heating of the protected device and prevents the thermal relay function from tripping. Tripping of the thermal relay function observed in this exercise, which slightly departs from what occurs in actual protection systems, exposes a minor limitation of using an internal relay test system to assess the operation of a numerical protective relay.



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

45. In DIGSI 5, start test sequence *Reset thermal protection* to reset the value of the relative temperature computed by the thermal relay function.

Reset the protective relay.

46. 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).

47. 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 the power rating of an ac machine or a power transformer is related to its thermal capability. You became familiar with the operation and settings of machine or transformer thermal relays of the temperature-sensor type. You also became familiar with the operation and settings of machine or transformer thermal relays of the thermal-replica type. You saw how to adjust the settings of a thermal relay of the thermal-replica type to obtain a specific inverse time-current characteristic. You learned how to use a numerical protective relay combining the protective functions of an instantaneous overcurrent relay (ANSI device no. 50) and a machine or transformer thermal relay (ANSI device no. 49) to achieve overcurrent and overload protection of an ac machine or a power transformer. You also learned that an IDMT overcurrent relay (ANSI device no. 51I) function can also be used to achieve overload protection of an ac machine or a power transformer. You used the internal relay test system of a numerical protective relay to assess that the machine or transformer thermal relay function operates as expected.

Review Questions

1. Describe what a thermal relay is.

   A thermal relay is a type of protective relay that is used to protect an ac machine or a power transformer against thermal overload. A thermal relay either directly measures or estimates the temperature of an ac machine or a power transformer and initiates an action (e.g., triggers an alarm or trips an HV circuit breaker to disconnect the machine or transformer) when the measured or estimated temperature exceeds a predetermined value.

2. Briefly explain how the power rating of an ac machine or a power transformer is related to its thermal capability.

   The temperature rating of the insulation (often referred to as the insulation class) of the windings in an electric device such as an ac machine or a power transformer is generally the main factor limiting the maximum operating temperature of the device. This, in turn, limits the maximum temperature rise ($\Delta\theta_{Max.}$) that is possible, and thus, the maximum current that can flow in the device continuously without causing damage to the device. This ultimately determines the power rating of the device.

3. Briefly describe how a machine or transformer thermal relay of the thermal-replica type operates.

A machine or transformer thermal relay of the thermal-replica type estimates the temperature of the protected device from the measured value of the current flowing through the protected device. A mathematical model is used to estimate the temperature of the protected device as accurately as possible. The thermal relay trips when the estimated temperature exceeds the maximum temperature threshold set in the relay.

4. A numerical relay with a thermal relay function of the thermal-replica type is used to protect a power transformer having a nominal current $I_{Nom.}$ of 400 A, a K factor of 1.2, and a heating time constant τ_H of 900 s. What is the operating time of the thermal relay function at each of the following two values of current flowing through the power transformer: 450 A and 900 A?

The maximum thermally-permissible current $I_{Therm.\ Max.}$ of the power transformer is equal to 480 A. Consequently, at a current of 450 A, the thermal relay function should not trip because this value of current is below the value of current $I_{Therm.\ Max.}$. At a current of 900 A, however, the operating time of the thermal relay function should be 301 s. The calculations are shown below.

$$t = \tau_H \ln\left[\frac{1}{1-\left(\frac{I_{Therm.\ Max.}}{I}\right)^2}\right]$$

$I_{Therm.\ Max.} = K\ I_{Nom.} = 1.2 \cdot 400\ A = 480\ A$

$\tau_H = 900\ s$

$$t(@I = 900\ A) = 900\ s \ln\left[\frac{1}{1-\left(\frac{480\ A}{900\ A}\right)^2}\right] = 301\ s$$

5. Which parameters related to the protected device directly affect the time-current characteristic of a thermal relay of the thermal-replica type? Describe how these parameters affect the time-current characteristic of the thermal relay.

The nominal current $I_{Nom.}$, the K factor, and the heating time constant τ_H directly affect the time-current characteristic of a thermal relay of the thermal-replica type. The values of the nominal current $I_{Nom.}$ and K factor determine the position of the vertical asymptotic line of the time-current characteristic. The time-current characteristic is moved right when the value of either one of these two parameters is increased and vice versa. On the other hand, the value of the heating time constant τ_H determines the vertical position of the time-current characteristic. Increasing the heating time constant τ_H moves the time-current characteristic up and vice versa.

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