BS EN 60255-149:2013

BSI Standards Publication

Measuring relays and protection equipment

Part 149: Functional requirements for thermal electrical relays

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National foreword

This British Standard is the UK implementation of EN 60255-149:2013. It is identical to IEC 60255-149:2013. It superseeds BS EN 60255-8:1998, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/95, Measuring relays and protection systems.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Measuring relays and protection equipment - Part 149: Functional requirements for thermal electrical relays
(IEC 60255-149:2013)

Relais de mesure et dispositifs de protection -
Partie 149: Exigences fonctionnelles pour les relais électriques thermiques
(CEI 60255-149:2013)

Messrelais und Schutzeinrichtungen -
Teil 149: Funktionsanforderungen an den thermischen Überlastschutz
(IEC 60255-149:2013)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Avenue Marnix 17, B - 1000 Brussels

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Foreword

The text of document 95/313/FDIS, future edition 1 of IEC 60255-149, prepared by IEC/TC 95 "Measuring relays and protection equipment" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60255-149:2013.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-06-03
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-09-03

This document supersedes EN 60255-8:1998.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60255-149:2013 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60034-11 NOTE Harmonized as EN 60034-11.

IEC 60947-4-1 NOTE Harmonized as EN 60947-4-1.

IEC 60947-4-2 NOTE Harmonized as EN 60947-4-2.

IEC 61850-9-2 NOTE Harmonized as EN 61850-9-2.

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050	Series	International Electrotechnical Vocabulary (IEV)	-	-
IEC 60085	2007	Electrical insulation - Thermal evaluation and designation	EN 60085	2008
IEC 60255-1	-	Measuring relays and protection equipment - Part 1: Common requirements	EN 60255-1	-
IEC 61850-7-4	-	Communication networks and systems for power utility automation - Part 7-4: Basic communication structure - Compatible logical node classes and data object classes	EN 61850-7-4	-

CONTENTS

MEASURING RELAYS AND PROTECTION EQUIPMENT –

Part 149: Functional requirements for thermal electrical relays

1 Scope

This part of the IEC 60255 series specifies minimum requirements for thermal protection relays. This standard includes specification of the protection function, measurement characteristics and test methodologies.

The object of this standard is to establish a common and reproducible reference for evaluating dependent time relays which protect equipment from thermal damage by measuring a.c. current flowing through the equipment. Complementary input energizing quantities such as ambient, coolant, top oil and winding temperature may be applicable for the thermal protection specification set forth in this standard. This standard covers protection relays based on a thermal model with memory function.

The test methodologies for verifying performance characteristics of the thermal protection function and accuracy are also included in this Standard.

This standard does not intend to cover the thermal overload protection trip classes indicated in IEC 60947-4-1 and IEC 60947-4-2, related to electromechanical and electronic protection devices for low voltage motor-starters.

The thermal protection functions covered by this standard are as follows:

Protection function	**IEC 61850-7-4**	**IEEE C37.2**
Thermal overload protection	**PTTR**	49
Rotor thermal overload protection	**PROL**	49R
Stator thermal overload protection	**PSOL**	49S

General requirements for measuring relays and protection equipment are specified in IEC 60255-1.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at http://www.electropedia.org)

IEC 60085, *Electrical insulation – Thermal evaluation and designation*

IEC 60255-1, *Measuring relays and protection equipment – Part 1: Common requirements*

IEC 61850-7-4, *Communication networks and systems for power utility automation – Part 7-4: Basic communication structure – Compatible logical node classes and data classes*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in IEC 60050-447, as well as the following apply.

3.1
hot curve
for a thermal electrical relay with a total memory function, characteristic curve representing the relationship between specified operating time and current, taking into account thermal effect of a specified steady-state load current before the overload occurs

Note 1 to entry: Hot curve is a plot of a particular time-current solution for a first-order thermal system differential equation, assuming a specific constant overload current and a specific preload current.

3.2
cold curve
for a thermal electrical relay, characteristic curve representing the relationship between specified operating time and current, with the relay at reference and steady-state conditions with no-load current flowing before the overload occurs

Note 1 to entry: Cold curve is a plot of a particular time-current solution for a first-order thermal system differential equation, assuming a specific constant overload current when there is no preload.

3.3
basic current
I_B
specified limiting (nominal) value of the current for which the relay is required not to operate at steady-state conditions of the equipment to be thermally protected

Note 1 to entry: The basic current serves as a reference for the definition of the operational characteristics of thermal electrical relays. The basic settings of a thermal electrical protection function are made in terms of this basic current (I_B) and the thermal time constant (τ) of the protected equipment.

3.4
equivalent heating current
I_{eq}
current which takes into account the additional heating sources such as imbalance currents and/or harmonics

3.5
factor *k*
factor by which the basic current (I_B) is multiplied to obtain the maximum permissible continuous operating current value of the equipment to be thermally protected, which is used in the thermal characteristic function

Note 1 to entry: The factor *k* indicates the maximum permissible constant between phase current (full load) and the basic (nominal) current of the protected equipment.

3.6
previous load ratio
ratio of the load current preceding the overload to basic current under specified conditions

3.7
reference limiting error
limiting error determined under reference conditions

[SOURCE: IEC 60050:2010, 447-08-07]

3.8
temperature rise
difference between the temperature of the part under consideration and a reference temperature

Note 1 to entry: The reference temperature may be for example the ambient air temperature or the temperature of a cooling fluid.

[SOURCE: IEC 60050:2001, 151-16-26]

3.9
thermal equilibrium
thermal state reached when the temperature rise of the several parts of the machine do not vary by more than a gradient of 2 K per hour

[SOURCE: IEC 60050:1996, 411-51-08]

3.10
thermal time constant
$\boldsymbol{T_{th}}$
time required for the temperature rise of the protected equipment relative to its initial temperature, to reach 63,2 % of its final, asymptotic value following a step increase in current

Note 1 to entry: The initial temperature for example can be ambient temperature.

3.11
thermal level
H
ratio expressed in percentage between the estimated actual temperature of the equipment and the temperature of the equipment when the equipment is operating at its maximum current ($k \times I_B$) for a long period, enough to allow equipment to reach its thermal equilibrium

4 Specification of the function

4.1 General

An example of a thermal protection function with its input energizing quantities, binary input signals, operate (trip), alarm and other binary outputs, and functional logic which includes measuring element, thermal level calculation, settings, and thresholds are shown in Figure 1. The manufacturer shall provide the functional block diagram of the specific thermal protection implementation.

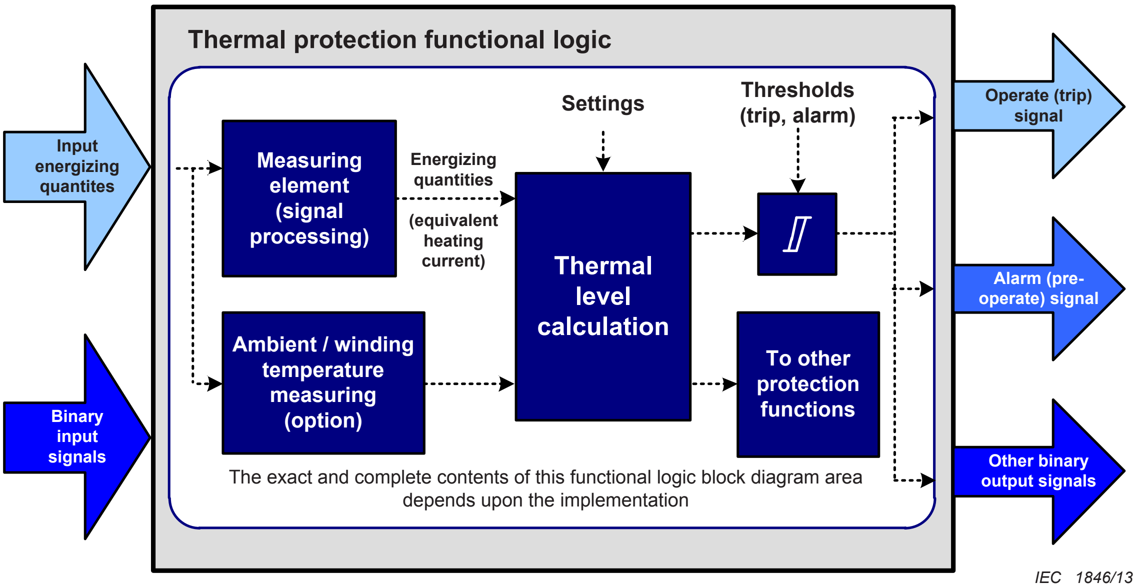


Figure 1 – Simplified thermal protection function block diagram

4.2 Input energizing quantities/energizing quantities

The input energizing quantities are the measuring signals, such as phase (or line) currents, and ambient/environmental or winding temperatures (if required or applicable). Their ratings and relevant requirements are specified in IEC 60255-1.

Input energizing quantities can be presented to the thermal protection functional logic either hardwired from current transformers and any additional input quantities such as ambient or winding temperature, or as a data packet over a communication ports using an appropriate data communication protocol, such as IEC 61850-9-2.

The input energizing quantities used by the thermal protection function need not be the current directly taken from the secondary side of the current transformers. Therefore the protection relay documentation shall state the type of energizing quantities used by the thermal protection function.

Examples of input energizing quantities are:

– single-phase current measurement;
– three-phase current measurement;
– positive and negative sequence current measurement;
– winding or ambient temperature sensor.

NOTE The ambient temperature, coolant temperature, top oil temperature or winding temperature of the equipment to be thermally protected can be measured by temperature sensors, such as resistance temperature detector (RTD), the values of which can be used for biasing the calculation of the thermal level replica specified in this standard. Output signals or values of these temperature sensors can be taken into account for the first-order thermal model algorithm, which can influence and compensate the calculated thermal level (based on the equivalent heating current and heating thermal time constant values).

4.3 Binary input signals

If any binary input signals (externally or internally driven) are used, their influence on the thermal protection function shall be clearly described on the functional logic diagram or in the protective device manufacturer documentation. Additional textual description may also be provided if this can further clarify the functionality of the input signals and their intended application or implementation.

Binary input signals to this function may emanate from a number of different sources. Examples include:

- traditionally wired to physical inputs;
- via a communications port from external devices;
- via internal logical connections from other functional elements within the relay.

The method of receiving the signal is largely irrelevant except to conform to operational requirements.

Definitions, ratings and standards for physical binary input signals are specified in IEC 60255-1.

The following are examples of binary input signal application in thermal protection.

1) When the thermal protection function is implemented with two operating modes of the protected equipment, such as power transformers with natural or forced ventilation, two-speed motors or a star/delta starting motor, a binary input can be implemented to discriminate the different operating modes and to select the required group of settings to be used for proper thermal protection application.
2) Another example of a binary input is to implement a reset function of the thermal memory during testing/commissioning procedures, using a binary input either directly hardwired or through data communications.

4.4 Functional logic

4.4.1 Equivalent heating current

The equivalent heating current I_{eq} takes into account the additional heating source such as imbalance currents and/or harmonics. The type of measurement of the equivalent heating current shall be stated in the protection relay documentation.

For the rms measurement, the manufacturer shall specify the bandwidth of the rms current measurement and define which harmonics are included in the equivalent heating current calculation.

Annex A gives an explanation of the definition of the equivalent heating current and different cases of implementation of thermal protection applications of electrical equipment.

4.4.2 Basic (setting) and operating current values for thermal protection

For the thermal electrical relay, the basic (setting) current value I_B is the specified limiting value of the current for which the relay is required not to operate. For motor or transformer applications, the basic current is usually set to the nominal current of the protected equipment.

To take into account the maximum continuous load current of the protected equipment, a factor k is applied to the basic (setting) current value, to determine the operating current for the thermal protection.

Therefore the value $k \times I_B$ defines the operating current of the thermal protection relays,

where

k may be a constant value or a user setting, as declared by the thermal relay manufacturer;

I_B is the basic (setting) current value expressed as the permissible current of the equipment to be thermally protected.

With the factor *k*, no operation of the thermal relay is guaranteed for phase currents equal to the setting value I_B. If the factor *k* is a user setting, it should include a range of at least 1,0 to 1,5. For motor or transformer applications, the factor *k* is usually set by the user, where $k \times I_B$ is equal to or less than maximum operating (full load) current of the equipment to be thermally protected. For relays which do not have a *k* factor setting (assumed to be fixed at 1,0) the setting for I_B should be adjusted to account for the *k* factor.

In some cases a fixed value of *k* may be defined by the manufacturer, equal to the accuracy of current measurement of the thermal electrical relay. This ensures that the thermal relay shall not operate for an operating current of I_B. In this case the ratio between the overload and the nominal current for the equipment being protected can be accommodated in the setting of the base current I_B.

4.4.3 Thermal level calculation

The thermal level calculation of the protected equipment is based on the equivalent heating phase current measurement and the recursive computation of a discrete-time equation of a differential first-order thermal model.

The thermal level $H(t)$ of the protected equipment is calculated by the following equation:

$$H(t) = \left(\frac{I_{eq}(t)}{k \cdot I_B} \right)^2 . \frac{\Delta t}{\tau + \Delta t} + \frac{\tau}{\tau + \Delta t} . H(t - \Delta t) \qquad (1)$$

where

$H(t)$ is the thermal level at time t;

$H(t–\Delta t)$ is the thermal level at time $t–\Delta t$;

Δt is the sample period which is the time interval between two consecutives samples of input currents;

$I_{eq}(t)$ is the equivalent heating phase current at time t (see 4.4.1 and Annex A);

$k \cdot I_B$ is the value of the maximum continuous current, including *k* factor;

τ is the heating/cooling thermal time constant of the equipment to be thermally protected, τ is assumed to be $>>\Delta t$.

Derivation of differential and time-current equations and dynamics for a simple first-order thermal system are given in detail in Annex A.

For a particular steady-state case with a constant I_{eq}, the thermal level H can be calculated by the following particular and simplified equation:

$$H = \left(\frac{I_{eq}}{k \cdot I_B} \right)^2 \qquad (2)$$

The thermal electrical relay operates if the thermal level reaches 100 % of maximum thermal level threshold.

According to the mechanical design of the electrical equipment to be thermally protected, the heating thermal time constant and cooling thermal time constant can have different values. For example, for electric motor protection application, the heating thermal time constant is lower than the cooling thermal time constant due to the rotor rotation and self-ventilation operation when the motor is running. In these cases, the thermal level is calculated according to the phase current level, with two different thermal time constants, according to the following equations.

If $I_{eq}(t) \geq 0$ (or if $I_{eq}(t)$ is greater than a fixed input current threshold, stated by the thermal relay manufacturer), the thermal level can be computed by the following equation:

$$H(t) = \left(\frac{I_{eq}(t)}{k.I_B} \right)^2 . \frac{\Delta t}{\tau_1 + \Delta t} + \frac{\tau_1}{\tau_1 + \Delta t} .H(t - \Delta t) \quad (3)$$

If $I_{eq}(t) \approx 0$ (or if $I_{eq}(t)$ is lower than a fixed input current threshold, stated by the thermal relay manufacturer), the thermal level can be computed by the following equation:

$$H(t) = \frac{\tau_2}{\tau_2 + \Delta t} .H(t - \Delta t) \quad (4)$$

where

τ_1 is the heating thermal time constant of the equipment to be thermally protected;

τ_2 is the cooling thermal time constant of the equipment to be thermally protected.

NOTE 1 Generally τ_1 is used when the protected equipment is energized and τ_2 is used when the protected equipment is deenergized.

NOTE 2 The heating thermal time constant τ_1 is also used when the equipment is energized and the phase current is reduced to a lower level, which causes a lowering of the equipment thermal level, causing a decrease in the equipment temperature.

NOTE 3 Manufacturers can implement multiple heating and multiple cooling time constants to cover the variety of heating and cooling conditions. For example, during direct on-line motor starting the time constant used in the thermal model can be changed (decreased) to allow for reduced cooling capability of the rotor at standstill/low speed and then revert to a longer time constant when normal running speed is achieved.

For most thermal protection applications, such as self-ventilated motor and generator, two-speed motors, star/delta starting motor, the thermal time constants τ_1 and τ_2 are different. For some other applications, such as motors with separated, independent forced ventilation or cooling systems, power transformers with or without forced ventilation cooling systems, cables, and capacitors, the thermal time constants τ_1 and τ_2 may have the same value. Some specific applications, such as two-speed motors or where star/delta starting is used, additional heating time constants may be used.

4.4.4 Time-current limit characteristic equations and curves

4.4.4.1 General

The time-current characteristics shall be published by the relay manufacturer either in the form of equations or by graphical methods. The time-current equations for a simple thermal model are given here for cold state and hot state.

4.4.4.2 Cold curve

The cold curve for thermal protection relays is a particular solution of the first-order differential Equation (1) for the following conditions.

– Starting from a thermal level with no load current before the overload occurs. Therefore, the equipment temperature is considered as the ambient temperature and its thermal level is considered equal to zero.
– A constant phase current during the overload.

The cold time-current limit characteristic is given by the following time-current equation:

$$t(I_{eq}) = \tau \cdot \ln\left(\frac{{I_{eq}}^2}{{I_{eq}}^2 - (k \cdot I_B)^2}\right) \tag{5}$$

where

$t(I_{eq})$ is the theoretical operate time with a constant phase current I_{eq}, with no load current before (prior) the overload occurs;

I_{eq} is the equivalent heating current;

τ is the heating thermal time constant of the protected equipment;

k is a constant (fixed) value or a setting, declared by the thermal relay manufacturer;

I_B is the basic current value expressed as permissible current of the equipment to be thermally protected.

A typical example of time-current characteristic curve for cold state of a first-order thermal system with no previous load before overload occurs is shown in Figure 2.

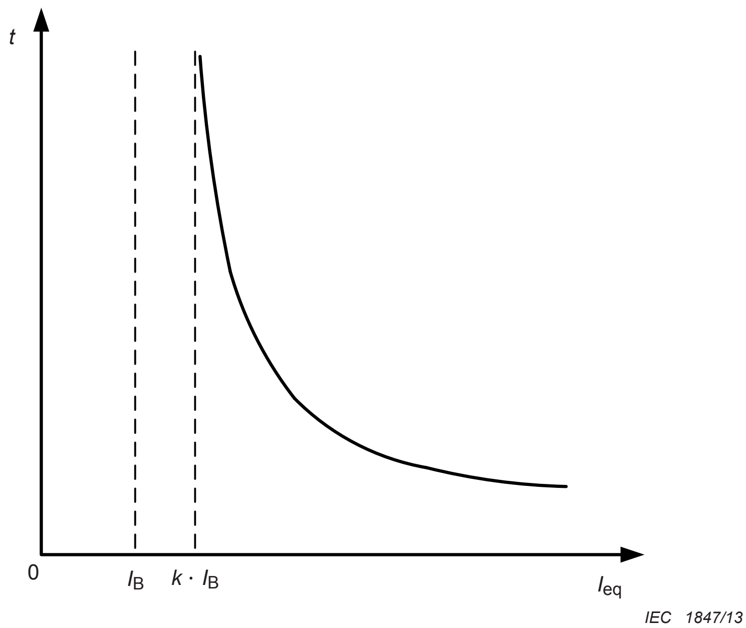


Figure 2 – Typical examples of characteristic curves for cold state of a first-order thermal system with no previous load before overload occurs

A detailed differential equation derivation, algorithm, dynamics, and cold time-current characteristic solution for the first-order thermal system are developed and given in Annex A.

4.4.4.3 Hot curve

The hot curve for thermal protection relays is a particular solution of the first-order differential Equation (1) and it is given by the following time-current equation:

$$t(I_{eq}) = \tau \cdot \ln\left(\frac{{I_{eq}}^2 - I_p^2}{{I_{eq}}^2 - (k \cdot I_B)^2}\right) \tag{6}$$

where

$t(I_{eq})$ is the theoretical operate time with a constant phase current I_{eq} with a constant current of I_p prior to the overload;

I_{eq} is the equivalent heating current;

I_p is the steady-state load current prior to the overload for a duration which would result in constant thermal level (duration is greater than several heating thermal time constants τ); $I_p = 0$ results in the cold curve;

τ is the heating thermal time constant of the equipment to be thermally protected;

k is a constant value (fixed) value or a setting, declared by the thermal relay manufacturer;

I_B is the basic current value expressed as permissible current of the equipment to be thermally protected.

The relay manufacturer can publish thermal tripping curves as in the example given below with the previous load ratio p as a parameter, described by the following equation:

$$p = \frac{I_P}{I_B} \tag{7}$$

Typical examples of current-time characteristic curves for hot states of a first-order thermal system for different values of previous load before overload occurs are shown in Figure 3.

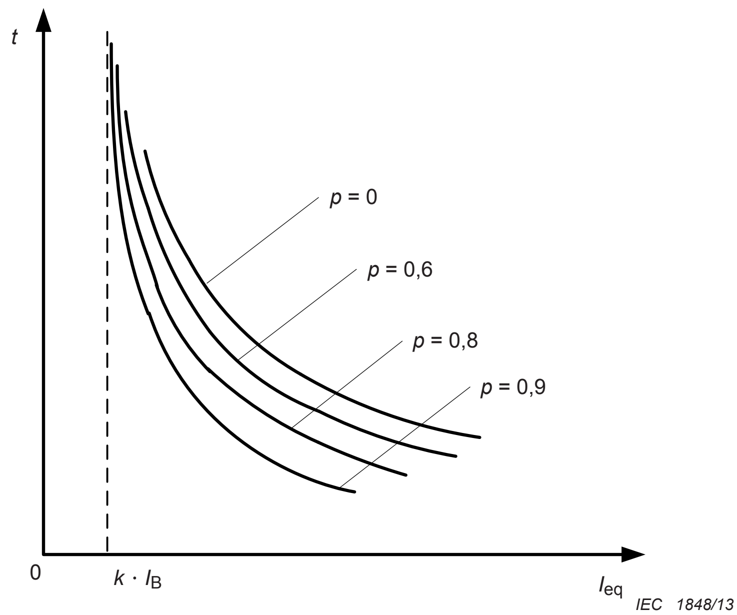


Figure 3 – Typical examples of characteristic curves for hot states of a first-order thermal system for different values of previous load before overload occurs

A detailed differential equation derivation, algorithm, dynamics, and hot time-current characteristic solution for the first-order thermal system are developed and given in Annex A.

4.4.5 Thermal level alarm threshold

If the thermal protection relay contains an alarm threshold level it can produce an alarm output signal when the thermal level exceeds a predetermined setting alarm threshold. This threshold can be defined as a percentage of the nominal (rated) thermal limit of the equipment to be thermally protected.

Nominal (rated) thermal limit ($H_{nominal}$ = 100 %) is considered as the maximum thermal level to which the equipment to be thermally protected can continuously withstand to avoid over temperature. An over temperature above the permitted limit could damage the chemical/physical properties of the materials component of the insulation system, reducing its expected life time.

This predictive overload alarm threshold level, if provided, shall include at least a range of 50 % to 100 % of the nominal (rated) thermal limit.

NOTE 1 The thermal level *H* can be compensated for the ambient temperature level of the equipment this is detailed in Equations (8) and (9).

NOTE 2 For motor thermal protection applications, the actual thermal level, measured by the thermal protection device using the equations shown in this standard, can be used as a restart blocking signal, as an input reference for the restarting blocking protection function (function 66), for a motor in a stopped condition (at rest), at a hot state, after operation. For this application, the remaining time for the next allowed motor start attempt can be indicated in the thermal protection device display, taking into account the cooling thermal time constant for the stopped motor, the actual thermal level of the motor at rest and the estimated or calculated thermal level required for motor starting (calculated based on the motor heating thermal time constant, starting current and starting time).

4.5 Binary output signals

4.5.1 General

Binary output signals from this function may be available in a number of different forms. Examples include:

- traditionally wired from physical relay output contacts,
- via a communications port to external devices,
- via internal logical connections to other functional elements within the relay.

The method of providing the signal is largely irrelevant except to conform to functional requirements.

Definitions, ratings and standards for physical binary output signals are specified in IEC 60255-1.

4.5.2 Operate (trip) output signal

The operate (trip) signal is the output of measuring and threshold elements, when the calculated thermal level $H(t)$, defined in Equation (1), exceeds 100 % (1,0 pu) of the nominal (rated) thermal level of the equipment to be thermally protected.

NOTE The trip signal could operate when the calculated thermal level of any of the three phases exceeds the nominal thermal level.

4.5.3 Alarm signal

The alarm signal is the output of measuring and threshold elements, when the calculated thermal level $H(t)$, defined in Equation (1), exceeds a predetermined overload alarm threshold setting.

4.5.4 Other binary output signals

If any other binary output signals are available for use, their method of operation shall be clearly shown on the functional logic diagram or in the protective device manufacturer documentation. Additional textual description may also be provided if this can further clarify the functionality of the output signal and its intended usage.

4.6 Additional influencing factors on thermal protection

4.6.1 General

The manufacturer shall declare if any specific algorithms are implemented in the relay. These algorithms shall be described by the manufacturer in the thermal protective device documentation.

For example, if the thermal protection relay is equipped with temperature measurement facilities the thermal protection can take into account the ambient or coolant temperature. One possible implementation of ambient temperature compensation is described in the following subclauses, but other methods could be used.

4.6.2 Influence of ambient temperature on thermal protection

Electrical machines, such as motors and power transformers, are designed to operate within a specific ambient temperature range. If the machine operates at a higher ambient temperature than specified, the windings may overheat and suffer insulation degradation even if it is operating within the permitted rated load and equivalent heating currents. In this case, it is beneficial to compensate or bias the calculated thermal level of the machine to maintain adequate thermal protection by directly measuring the ambient temperature.

Typically, the design limits (or maximum ambient temperature) of the protected machine is in the region of 40 °C. When the measurement of ambient temperature is other than this design limit, the thermal level $H(t)$ can be compensated by a factor F_a, defined by the following equation:

$$F_a = \frac{T_{max} - T_{limit}}{T_{max} - T_a} \tag{8}$$

where

T_{max} is the equipment maximum temperature (according to equipment thermal insulation class, as indicated in IEC 60085);

T_a is the actual ambient (environment) temperature of the equipment, measured by the thermal protection relay;

T_{limit} is the ambient temperature design limits for operation at rated load without causing thermal degradation of insulation, typically 40 °C.

In the case of a thermal protection relay which is equipped with ambient temperature sensor and ambient temperature correction factor, the thermal level $H(t)$ of the equipment is calculated by the following equation:

$$H(t) = \left(\frac{I_{eq}(t)}{k \cdot I_B}\right)^2 \cdot \frac{\Delta t}{\tau + \Delta t} \cdot F_a + \frac{\tau}{\tau + \Delta t} \cdot H(t - \Delta t) \tag{9}$$

The derivation of the ambient temperature factor F_a is given in detail in Annex A.

4.6.3 Thermal reset facilities

During testing of the thermal element, it is preferable to be able to force the thermal element to a fully reset (zero) state, or other known value. If such a facility is available on the device, its method of operation, capability and any relevant settings should be clearly shown on the functional diagram and within the relay documentation.

4.7 Behaviour of thermal protective device during auxiliary power supply failure

The thermal protection function continuously calculates and stores the thermal level in its thermal memory using the recursive equation.

When energizing the thermal protective device, the state of the thermal memory shall be clearly defined and stated by the relay manufacturer in the protective device documentation.

In some cases, it is a parameter setting which defines the starting level of the thermal memory. Depending on the setting of the thermal protective device, the stored value of the thermal level of the protected equipment should be either reset to zero (in the event of an auxiliary power supply failure) or stored in a non-volatile type memory, so that the previous thermal level is maintained if the power supply fails.

The manufacturer shall declare in the thermal protective device documentation the behaviour of the thermal level in the event of a power system supply failure along with user settings and the factory (default) settings.

5 Performance specification

5.1 Accuracy related to the characteristic quantity

The accuracy related to the characteristic quantity shall be declared by the manufacturer at operate value $k \times I_B$, in the setting value range over which it is applicable.

The range of k shall be specified which is supported by the thermal electrical relay (e.g. $1,0 \leq k \leq 1,5$). The manufacturer shall prove that no operation occurs due to measurement inaccuracies of current and temperature as well as thermal calculation at I_B.

For functions with an ambient temperature measurement, the manufacturer shall declare the influence of the ambient temperature measurement on the characteristic accuracy. In order to avoid the combination of a varying characteristic quantity and a varying ambient temperature, it is sufficient to specify the accuracy with an ambient temperature measurement T_a lower than 40 °C and one value higher than 40 °C (e.g. T_a = 0 °C and $T_a = 0,5\ T_{max}$).

5.2 Accuracy related to the operate time

The effective range of the time-current characteristics shall be specified by the manufacturer ($I_{min} \leq I_{eq} \leq I_{max}$). I_{min} and I_{max} shall be stated by the manufacturer and I_{min} shall lie between $k \times I_B$ and $1,2 \times k \times I_B$. This results in a maximum operating time for a value of $I_{eq} = I_{min}$ and a minimum operating time of $I_{eq} = I_{max}$. The accuracy of the characteristic is specified within this effective range. In addition the manufacturer shall declare the behaviour of the function above the effective range, under high fault current conditions (e.g. if the function is blocked or I_{eq} is limited to I_{max}).

The reference limiting error is identified by an assigned error declared by the manufacturer, which may be multiplied by factors corresponding to different values of the characteristic quantity. The value of the assigned error shall be declared at the maximum limit of the effective range (I_{max}). The reference limiting error may be declared either as:

1) a theoretical curve of time plotted against multiples of the setting value of the characteristic quantity bounded by two curves representing the maximum and minimum limits of the limiting error over the effective range, or
2) an assigned error claimed at the maximum limit of the effective range of the time-current characteristic multiplied by stated factors corresponding to different values of the characteristic quantity within its effective range of the characteristic, as specified in Table 1.

Table 1 – Limiting error as multiples of assigned error

Value of characteristic quantity as multiple of setting value ($k \times I_B$)	1,2 to 1,5	1,5 to 2	2 to I_{max}
Limiting error as multiples of assigned error	2,5	1,5	1

NOTE The characteristic quantity can be different depending on the nature of the thermal protection being provided. As an example it can be phase current combined or not with negative sequence current in the case of motor thermal protection.

The manufacturer shall declare if compensation of the internal measurement time of the characteristic quantity and the output contact operation is included in the operate time and its stated accuracy.

Nominal accuracy will be stated based on a sinusoidal input at nominal frequency; however the manufacturer shall state the effect of harmonics on the characteristic quantity and the operating frequency range where the nominal accuracy is met. In addition, the manufacturer shall state if harmonics are included in the calculation of the characteristic quantity.

5.3 Performance during frequency variations

The purpose of these tests is to verify the relay performance when the frequency of the energizing quantities deviates from the nominal value. The influence of frequency deviation from f_{min} to f_{max} is determined by means of testing accuracy when the frequency of the characteristic quantity is varied between f_{min} and f_{max}.

6 Functional test methodology

6.1 General

Tests described in this clause are for type tests. These tests shall be designed in such a way to exercise all aspects of hardware and firmware (if applicable) of the thermal protection relay. This means that injection of current shall be at the interface to the relay, either directly into the conventional current transformer input terminals, or an equivalent signal at the appropriate interface.

The manufacturer shall clearly indicate the test methodology, procedure, structure and architecture used in this protective device performance test.

Whenever applicable, other influencing input quantities like inputs for ambient temperature measurement, reset inputs, or power supply failure functions shall be considered in the type tests. Similarly, operation shall be taken from output contacts wherever possible or equivalent signals at an appropriate interface.

The accuracy of the relay shall be determined in steady-state conditions. The injected characteristic quantity shall be a sinusoid of rated frequency and its magnitude shall be varied according to the test requirements.

When determining the influence of harmonics the injected characteristic quantity shall be superimposed sinusoidal signals with the fundamental signal of rated frequency and its magnitude shall be varied according to the test requirements.

When determining the influence of abnormal frequencies the injected characteristic quantity shall be a sinusoidal signal at required test frequencies and its magnitude shall be varied according to the test requirements.

In accordance with IEC 60255-1 each test point related to accuracy shall be repeated 5 times to ensure repeatability of results, with the maximum and average error values of all the tests being used for the accuracy claim. Sufficient test points should be used to assess the performance over the entire setting range of the element, but as a minimum three settings shall be used. Preferred values are: minimum setting (or 0 % of the range); 50 %; maximum setting (or 100 % of the range).

In the following subclauses, the test settings to be used are expressed in a percentage of the available range with 0 % representing the minimum available setting and 100 % representing the maximum available setting. Similarly 50 % would represent the mid-point of the available setting range. The actual setting to be used can be calculated using the following equation:

$$S_{AV} = (S_{MAX} - S_{MIN})\,X + S_{MIN} \tag{10}$$

where

S_{AV} is the actual setting value to be used in test;

S_{MAX} is the maximum available setting value;

S_{MIN} is the minimum available setting value;

X is the test point percentage value expressed in test methodology.

6.2 Determination of steady-state errors related to the operating current value

It is not easy to verify the accuracy of the operating current value $k \times I_B$ directly, due to the very long operating time near the threshold. However, in order to check the basic current value I_B, the specified limiting value of the current for which the thermal relay is required not to operate, the following test is performed.

A current equal to I_B shall be applied to the thermal relay during a period longer than 10 times the heating thermal constant setting. The operate output contact of the element shall be monitored, and no tripping shall occur.

This test shall be done with the following settings.

– The minimum heating thermal constant of the setting range.
– If the factor *k* is a setting value, *k* is set to the specified accuracy level, declared by the manufacturer (i.e. with a specified accuracy level of 5 %, the factor *k* is set to 1,05).
– If the factor *k* is a fixed value, it is generally defined to cover the current measuring accuracy to ensure no operation for a continuous current I_B. In the particular case where *k* is a fixed value equal to 1, a reduced current shall be applied according to the declared accuracy level (i.e. with a specified accuracy level of 5 %, the injected current is equal to $0{,}95 \times I_B$).
– The basic current I_B is set to 3 test points: minimum setting (or 0 % of the range); 50 %; maximum setting (or 100 % of the range).

The test can be done with or without previous thermal level. The impact of the previous thermal level after the duration of the current injection (10 times the heating thermal time constant) is not significant.

At the end of the test and, if the relay displays the thermal level of the protected equipment, the thermal level shall be less than 100 %.

6.3 Determination of steady-state errors related to the characteristic quantity and the operate time

6.3.1 Accuracy determination of the cold curve

The verification of the specified cold curve is required to indirectly verify the stated accuracies for the characteristic quantity and operate time. To determine the cold curve response the thermal model of thermal protection relay shall be reset prior to instantly applying the calculated test signal.

According to Equation (5) the cold curve is verified with sufficient test points to assess the performance over the entire basic current and heating thermal time constant setting range, at various current values throughout the effective range of the thermal characteristic. The times recorded for the operate output contact provides a measure of the cold curve operating time accuracy. The suggested test points are indicated in the Table 2. Each test point shall be tested one time, except for the minimum thermal time constant setting where each test point shall be repeated at least 5 times to ensure repeatability of results, with the maximum and average error values of all the tests being used for the accuracy claim.

If the factor k is a setting, the operating current value is defined with a combination of the basic current I_B and the factor k, in their setting ranges. For example, assuming the available setting range for the basic current I_B is 1 A to 5 A and the setting range of the factor k is 1,0 to 1,5, the actual operating current value to be used would be: 1 A; 3,75 A; 7,5 A.

Table 2 – Test points of the cold curve

Operating current value ($k \times I_B$)	Heating thermal time constant (τ_1)	Initial test current value	End test current value
Minimum (0 %) for I_B and k	Minimum (0 %)	Zero	$1{,}2 \times k \times I_B$
50 % for I_B and k	50 %	Zero	$1{,}6 \times k \times I_B$
Maximum (100 %) for I_B and k	Maximum (100 %)	Zero	$2 \times k \times I_B$
		Zero	$5 \times k \times I_B$
		Zero	$10 \times k \times I_B$
NOTE The total number of test points is 45 (with repetitions a total of 105 tests). Five test points defined by the end test current values, with the 3 defined settings for the operating current value ($k \times I_B$), and the 3 defined settings for the thermal time constant.			

If test points specified in Table 2 exceed the effective range of the device under test, the test is performed until the maximum allowed characteristic quantity. None of the test points shall be outside the specified accuracy that result from the specified accuracies for the characteristic quantity and operate time.

For the cold curve test: The input current shall be suddenly changed from zero to the appropriate multiple of I_B. The relay shall then be allowed sufficient time to return to its initial condition before re-application of current.

To reduce the testing time of cold curve a forced reset by logic input or a setting can be used to reset the thermal memory between each test point.

6.3.2 Accuracy determination of the hot curves

The verification of the specified hot curve is required to indirectly verify the stated accuracies for the characteristic quantity and operate time. The test will be carried out, at least, for 5 different preload levels (10 %, 30 %, 50 %, 70 %, 90 %).

These tests are defined to check the impact of the preload levels on the operating time (hot curves). The test points can be done with only one setting value for the operating current and the heating thermal time constant (τ_1). The tests points are suggested in the following Table 3. Each test point shall be tested once.

Table 3 – Test points of the hot curve

Operating current value ($k \times I_B$)	Heating thermal time constant (τ_1)	Preload levels (in % of I_p)	End test current value
50 % for I_B and k	50 %	10 %	$1,2 \times k \times I_B$
-	-	30 %	$1,6 \times k \times I_B$
-	-	50 %	$2 \times k \times I_B$
-	-	70 %	$5 \times k \times I_B$
-	-	90 %	$10 \times k \times I_B$
NOTE The total number of test points is 25; five end test current values times 5 defined preload levels.			

If test points specified in Table 3 exceed the effective range of the device under test, the test is performed until the maximum allowed characteristic quantity. None of the test points shall be outside the specified accuracy that result from the specified accuracies for the characteristic quantity and operate time.

For the hot curve test: the protective device shall be energized with an equivalent current corresponding to the preload level for a time to allow the relay to reach thermal equilibrium at that point. The protective device shall then be energized at the appropriate multiple of the basic current I_B.

The protective device shall then be allowed sufficient time as specified by the manufacturer to return to and stabilize at the previous load current before further testing.

6.4 Performance with specific cooling thermal time constant

If the relay can handle different heating and cooling thermal time constants (τ_1 and τ_2), the following test shall be performed.

A current above the operating current value $k \times I_B$ is applied to the thermal relay until operation. When the relay operation occurs, the current injection is switched off during a time $T_{cooling}$. After this time $T_{cooling}$, a current I_{fault} above the operating current value $k \times I_B$ is applied again to the thermal relay. The time T_{fault} recorded between the injection of the current I_{fault} and the operate output contact shall be equal to the following equation.

$$T_{fault} = \tau_1 \cdot \ln\left(\frac{I_{fault}^2 - (k \cdot I_B)^2 . e^{\left(-T_{cooling}/\tau_2\right)}}{I_{fault}^2 - (k \cdot I_B)^2}\right) \tag{11}$$

where

τ_1	is the heating thermal time constant 1 of the equipment to be thermally protected;
τ_2	is the cooling thermal time constant 2 of the equipment to be thermally protected;
I_{fault}	is the current applied to the thermal relay after the cooling period;
$T_{cooling}$	is the time duration of the cooling period previous to the overload;
$k \cdot I_B$	is the operating current value.

The test shall be performed with 2 different settings (0 % and 50 %) for the cooling thermal time constant (τ_2), in the following conditions.

– The operating current value ($k \times I_B$) shall be set at 50 % of the setting range.

– The heating thermal time constant (τ_1) shall be selected as 50 % of the setting range.

– The current I_{fault} shall be equal to 2 times the operating current value ($k \times I_B$).

None of the test points shall be outside the specified accuracy that result from the specified accuracies for the characteristic quantity and operate time.

6.5 Performance with harmonics

At least one curve test for cold curve shall be carried out while the characteristic quantity includes 10 % of 3rd harmonic.

At least one curve test for cold curve shall be carried out while the characteristic quantity includes 25 % of 5th harmonic.

At least one curve test for cold curve shall be carried out while the characteristic quantity includes 15 % of 7th harmonic.

The percentage harmonic is based on the fundamental frequency component with a phase angle between the fundamental and harmonic component at zero degrees. Three test points are suggested in the following Table 4.

Table 4 – Test points of the cold curve with harmonics

Operating current value ($k \times I_B$)	Heating thermal time constant (τ_1)	Initial test current value	End test current value
50 % for I_B and k	Minimum (0 %)	Zero	$1,2 \times k \times I_B$
		Zero	$2 \times k \times I_B$
		Zero	$10 \times k \times I_B$

If test points specified in Table 4 exceed the effective range of the device under test, the test is performed until the maximum allowed characteristic quantity is reached. None of the test point results shall be outside the specified accuracy that result from the specified accuracies for the characteristic quantity and operate time.

6.6 Performance during frequency variations

At least one curve test for cold curve shall be carried out while the characteristic quantity fundamental frequency is set to f_{min} as specified by the manufacturer.

At least one curve test for cold curve shall be carried out while the characteristic quantity fundamental frequency is set to f_{max} as specified by the manufacturer.

Three test points are suggested in the following Table 5.

Table 5 – Test points of the cold curve during frequency variations

Operating current value ($k \times I_B$)	Heating thermal time constant (τ_1)	Initial test current value	End test current value
50 % for I_B and k	Minimum (0 %)	Zero	$1,2 \times k \times I_B$
		Zero	$2 \times k \times I_B$
		Zero	$10 \times k \times I_B$

If the test points specified in Table 5 exceed the effective range of the device under test, the test is performed until the maximum allowed characteristic quantity is reached.

None of the test point results shall be outside the specified accuracy that result from the specified accuracies for the characteristic quantity and operate time.

6.7 Performance during different ambient temperatures

If the thermal protection relay is equipped with temperature sensor to measure the ambient temperature of the protected equipment, the following test shall be performed in order to check that the thermal level calculation takes into account the factor F_a, defined by the Equation (9).

The tests described in 6.3 shall be done with the following conditions:

- thermal insulation class of the protected equipment: Class F – T_{max}= 155 °C
- 2 test points for ambient temperature: 20 °C and 60 °C:
  - for 20 °C test points, the factor F_a = 0,852
  - for 60 °C test points, the factor F_a = 1,21
- determination of one cold curve (see Table 1) for both ambient temperatures, with the following settings:
  - operating current value ($k \times I_B$): 50 % for I_B and k
  - heating thermal time constant (τ_1): 50 %
- determination of one hot curve (see Table 2) for both ambient temperatures, with the following settings:
  - operating current value ($k \times I_B$): 50 % for I_B and k
  - heating thermal time constant (τ_1): 50 %
  - preload level: 50 %

With the factor F_a, the cold and hot time-current limit characteristic is given by the following equation:

$$t(I_{eq}) = \tau \cdot \ln\left(\frac{F_a . I_{eq}^2 - I_p{}^2}{F_a . I_{eq}^2 - (k \cdot I_B)^2}\right) \qquad (12)$$

where

$t(I_{eq})$	is the theoretical operate time with a constant phase current I_{eq};
I_{eq}	is the end test equivalent heating current value;
τ	is the heating thermal time constant of the protected equipment;
k	is a constant (fixed) value or a setting, declared by the thermal relay manufacturer;
I_B	is the basic current value expressed as permissible current of the equipment to be thermally protected;
I_p	is the steady-state load current prior the overload (I_p = 0 for the cold curve).

None of the test point results shall be outside the specified accuracy that result from the specified accuracies for the characteristic quantity and operate time.

7 Documentation requirements

7.1 Type test report

The type test report for the thermal protection function described in this standard shall be in accordance with IEC 60255-1.

As a minimum the following aspects shall be recorded:

Protective device under test: This includes details of the protective device/IED/function under test as well as specific details such as model number, firmware version which shall be recorded as applicable.

- Test equipment: equipment name, model number, calibration information.
- Functional block diagram showing the conceptual operation of the element including interaction of all binary input and output signals with the function.
- Details of the input energizing quantity and the type of measurement being used by the protection function.
- Details of the available characteristic curves/operation for both operating and stopped states that have been implemented in the function, preferably by means of an equation.
- Details of the effective range (I_{min} and I_{max} values) and the behaviour of the function for currents above the effective range, under high fault current conditions (e.g. if the function is blocked or I_{eq} is limited to I_{max}).
- Details of all settings utilised by the function, including k, q, τ_1, τ_2, and F_a.
- Details of any specific algorithms that are implemented to improve the applicability of this thermal function to a real power system and their performance claims. In the case of generic algorithms that are used by more than one function, for example current transformer or RTD supervision for ambient temperature, coolant temperature, top oil temperature or winding temperature, it is sufficient to describe the operation of the algorithm once within the user documentation but its effect on the operation of all functions shall be described.
- Test method and settings: This includes details of the test procedure being used as well as the settings that are applied to the equipment under test to facilitate the testing. This may include settings other than those for the function being tested. This permits repeated testing to be performed with confidence that the same test conditions are being used.
- Test results: For every test case outlined in the test method and settings, the complete sets of results are recorded as well as a reference to the particular test case. From these results, accuracy claims are established.
- Test conclusions: Based upon the recorded test results, all claims required by Clause 5 of this standard shall be clearly stated. Where appropriate, these claims are compared with the performance specifications contained in this standard to allow individual pass/fail decisions to be given, as well as an overall pass/fail decision for the entire function.

7.2 Other user documentation

Not all users insist on viewing the complete type test documentation, but require a subset of the information that it contains. For this purpose, as a minimum the following aspects shall be recorded in generally available user documentation although this may not be required in a single document.

Functional block diagram showing the conceptual operation of the thermal protection element including interaction of all binary input and output signals with the function;

- details of the input energizing quantity and the type of measurement being used by the thermal protection function;
- details of the available characteristic curves/operation for both operating and stopped states that have been implemented in the function, preferably by means of an equation;

– details of the effective range (I_{min} and I_{max} values) and the behaviour of the function for currents above the effective range, under high fault current conditions (e.g. if the function is blocked or I_{eq} is limited to I_{max});
– details of all settings utilised by the function, including k, q, τ_1, τ_2, and F_a;
– details of the safety behaviour of the actual thermal level memory, in case of power supply failure, default/factory settings, user options and setting procedures;
– details of any specific algorithms that are implemented to improve the applicability of this thermal function to a real power system and their performance claims. In the case of generic algorithms that are used by more than one function, for example current transformer or RTD supervision for ambient temperature, coolant temperature, top oil temperature or winding temperature, it is sufficient to describe the operation of the algorithm once within the user documentation but its effect on the operation of all functions shall be described;
– all declarations required by Clause 5 of this standard shall be clearly stated.

Annex A
(informative)

Simple first-order thermal model of electrical equipment

A.1 General

This Annex A introduces the basics of differential and time-current equations and dynamics found in thermal protection modelling. A simple first-order thermal process is used to represent the electrical equipment to be thermally protected.

This Annex A also introduces a recursive algorithm for continuously calculating and keeping track, in real time, the actual thermal level of a simple first-order thermal process which is suitable for digital implementation in microprocessor-based protection devices.

A.2 Simple first-order thermal process representation of electrical equipment

A.2.1 General

Considering a simple first-order thermal system represented by generic electrical equipment to be thermally protected, modelled as a resistor (*r*), representing the ohmic winding resistance through which an equivalent heating current (I_{eq}) is being circulated as shown in Figure A.1.

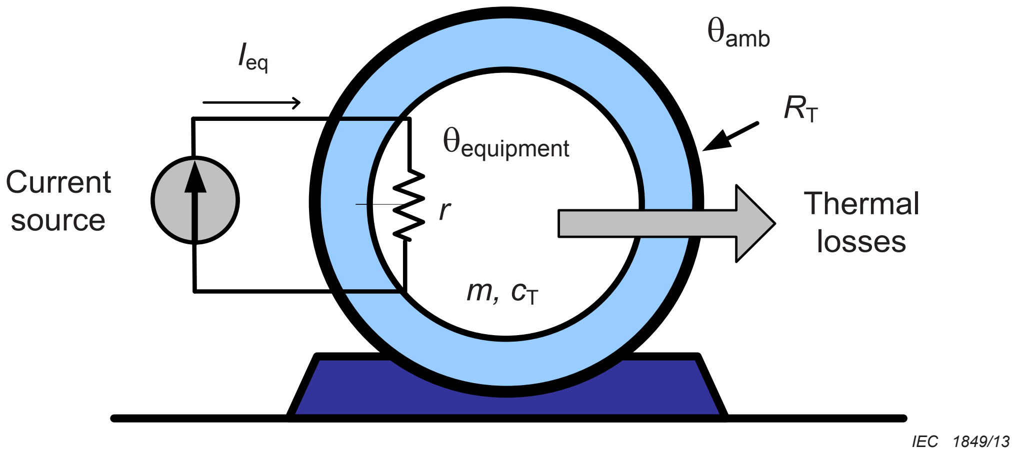


Figure A.1 – An electrical equipment to be thermally protected represented as a simple first-order thermal system

A.2.2 Calculation of the equivalent heating current (I_{eq})

The heating source is represented by an equivalent heating current I_{eq}.

In general the equivalent heating current (I_{eq}) is the same as rms phase current. However, for motor protection applications other heating sources need to be considered and they are described here.

In case of motor protection applications, the thermal model shall be biased to reflect the additional heating that is caused by negative sequence current when the motor is running. This biasing can be done by creating an equivalent motor heating current rather than simply using average three-phase rms current values.

Unbalanced motor phase currents will cause rotor heating that is not shown in the motor thermal damage curve. When the motor is running, the rotor will rotate in the direction of the positive sequence current at near synchronous speed. Negative sequence current, which has a phase rotation that is opposite to the positive sequence current, and hence opposite to the direction of rotor rotation, will generate a rotor voltage that will produce a substantial current in the rotor. This current will have a frequency that is approximately twice the line frequency: 100 Hz for a 50 Hz system or 120 Hz for a 60 Hz system.

Skin effect in the rotor bars at this frequency will cause a significant increase in rotor resistance and therefore, a significant increase in rotor heating. This extra heating is not accounted for in the thermal limit curves supplied by the motor manufacturer as these curves assume positive sequence currents from a perfectly balanced supply voltage and motor design.

To take into account the effect of unbalanced conditions, the equivalent heating current can be computed in accordance with the following equation:

$$I_{eq} = \sqrt{I_{rms}^2 + q \cdot {I_2}^2} \qquad \text{(A.1)}$$

where

I_{eq} is the equivalent heating current;

I_{rms} is the rms value of the phase current;

I_2 is the negative sequence phase current;

q is the unbalance factor, a user settable constant, proportional to the thermal capacity of the electrical motor (equipment to be thermally protected).

The coefficient q is a factor relating to the additional heat produced by negative sequence phase current (I_2) relative to the positive sequence phase currents (I_{rms}). The factor q is used to account for the influence of negative sequence phase current on the equivalent heating current (I_{eq}) in thermal motor protection applications. This factor should be set equal to the ratio of negative sequence rotor resistance to positive sequence rotor resistance at rated motor speed.

The values of positive and negative rotor resistance shall be obtained from motor manufacturer data sheet or motor documentation.

NOTE 1 When an exact setting of the positive/negative rotor resistance is not published by motor manufacturer or cannot be calculated, typical values of *q* from 3 (three) to 5 (five) could be used. This is a typical setting and will be adequate for most of the motor thermal protection applications.

NOTE 2 For thermal protection applications of electrical equipment such as power transformers, cables, lines, and capacitors, the factor *q* could be set to zero.

A.2.3 First-order thermal model of electrical equipment

The ambient temperature is θ_{amb} and the equipment temperature is $\theta_{equipment}$. The equipment temperature shall not go beyond the thermal limit temperature according to its Electrical Insulation System (EIS) thermal classification class, in accordance with IEC 60085 and IEC 60034-11. This temperature is defined as the maximum or hot-spot temperature θ_{max} and above this point the input equivalent heating current shall be switched off by a protective device.

A simple first-order thermal system can be modelled by a single lumped thermal resistivity to the surrounding environment (R_T, expressed in °C/W), by a mass (m, expressed in kg) and the thermal system specific heat capacity (c_T, expressed in J/kg/°C).

The thermal resistivity (R_T) is a constant that depends upon the thermal system insulation level to the environment and mechanical properties. The higher the value of R_T, the less heat is transferred to the surrounding environment. The smaller the value of R_T, the more heat is transferred to the surrounding environment.

It can be defined θ as the temperature of the thermal system (equipment) above the ambient temperature, in accordance with the following equation:

$$\theta = \theta_{\text{equipment}} - \theta_{\text{amb}} \tag{A.2}$$

The rate of increase of the equipment (thermal system) is provided by the differential equation expressing the thermal equilibrium:

$$\textit{Power supplied} - \textit{Thermal losses} = mc_T \frac{\mathrm{d}\theta(t)}{\mathrm{d}t} \tag{A.3}$$

where

m is the thermal system (equipment) mass, considering a lumped model (kg)

c_T is the specific heat of the thermal system (equipment), considering a lumped model (J/kg/°C)

The thermal system (equipment) thermal capacitance (C_T) is the product of its mass (m) and its specific heat (c_T), in accordance with the following equation:

$$C_T = m \times c_T \tag{A.4}$$

The thermal losses or the quantity of heat transferred by the equipment (thermal system) to the surrounding environment can be expressed by the following equation:

$$\textit{Thermal losses} = \frac{\theta_{\text{equipment}} - \theta_{\text{amb}}}{R_T} = \frac{\theta(t)}{R_T} \tag{A.5}$$

From Equations (A.4) and (A.5) Equation (A.3) can be expressed as:

$$rI_{eq}^2 - \frac{\theta(t)}{R_T} = C_T \frac{\mathrm{d}\theta(t)}{\mathrm{d}t} \tag{A.6}$$

or

$$R_T r I_{eq}^2 = R_T C_T \frac{\mathrm{d}\theta(t)}{\mathrm{d}t} + \theta(t) \tag{A.7}$$

The product of the thermal resistance (R_T) and the thermal capacitance (C_T) has units of seconds and represents the thermal time constant (τ) of a first-order thermal system:

$$\tau = R_T \cdot C_T \tag{A.8}$$

Equation (A.7) can be expressed as:

$$R_T r I_{eq}^2 = \tau \frac{\mathrm{d}\theta(t)}{\mathrm{d}t} + \theta(t) \tag{A.9}$$

The steady-state temperature raise, above ambient, for an operating equipment with current I_{eq} is obtained by setting $d\theta(t) / dt = 0$ in Equation (A.9). At this condition, the nominal temperature raise (θ_{nom}), resulting from equivalent nominal operating current ($I_{eq\ nom}$) is given by:

$$R_T r I^2_{eq\,nom} = \theta_{nom} \tag{A.10}$$

Using per unit values, the actual operating equipment current, measured by the protection relay, considering the heating effects of both positive and negative sequence currents for motor applications, using the nominal equipment current, is given by:

$$I_{eq} = I_{eq\,pu} . I_{eq\,nom} \tag{A.11}$$

Using this per unit current value, Equation (A.9) can be written as:

$$R_T r I^2_{eq\,pu} . I^2_{eq\,nom} = \tau \frac{d\theta(t)}{dt} + \theta(t) \tag{A.12}$$

Making the substitution of Equation (A.10) into Equation (A.12) yields:

$$I^2_{eq\,pu} \theta_{nom} = \tau \frac{d\theta(t)}{dt} + \theta(t) \tag{A.13}$$

or

$$I^2_{eq\,pu} = \tau \frac{d\theta(t) / \theta_{nom}}{dt} + \frac{\theta(t)}{\theta_{nom}} \tag{A.14}$$

Thermal protection relays based on current measurement do not measure the temperature directly. The variable $\theta(t) / \theta_{nom}$ represents the equipment (thermal system) temperature raise, above ambient, in per unit values when nominal current is flowing through the equipment. This variable can be considered as the actual equipment thermal level and denoted as $H(t)$:

$$H(t) = \frac{\theta(t)}{\theta_{nom}} \tag{A.15}$$

Equation (A.14) can now be written as:

$$I^2_{eq\,pu} = \tau \frac{dH(t)}{dt} + H(t) \tag{A.16}$$

It can be noticed that the actual equipment thermal level ($H(t)$) is proportional to the actual equipment per unit current squared (I^2_{eq}).

A.3 Analogue thermal and electrical circuit models

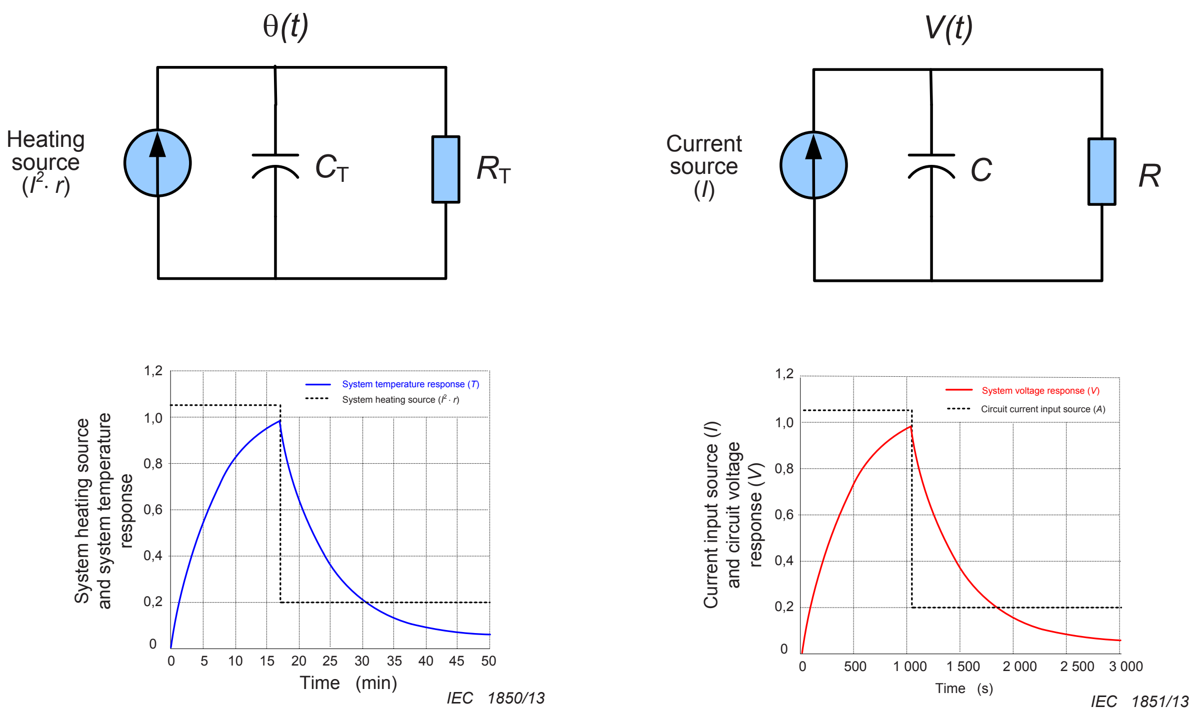
Equation (A.7) is a first-order differential equation and has an electrical equivalent of an RC circuit supplied by a current source. The power supplied to the equipment in the thermal process (I^2r) is equivalent to the current source (I) supplying the electric parallel RC circuit.

The temperature in the thermal process ($\theta(t)$) is equivalent to the voltage ($V(t)$) across the capacitor in the RC circuit. The equivalence between the two systems is shown in Figure A.2 and shown in Table A.1. When fed by a current step function, the response times of temperature in the thermal model and voltage in the electrical model have the same form.

Table A.1 – Thermal and electrical models

Thermal model	Electrical model
Analogue thermal circuit of a first-order thermal system	Analogue electric circuit of a parallel RC circuit
$I^2.r = C_T.R_T.\dfrac{d\theta(t)}{dt} + \theta(t)$ Differential equation of a first-order thermal system	$I = C.\dfrac{dV(t)}{dt} + \dfrac{V(t)}{R}$ Differential equation of a first-order electrical system
Thermal system response to a step heating current input	Electrical system response to a step current input

The analogue thermal circuit representations of a thermal process are given in Figures A.3, A.4 and A.5. In these figures the voltage across the thermal capacity (C_T) has a value proportional to the temperature rise above the ambient temperature. When the applied current is zero, this voltage becomes zero.



a) Thermal model – First-order thermal system dynamics response

b) Electrical model – First-order parallel RC circuit dynamics response

Figure A.2 – Equivalence between a first-order thermal system and an electric parallel RC circuit

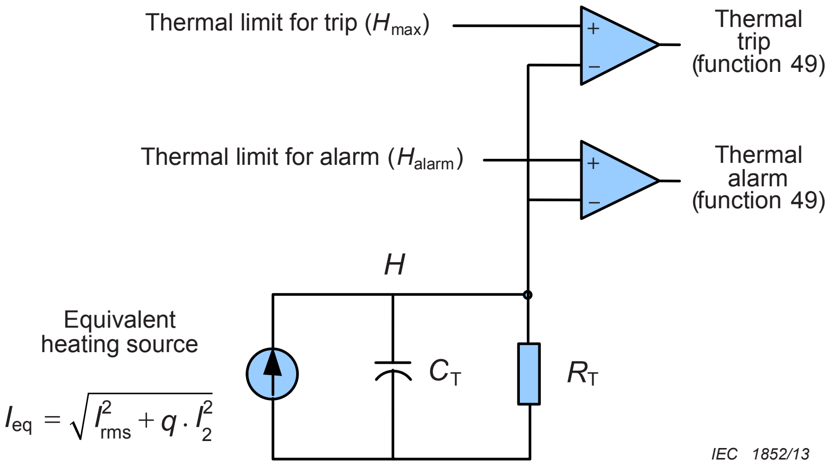


Figure A.3 – Analogue thermal circuit representation of a simple first-order thermal system

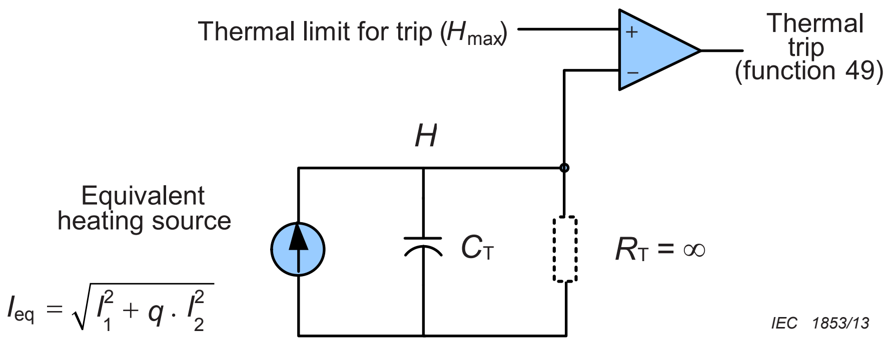
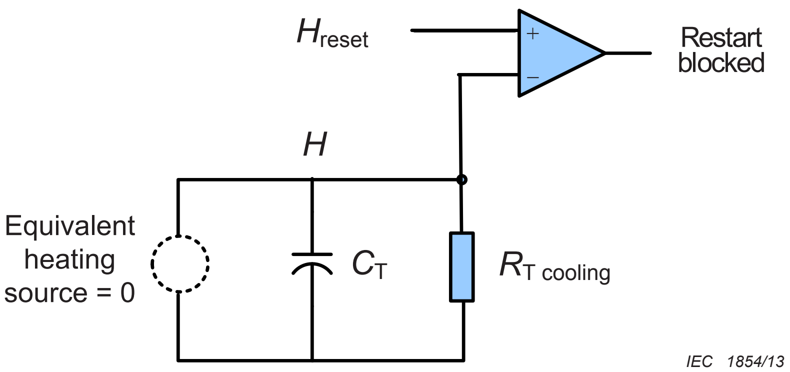


Figure A.4 – Analogue thermal circuit representation of a simple first-order thermal system – motor starting condition



The restart blocked state has the logic value of one (attempt for new motor starting disabled) when $H > H_{reset}$. Otherwise, if $H < H_{reset}$, the restart blocked state from the logic has a value of 0 (attempt for new motor starting enabled).

Figure A.5 – Analogue thermal circuit representation of a simple first-order thermal system – motor stopped condition

A.4 Dynamics of a thermal protection system based on a simple first-order thermal process

The differential equation of a first-order thermal system can be written as a recursive discrete time algorithm, suitable for implementation in a microprocessor-based protection device.

Equation (A.16), in discrete-time form can be written as:

$$I_{\text{eq pu}}^2 = \tau . \frac{H_n - H_{n-1}}{\Delta t} + H_n \tag{A.17}$$

where

H_n and H_{n-1} are two consecutives values of the actual equipment thermal level, relating to a two consecutive samples of current, displaced by one time interval, in a recursive discrete process of the measured equivalent current (sampled values *n* and *n–1* of I_{eq});

Δt is the time interval between two consecutive samples of input current.

Solving Equation (A.17) for H_n provides the following recursive discrete-time form of the differential equation, which is processed at each sample period to calculate the actual value of the thermal model response:

$$H_n = I_{\text{eq pu}}^2 \frac{\Delta t}{\tau + \Delta t} + \frac{\tau}{\tau + \Delta t} \cdot H_{n-1} \tag{A.18}$$

The value of the thermal time constant (τ) to be utilized by the algorithm shall be in accordance with the actual state of the protected equipment. For self-ventilated motor applications, for example, the motor thermal time constant for running state (τ_1) is normally smaller than the motor thermal time constant for the stopped state (τ_2).

For equipment in operation, $I_{\text{eq}}(t) \geq 0$ or $I_{\text{eq}}(t)$ greater than a fixed input current threshold stated by the thermal protective device manufacturer, then the thermal time constant τ_1 is applicable, and the equipment thermal level can be computed by the following equation:

$$H_n = I_{\text{eq pu}}^2 \frac{\Delta t}{\tau_1 + \Delta t} + \frac{\tau_1}{\tau_1 + \Delta t} \cdot H_{n-1} \tag{A.19}$$

Otherwise, in a similar way, for a de-energized equipment, $I_{\text{eq}}(t) \approx 0$ or $I_{\text{eq}}(t)$ is lower than a fixed input current threshold stated by the thermal protective device manufacturer, then the thermal time constant τ_2 is applicable and, the equipment thermal level can be computed by the following equation:

$$H_n = I_{\text{eq pu}}^2 \frac{\Delta t}{\tau_2 + \Delta t} + \frac{\tau_2}{\tau_2 + \Delta t} \cdot H_{n-1} \tag{A.20}$$

Equation (A.18) can be considered as a basis of a discrete-time algorithm that enables a thermal electrical microprocessor-based protection relay to continuously compute, in real time, the actual thermal level of a first-order thermal system during different operating conditions, such as starting, normal load and overload conditions.

By implementing this algorithm it is also possible to monitor and keep track of the thermal level, and assert a trip or an alarm signal when it exceeds predetermined thresholds.

Figure A.6 shows an example of a dynamic response of a simple first-order thermal model algorithm to a current below pickup (0,9 pu, in the example, considering k = 1,05). The thermal level rises exponentially, according to the input heating source and the thermal time constant, up to the steady-state thermal equilibrium level of $0,9^2$.

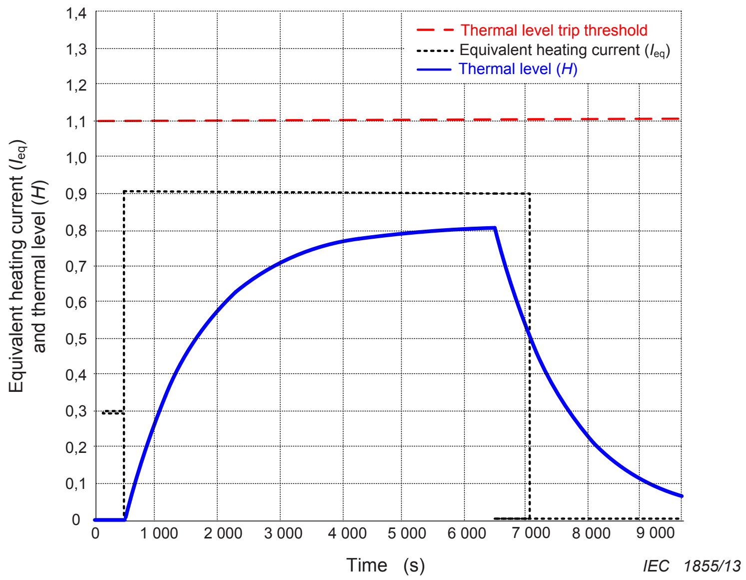


Figure A.6 – Dynamic step response of a simple first-order thermal system algorithm to a current below pickup

Figures A.7 and A.8 show examples of dynamic response when subject to an overload equivalent current (1,15 pu, in the example, considering k = 1,05), followed by a load constant current below pickup (0,5 pu in the example).

In the example of the dynamic response shown in Figure A.7, the equipment is at an initial cold condition (H_0 = 0). In the example of the dynamic response shown in Figure A.8, equipment is at an initial hot condition (H_0 = 0,6, in the example). In both cases the first-order thermal model response shows an exponential rise to a peak, according to the thermal time constant of the thermal system, followed by an exponential decay to the final value, corresponding to the load equivalent current ($0,5^2$ = 0,25, in the example).

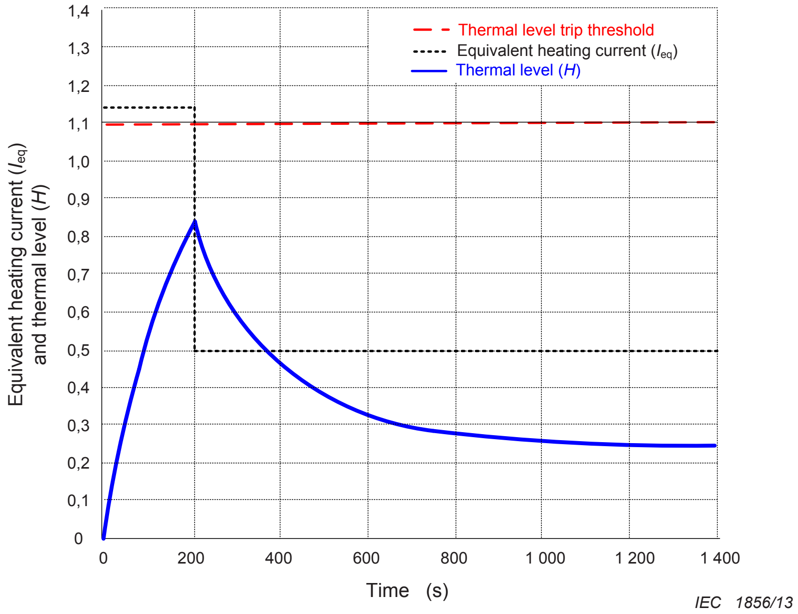


Figure A.7 – Dynamic step response of a first-order thermal system (cold initial state)

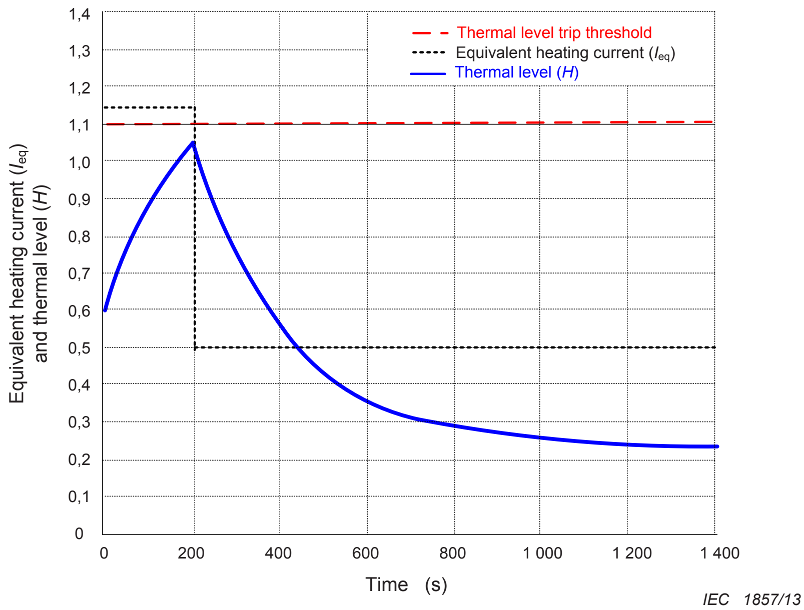


Figure A.8 – Dynamic step response of a first-order thermal system (hot initial state)

Figure A.9 shows an example of a dynamic response when subject to load equivalent current (0,9 pu, in the example), followed by an overload equivalent current (1,2 pu, in the example, considering k = 1,05). Initial state: cold (prior thermal level = 0). The thermal limit threshold is k^2 = 1,10, which causes the thermal protection device to operate.

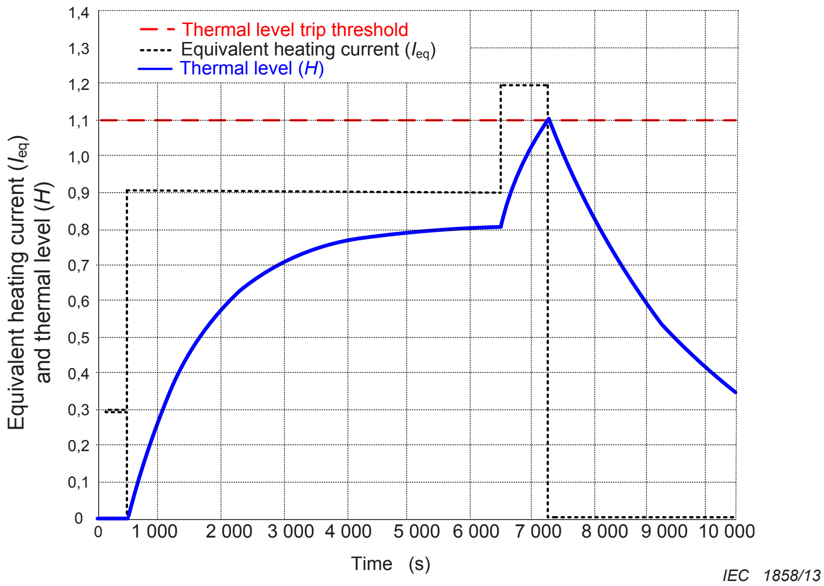


Figure A.9 – Dynamic step response of a first-order thermal system to a load current followed by an overload current (initial state: cold)

Figure A.10 shows an example of dynamics response when subject to load equivalent current (0,9 pu, in the example), followed by an overload equivalent current (1,2 pu, in the example, considering k = 1,05). Initial state: hot (prior thermal level = 0,6). The thermal limit threshold is k^2 = 1,10, which causes the thermal protection device to operate.

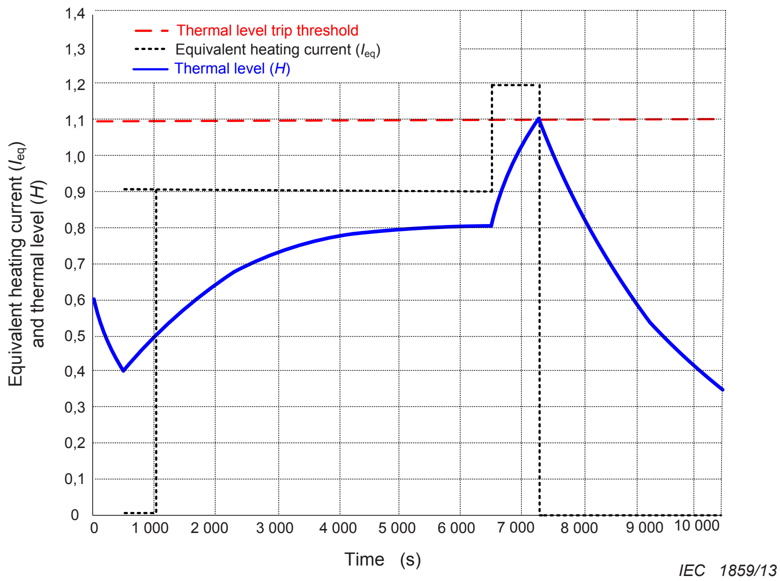


Figure A.10 – Dynamic step response of a first-order thermal system to a load current followed by an overload current (initial state: hot)

A.5 Solution in time domain for the thermal model differential equation as a function of current and time limit

The solution in the time domain of Equation (A.9) is the time required for the temperature to raise from the initial temperature (determined by the previous load current) up to the preset thermal limit, which determines the operation (trip) of the protection relay.

The solution in the time domain for the thermal model as a function of time and equivalent load current (assuming I_{eq} is constant) is (considering θ_0 = 0):

$$\theta(t) = R_T r I_{eq}^2 \left(1 - e^{-t/\tau}\right) \tag{A.21}$$

Remembering that θ is the temperature above ambient, it can be obtained for the expression of the thermal system (equipment) temperature:

$$\theta_{equipment}(t) = R_T r I_{eq}^2 \left(1 - e^{-t/\tau}\right) + \theta_{amb} \tag{A.22}$$

Whatever the equivalent load current supplied to the thermal system, there will always be an increase in the thermal system temperature. The final steady-state equipment (thermal system) temperature for a constant equivalent load current is in accordance with the following equation:

$$\theta_{equipment}(t \to \infty) = R_T r I_{eq}^2 + \theta_{amb} \tag{A.23}$$

Assuming that the thermal system (equipment) has a previous rated operating equivalent current $I_{eq\ op}$, which is otherwise called the load current in some applications, the equipment (thermal system) steady-state operating temperature is given by the following equation:

$$\theta_{op} = R_T r I_{eq\ op}{}^2 + \theta_{amb} \tag{A.24}$$

The thermal system (equipment) temperature shall not go beyond a maximum temperature θ_{max}, established for its electrical insulation thermal system. Then the equation with time as a variable is:

$$\theta_{max} = R_T r I_{eq}^2 \left(1 - e^{-t_{trip}/\tau}\right) + \theta_{amb} \tag{A.25}$$

Solving Equation (A.25) for the variable t_{trip} yields the following time-current equation:

$$t_{trip} = \tau . \ln \frac{R_T r I_{eq}^2}{R_T r I_{eq}^2 - \left(\theta_{max} - \theta_{amb}\right)} \tag{A.26}$$

Defining the current $I_{eq\ max}$ as the maximum current that can be supplied by the heating source to the heating resistor without the thermal system (equipment) reaching the maximum temperature as time goes to infinity; the maximum current would have to satisfy Equation (A.24) as in:

$$\theta_{max} = R_T r I_{eq\ max}^2 + \theta_{amb} \tag{A.27}$$

or

$$\theta_{\text{max}} - \theta_{\text{amb}} = R_T r I_{\text{eq max}}^2 \tag{A.28}$$

Substituting the expression $\theta_{\text{max}} - \theta_{\text{amb}}$ given in Equation (A.28) in Equation (A.26) yields:

$$t_{\text{trip cold}} = \tau . \ln \frac{R_\text{T} r I_{\text{eq}}^2}{R_\text{T} r I_{\text{eq}}^2 - R_\text{T} r I_{\text{eq max}}^2} \tag{A.29}$$

or

$$t_{\text{trip cold}} = \tau . \ln \frac{I_{\text{eq}}^2}{I_{\text{eq}}^2 - I_{\text{eq max}}^2} \tag{A.30}$$

The Equation (A.30) finally gives the time to reach the maximum (hot-spot) temperature as a function of the equivalent maximum current. Equation (A.30) is also important because it removes references of all temperature variables and replaces them with the maximum current $I_{\text{eq max}}$.

It should be noted that Equation (A.30) has no solution unless:

$$I_{\text{eq}} > I_{\text{eq max}} \tag{A.31}$$

Any current less than $I_{\text{eq max}}$ will raise exponentially the thermal system temperature to a steady-state temperature given by Equation (A.21).

In Equation (A.30), the time to maximum temperature is expressed implicitly with reference to the ambient temperature or with the initial load current equal to zero.

It is needed to develop an equation for the time to maximum (hot-spot) thermal level when the steady-state current is the operating current $I_{\text{eq op}}$.

In Equation (A.22), the time to maximum temperature starts with the temperature at ambient (or with the load current supplied at zero value). With the newer equation, the time to maximum temperature starts with the temperature at operating or the current at equivalent load current.

The time to reach the maximum temperature for some equivalent operating current $I_{\text{eq op}}$ from the operating current is equal to the time to reach the maximum temperature from ambient with the same current minus the time to reach the operating temperature from ambient with the same current.

The steady-state operation temperature θ_{op} can be calculated from Equation (A.23), in accordance with the following equation:

$$\theta_{\text{op}} = R_\text{T} r I_{\text{eq op}}^2 + \theta_{\text{amb}} \tag{A.32}$$

or

$$\theta_{\text{op}} - \theta_{\text{amb}} = R_\text{T} r I_{\text{eq op}}^2 \tag{A.33}$$

The time t_{op} to reach the operating temperature from ambient for an equivalent current I_{eq} can be calculated from Equation (A.22):

$$\theta_{op} = I_{eq}^2 r R_T \left(1 - e^{-t_{op}/\tau}\right) + \theta_{amb} \tag{A.34}$$

From this Equation (A.34) it can be calculated the operating time (t_{op}), solving as follows:

$$t_{op} = \tau \ln \frac{R_T r I_{eq}^2}{R_T r I_{eq}^2 - (\theta_{op} - \theta_{amb})} \tag{A.35}$$

Replacing the expression $\theta_{op} - \theta_{amb}$ by its value given in Equation (A.33) in Equation (A.35) yields:

$$t_{op} = \tau \ln \frac{R_T r I_{eq}^2}{R_T r I_{eq}^2 - R_T r I_{eq\,op}^2} = \tau \ln \frac{I_{eq}^2}{I_{eq}^2 - I_{eq\,op}^2} \tag{A.36}$$

Finally, the time to trip from operating current or temperature is provided by the following equation:

$$t_{trip\,hot} = \tau \ln \frac{I_{eq}^2}{I_{eq}^2 - I_{eq\,max}^2} - \tau \ln \frac{I_{eq}^2}{I_{eq}^2 - I_{eq\,op}^2} \tag{A.37}$$

or

$$t_{trip\,hot} = \tau \ln \frac{I_{eq}^2 - I_{eq\,op}^2}{I_{eq}^2 - I_{eq\,max}^2} \tag{A.38}$$

This Equation (A.38) provides the time to reach the maximum (hot-spot) temperature for an equivalent current I_{eq} when starting from a previous equivalent operating current $I_{eq\,op}$ or operating temperature.

The maximum equivalent current is defined by the k factor (see 3.4) as:

$$I_{eq\,max} = k\, I_B \tag{A.39}$$

Replacing the expression (A.39) in (A.38) yields:

$$t_{trip\,hot} = \tau \ln \frac{I_{eq}^2 - I_{eq\,op}^2}{I_{eq}^2 - (k\, I_B)^2} \tag{A.40}$$

Equation (A.40) is the time to trip based on the hot characteristic curve, as indicated in Equation (A.6) of this standard. Thus, in the algorithm indicated in Equation (A.18), implementing a recursive process of a time-discrete differential equation of a first order thermal system, the time current equations for cold and hot states given in Equations (A.30) and (A.40) are intrinsically embedded in the process.

When thermal protection is implemented by using the algorithm indicated in Equation (A.18), the cold and hot time-current limit characteristic equations given in Equation (A.5) (cold state) and Equation (A.6) (hot state) of this standard are intrinsically embedded in the process, irrespective of the starting thermal level or previous equipment load current.

The algorithm indicated in Equation (A.18) continuously calculates, in real time, the actual state of the thermal model, which is appropriate for digital implementation in microprocessor-based protection devices. Thermal history recording and a pre-alarm setting before trip when overload occurs, prevent undesired trips and process shutdowns.

A.6 Derivation of the ambient temperature factor F_a

In the Equation (A.15), which defines the thermal level $H(t)$ of the equipment, the variable θ_{nom} can be replaced by the expression defined by the Equation (A.10):

$$H(t) = \frac{\theta(t)}{\theta_{nom}} = \frac{\theta_{equipment} - \theta_{amb}}{\theta_{nom}} = \frac{\theta_{equipment} - \theta_{amb}}{r \cdot I_{nom}^2 \cdot R} \quad \text{(A.41)}$$

When the equipment temperature $\theta_{equipment}$ reaches the maximum temperature θ_{max} allowed by the insulation class, the thermal level $H(t)$ is equal to the following equation:

$$H_{max} = \frac{\theta_{max} - \theta_{amb}}{r \cdot I_{nom}^2 \cdot R} \quad \text{(A.42)}$$

where

H_{max} is the maximum thermal level to be reached which causes the thermal protection function to operate.

The thermal protection device calculates the thermal level $H(t)$, which takes into account the ambient (or environmental) temperature θ_{amb}. In general applications, the threshold is generally defined for an ambient temperature of 40 °C. In this case, the setting for the thermal level threshold is equivalent to a maximum thermal level, according to the following equation:

$$H_{setting} = \frac{\theta_{max} - 40}{r \cdot I_{nom}^2 \cdot R} \quad \text{(A.43)}$$

where

$H_{setting}$ is the maximum thermal level to be reached by the equipment to be thermally protected, considering an ambient temperature other than 40 °C, which causes the thermal protection function to operate.

When the ambient (or environmental) temperature fluctuates and is not equal to 40 °C, the setting applied to the thermal level calculation is not equal to the maximum thermal level authorized by the insulation class.

The relation between the 2 thresholds is defined as the correction factor F_a, according to the following equation:

$$\frac{H_{setting}}{H_{max}} = \frac{\theta_{max} - 40}{\theta_{max} - \theta_{amb}} = F_a \quad \text{(A.44)}$$

Where applicable and when the thermal protection device has an ambient temperature measurement input, the thermal level calculation $H(t)$ can be increased by the factor F_a, to take into account the real ambient (or environmental) equipment temperature T_a. The condition to operate the output signal will be defined according to the following inequality:

$$H(t) \geq H_{max} \Leftrightarrow H(t) \cdot \frac{H_{setting}}{H_{max}} \geq H_{setting} \Leftrightarrow H(t) \cdot F_a \geq H_{setting} \tag{A.45}$$

IEC 60085 defines the maximum temperature T_{max} according to the thermal insulation class, as indicated in Table A.2.

Table A.2 – Thermal insulation classes and maximum temperatures, according to IEC 60085

Thermal class	Y	A	E	B	F	H	N	R	250
T_{max}	90 °C	105 °C	120 °C	130 °C	155 °C	180 °C	200 °C	220 °C	250 °C

Based on the Equation (A.44) the particular values of the thermal level threshold correction factor F_a, for typical industrial equipment with insulation class F (155 °C) according to IEC 60085, such as industrial electrical motor, for various equipment ambient temperatures are shown in Table A.3.

Table A.3 – Example of correction factor values (F_a) for class F equipment according to the ambient temperature (T_a)

Equipment ambient temperature (T_a)	40 °C	45 °C	50 °C	55 °C	60 °C
Correction factor F_a for class F equipment	1,0	1,045	1,095	1,15	1,21

Annex B
(informative)

Thermal electrical relays which use temperature as setting parameters

B.1 General

This Annex B provides information about setting and testing the thermal electrical relays which use temperatures as setting parameters.

B.2 Interpretation of the thermal differential equation in terms of temperatures

The form of the first-order thermal differential Equation (B.1) below can be derived if $I_{eq.pu}$ from Equation (A.11) is substituted into Equation (A.13):

$$I_{eq}^2 \frac{\theta_{nom}}{I_{eq.nom}^2} = \tau \frac{d\theta(t)}{d(t)} + \theta(t) \tag{B.1}$$

where

$\theta(t)$ is the temperature above the ambient temperature, varying with time;

$I_{eq.nom}$ is the nominal (rated) value of the equivalent heating current;

θ_{nom} is the steady-state temperature above the ambient temperature if $I_{eq.nom}$ continuous current is flowing.

In Equation (B.1), the factor $\frac{\theta_{nom}}{I_{eq.nom}^2}$ is the scaling factor between the temperature θ and the current square I^2. The value of the scaling factor is the same if $I_{eq.ref}$ reference current is given and the corresponding θ_{ref} steady-state temperature above the ambient temperature is substituted. i.e.:

$$\frac{\theta_{nom}}{I_{eq.nom}^2} = \frac{\theta_{ref}}{I_{eq.ref}^2} = \ldots = \frac{\theta_0}{I_0^2} = \frac{\theta_{max}}{I_{max}^2} \tag{B.2}$$

where

$I_{eq.ref}$ is the reference value of the equivalent heating current;

θ_{ref} is the steady-state reference temperature above the ambient temperature, if $I_{eq.ref}$ current is flowing continuously.

The index "0" or "max" means here any current and corresponding temperature.

The reference current can be any value (e.g. rated current of the protected object, rated current of the CT,) but the reference temperature shall be the steady-state temperature above the ambient temperature, which is reached when reference current is flowing.

The manufacturer shall clearly define how the equivalent heating current is calculated (asymmetry, harmonics).

B.3 Discrete-time solution of the thermal differential equation in terms of temperatures

In microprocessor-based protection devices the discrete-time solution of the first-order thermal differential Equation (B.1) is implemented and it is given in Equation (B.3) as follows:

$$\theta(t) = I_{\text{eq.ref}}^{2} \frac{\theta_{\text{ref}}}{I_{\text{eq.ref}}^{2}} \frac{\Delta t}{\tau + \Delta t} + \frac{\tau}{\tau + \Delta t} \theta(t - \Delta t) \quad \text{(B.3)}$$

The result is the temperature above the ambient temperature. To obtain the temperature of the protected equipment, the ambient temperature Θ_{amb} shall be added (See also Equation (A.2)):

$$\theta_{\text{equipment}}(t) = I_{\text{eq}}^{2} \frac{\theta_{\text{ref}}}{I_{\text{eq.ref}}^{2}} \frac{\Delta t}{\tau + \Delta t} + \frac{\tau}{\tau + \Delta t} \theta(t - \Delta t) + \theta_{\text{amb}} \quad \text{(B.4)}$$

The application of this equation assumes that during the Δt calculation time step, the I_{eq} equivalent current can be considered constant and during the time step, the curve of the temperature changing in time can be substituted by a straight line. Both criteria are fulfilled if the Δt calculation time step is much smaller than the τ time constant of the thermal process. This is the responsibility of the relay manufacturer.

Equations (B.3) or (B.4) clearly show the memory functions of the thermal electric relays. The calculated temperature in the preceding time step shall be known to calculate the subsequent temperature value. It is not important, if the temperature in the preceding step was reached in a heating or cooling process or if it was a steady-state temperature value.

Main parameters to be provided by the user to calculate the temperature above the ambient temperature

$I_{\text{eq.ref}}$ is the reference value of the equivalent heating current;

Θ_{ref} is the steady-state reference temperature above the ambient temperature, if $I_{\text{eq.ref}}$ current is flowing continuously;

τ time constant of the thermal process.

When defining Θ_{ref} the user shall clearly define if the value is given as temperature above the assumed ambient temperature or as the difference of the measured equipment temperature and the ambient temperature at the time of the measurement.

The time constant of the thermal process depends on the state of the protected equipment. E.g. for a motor it is different in a rotating state from standstill; for transformers it is different for natural cooling or in a forced cooling state; etc. The manufacturer shall state how the time constant is handled.

Parameters defining the relay operation

The objects are protected against high temperatures according to thermal insulation classes, as defined in IEC 60085. It is indicated also as T_{max} in Table A.2 of this standard. These temperatures are maximum $\theta_{\text{equipment}}$ temperatures.

The easiest way to define the operating temperatures is as described in Table A.2:

θ_{TRIP} maximum temperature as T_{max} in Table A.2,

θ_{ALARM} alarm temperature (if this temperature is reached, the relay generates an alarm signal),

$\theta_{RESTART}$ restart temperature (the equipment may not be restarted, only if the temperature is below this level).

The manufacturer shall clearly declare how these values are interpreted (e.g.: equipment temperature in °C, above the ambient temperature related to a reference value, temperature in %, etc.)

About the temperature of the environment

The equipment temperature is calculated according to Equation (B.4). This calculation needs the value of θ_{amb} ambient temperature. It is obvious from Equation (B.4) that under low ambient temperature conditions, the equipment can be more overloaded than in hot ambient temperature. To track this, the measurement of the ambient temperature is needed. According to the manufacturer's declaration:

- the ambient temperature can be measured,
- it can be a parameter setting, or
- only the temperature above the ambient is calculated, and the setting for the operating values shall be defined, taking the hottest temperature of the environment into consideration.

The manufacturer shall clearly define which solution is used.

B.4 Testing thermal electrical relays operating in terms of temperatures

As the thermal electrical relays calculate the temperature which is not easy to measure, there is usually no possibility to check the coincidence of the calculated and the real temperature values. For testing a transformation is needed. As the thermal electrical relays measure basically currents, it is obvious that it is necessary to perform a transformation from temperature to currents, and perform the testing similarly to the test procedures for overcurrent relays.

The testing is intended to be performed using symmetrical, basic harmonic currents, so $I_{eq}=I$, (the index "eq" can be neglected).

Equations (B.3) or (B.4) perform a calculation which is valid for continuously varying currents as well, but tests are easier to perform using steady-state continuous currents. To do this the well-known solution of the thermal differential Equation (B.1) for constant current is applied:

$$\theta_{equipment}(t)=\frac{I^2\,\theta_{ref}}{I_{ref}^2}\left(1-e^{-\frac{t}{\tau}}\right)+\theta_0 e^{-\frac{t}{\tau}}+\theta_{amb} \quad (B.5)$$

or:

$$\theta(t)=\theta_{equipment}(t)-\theta_{amb}=\frac{I^2\,\theta_{ref}}{I_{ref}^2}\left(1-e^{-\frac{t}{\tau}}\right)+\theta_0 e^{-\frac{t}{\tau}} \quad (B.6)$$

In Equations (B.5) and (B.6):

θ_0 The temperature of the protected object above the ambient temperature at t = 0.

When substituting $\theta(t)$ by $\theta_{max} = \theta_{TRIP} - \theta_{amb}$ in Equation (B.6) and resolving the temperatures in Equation (B.6), using Equation (B.2) the following Equation (B.7) results:

$$k_{\Phi} = \frac{\theta_{max}}{\theta_{ref}} = \frac{I_{max}^2}{I_{ref}^2} = \frac{I^2}{I_{ref}^2}\left(1 - e^{-\frac{t}{\tau}}\right) + \frac{I_0^2}{I_{ref}^2} e^{-\frac{t}{\tau}} \qquad (B.7)$$

where

θ_{max} is the permitted maximum temperature above the temperature of the environment $\theta_{max} = \theta_{TRIP} - \theta_{amb}$;

Φ_{ref} is the steady-state reference temperature above the ambient temperature, if I_{ref} current is flowing continuously (setting value);

I_{max} is the steady-state current, needed to reach the θ_{max} steady-state temperature above the ambient temperature;

I_0 is the steady-state current, needed to reach the θ_0 steady-state temperature (temperature above the ambient temperature at $t = 0$);

I_{ref} is the reference value of the equivalent heating current, (setting value);

τ is the time constant of the thermal process (setting value).

From Equation (B.7) the expected time to trip *“t”* can be derived:

$$t = \tau \ln \frac{I^2 - I_0^2}{I^2 - I_{max}^2} \qquad (B.8)$$

where

I is the injected steady-state current, needed to reach a θ steady-state temperature above the ambient temperature, (this temperature would be above the θ_{max} temperature),

I_{max} is the steady-state current, needed to reach the θ_{max} steady-state temperature. It can be calculated using the formula from Equation (B.2):

$$I_{max}^2 = \frac{I_{eq.ref}}{\theta_{ref}} \theta_{max} \qquad (B.9)$$

I_0 is the supposed steady-state current, needed to reach the θ_0 steady-state temperature. The temperature above the ambient temperature at $t = 0$, can be calculated using the formula from Equation (B.2):

$$I_0^2 = \frac{I_{eq.ref}^2}{\theta_{ref}} \theta_0 \qquad (B.10)$$

τ time constant of the thermal process, (setting value).

NOTE 1 Equation (B.8) is equivalent to Equation (A.38) (the definition of the hot curve).

NOTE 2 When substituting $I_0 = 0$, the definition of the cold curve is derived, with the meaning that the heating procedure starts when the protected object is at the temperature of the environment.

B.5 About θ_0, the starting temperature

Because of the long thermal time constants of the protected object, during a test, a long time would be needed to reach this θ_0 starting temperature value. The manufacturer shall provide guidance to accelerate the test procedure: e.g. reset the accumulated thermal level, then high current injection during a well-defined time; or parameter setting for the starting temperature, which is activated by a dedicated binary input signal; etc.

B.6 Factors k and k_θ

The factor k_θ is defined in Equation (B.7):

$$k_\theta = \frac{\theta_{\max}}{\theta_{\mathrm{ref}}} = \frac{I_{\max}^2}{I_{\mathrm{ref}}^2} \tag{B.11}$$

It can be seen that

$$k_\theta = \frac{I_{\max}^2}{I_{\mathrm{ref}}^2} = k^2 \tag{B.12}$$

The manufacturer shall clearly define the meaning of the factor to be set (if applicable).

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