EUROPROT +

Motor thermal protection function block description

PROTECTA
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CONTENTS

1 Motor thermal protection function

Basically, the motor thermal protection function measures the three sampled phase currents. Positive sequence and negative sequence basic harmonic components are calculated. The temperature calculation is based on the weighted sum of the positive and negative sequence components.

$$I = \sqrt{I_1^2 + k * I_2^2}$$

Where
I_1 positive sequence current component
I_2 negative sequence current component
k weighting factor (parameter “INeg Scale”)

NOTE: I_2 is limited to 1.5 I_n. Above this value the considered I_2=1.5 I_n and the k weighting factor is constant 500%.

The weighting factor is defined by the user applying the required parameter setting TTR49M_NegScale_IPar_ (Neg.Seq. scale). The purpose of weighting is to take into consideration the increased heating of the rotor due to inverse rotating (nearly double speed) negative sequence magnetic field.

The setting allows two different thermal time constants to be considered: one for the rotating state (heating) - TTR49M_pT_IPar_ (Time constant) - and one for the still stand (cooling), which is defined by parameter TTR49M_cpT_IPar_ (Cooling/Heating) as a percentage of the heating time constant.

The temperature calculation is based on the step-by-step solution of the thermal differential equation. This method yields “overtemperature”, meaning the temperature above the ambient temperature (of the environment). Accordingly, the temperature of the protected object is the sum of the calculated “overtemperature” and the ambient temperature.

The ambient temperature can be measured using e.g. a temperature probe generating electric analog signals proportional to the temperature. In the absence of such measurement, the temperature of the environment can be set using the dedicated parameter TTR49M_Amb_IPar_ (Ambient Temperature). The selection between parameter value and direct measurement is made by setting the binary parameter TTR49M_Sens_BPar_ (Temperature sensor).

If the calculated temperature (calculated “overtemperature”+ambient temperature) is above the threshold values, status signals are generated:

TTR49M_Alm_IPar_ (Alarm temperature)
TTR49M_Trip_IPar_ (Trip temperature)
TTR49M_Unl_IPar_ (Unlock temperature)

For correct setting, the following values must be measured and set as parameters:

TTR49M_Inom_IPar_	(Rated load current: the measuring continuous current)
TTR49M_Max_IPar_	(Rated temperature: the steady state temperature at rated load current)
TTR49M_Ref_IPar_	(Base Temperature: the temperature of the environment during the measurement of the rated values)
TTR49M_pT_IPar_	(Time constant: separately measured heating/cooling time constant of the exponential temperature functions.)

When energizing the protection device, the algorithm permits the definition of the starting temperature as the initial value of the calculated temperature:

TTR49M_Str_IPar_	(Startup Term.: Initial temperature above the temperature of the environment as compared to the rated temperature above the temperature of the environment)

For motors with heavy starting conditions a binary signal can decrease the calculated heat to the half value ($I^2/2$), preventing trip command for overheating during motor starting.

The application of thermal protection of the motor is a better solution than simple overcurrent-based overload protection because thermal protection “remembers” the preceding load state of the motor, consequently, the setting of the thermal protection does not need such a high security margin between the permitted current and the permitted continuous thermal current of the motor. In case of previous load states and in a broad range of ambient temperatures this permits the better exploitation of the thermal and consequently current carrying capacity of the motor.

1.1 Theory of the thermal replica calculations

1.1.1 The thermal differential equation

The theory of solving the thermal differential equation is described and explained in detail in a separate document [“The thermal differential equation”].

The source of the formulas below is that document.

The thermal differential equation to be solved is:

$$\frac{d\Theta}{dt} = \frac{1}{T}\left(\frac{I^2(t)R}{hA} - \Theta\right) \tag{1}$$

The definition of the heat time constant is:

$$\boxed{T = \frac{cm}{hA}}$$

In this differential equation:

I(t)	(RMS) heating current, the RMS value usually changes over time;
R	resistance of the motor;
c	specific heat capacity of the conductor;
m	mass of the conductor;
θ	rise of the temperature above the temperature of the environment;
h	heat transfer coefficient of the surface of the conductor;
A	area of the surface of the conductor;
t	time.

1.1.2 The temperature-time function for constant current

The solution of the thermal differential equation for constant current is the temperature as the function of time. (The mathematical derivation of this equation is described in a separate document.)

$$\Theta(t) = \frac{I^2 R}{hA}\left(1 - e^{-\frac{t}{T}}\right) + \Theta_o e^{-\frac{t}{T}} \qquad (2)$$

Remember that the calculation of the measurable temperature is as follows:

Temperature(t) = Θ(t)+Temp_ambient

Where:
Temp_ambient is the ambient temperature.

In that separate document it is proven that some more easily measurable parameters can be introduced instead of the aforementioned ones. Thus, the general form of equation (2) is:

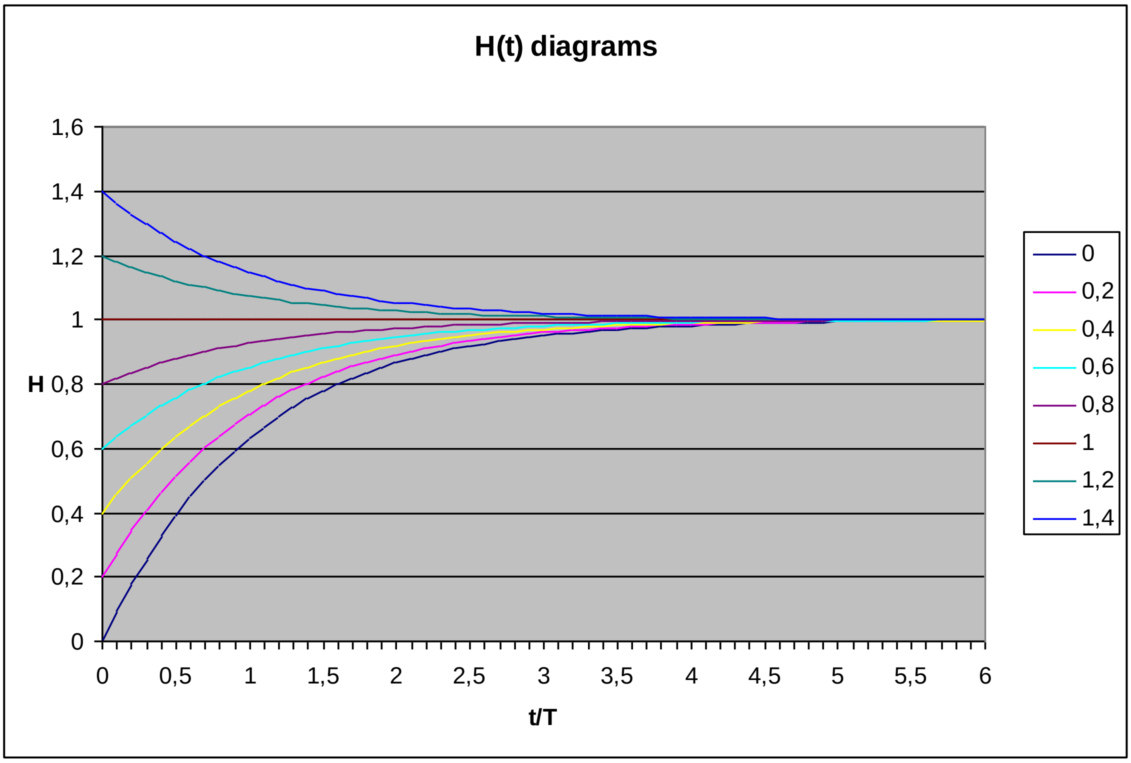
$$H(t) = \frac{\Theta(t)}{\Theta_n} = \frac{I^2}{I_n^2}\left(1 - e^{-\frac{t}{T}}\right) + \frac{\Theta_o}{\Theta_n} e^{-\frac{t}{T}} \qquad (3)$$

where:

H(t)	is the „thermal level” of the heated object, **this is the temperature as a percentage of the Θ_n reference temperature.** (This is a dimensionless quantity but it can also be expressed in a percentage form.)
Θ_n	is the reference temperature above the temperature of the environment, which can be measured in steady state, in case of a continuous I_n reference current.
I_n	is the reference current (can be considered as the nominal current of the heated object). If it flows continuously, then the reference temperature can be measured in steady state.

1.1.3 Formulas for checking the thermal protection functions

Equation (3) offers a general formula to check the operation of the thermal protection using constant current.
The changes of temperature over time, (above the temperature of the environment), described by equation (3), are plotted in the diagram below. Parameter of the individual curves is the starting temperature as a percentage of the reference temperature $\frac{\Theta_o}{\Theta_n}$.



For further tests, the time needed to reach a specific temperature value can be calculated based on equation (3). The derived formula with relative quantities is:

$$\frac{t}{T} = \ln\left(\frac{\frac{\Theta_S}{\Theta_n} - \frac{\Theta_o}{\Theta_n}}{\frac{\Theta_S}{\Theta_n} - \frac{\Theta_{set}}{\Theta_n}}\right) \qquad (4)$$

Where:

$\Theta_S = \frac{I^2\Theta_n}{I_n^2}$ is the steady state temperature in case of continuous I current,

Θ_{set} is the momentary temperature above the ambient temperature; the time to reach this is to be calculated,

Θ_o is the starting „overtemperature”,

Θ_n is the reference temperature above the temperature of the environment, which can be measured in steady state, in case of a continuous I_n reference current.

To be able to compare the current–time characteristics of the thermal protection with that of the inverse characteristics, formula (4) can be rearranged using currents and per unit quantities:

$$\frac{t}{T} = \ln \frac{\frac{I^2}{I_{set}^2} - \frac{I_0^2}{I_{set}^2}}{\frac{I^2}{I_{set}^2} - 1} \qquad (5)$$

where:

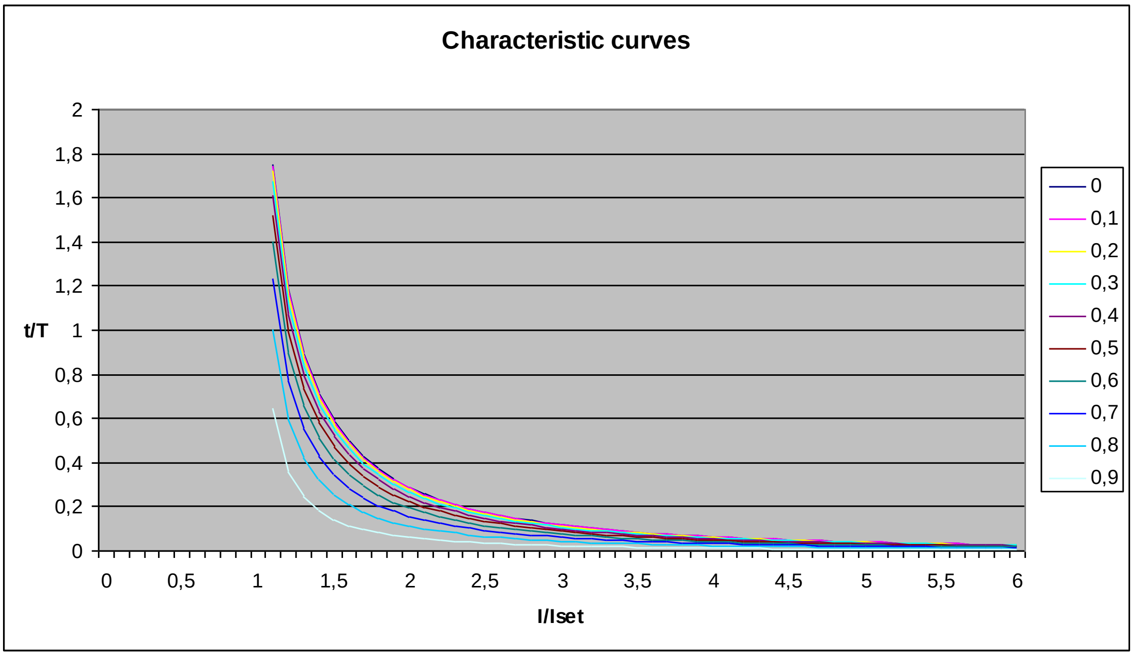
I_o is the continuous current that results Θ_o steady state “overtemperature” at the beginning of the calculation,

I is the current that is applied to reach the steady state Θ_S “overtemperature”, $(\Theta_S = \frac{I^2 \Theta_n}{I_n^2})$.

I_{set} is the setting current of the „overcurrent” function.

The plots_according to equation (5) can be seen below. They show how much time is left to reach the „trip temperature” in case of a continuous I (RMS) current. The parameter is the continuous Io current related to the I_n rated current, which generates the steady state starting temperature. The top-most curve is the „cold curve”.

The plots_below clearly show that the thermal replica method “remembers” the starting temperature. If the starting temperature (Io pre-faulty steady state current) is increased, the time to trip at a fault current $I/I_{set}>1$ automatically decreases.



1.1.4 Numerical solution of the thermal differential equation

The formulas (2-6) above refer to a constant current and can be used to test the thermal protection. In reality, the RMS value of the currents change over time; consequently, differential equation (1) must be solved using a numerical method. The separate document explains the steps to obtain the calculation formula:

$$H_k = \frac{\Theta_k}{\Theta_n} = \left(1 - \frac{\Delta t}{T}\right)\frac{\Theta_{k-1}}{\Theta_n} + \frac{\Delta t}{T}\frac{I^2}{I_n^2} \qquad (6)$$

where:

Θ_k is the temperature (above the temperature of the environment) at the k-th calculation step;

Θ_k is the temperature (above the temperature of the environment) one calculation step before.

(The user of the thermal protection does not need to apply formula (6) above.)

1.2 Structure of the motor thermal overload protection

Fig.1-1 shows the structure of the motor thermal overload protection (TTR49M) algorithm.

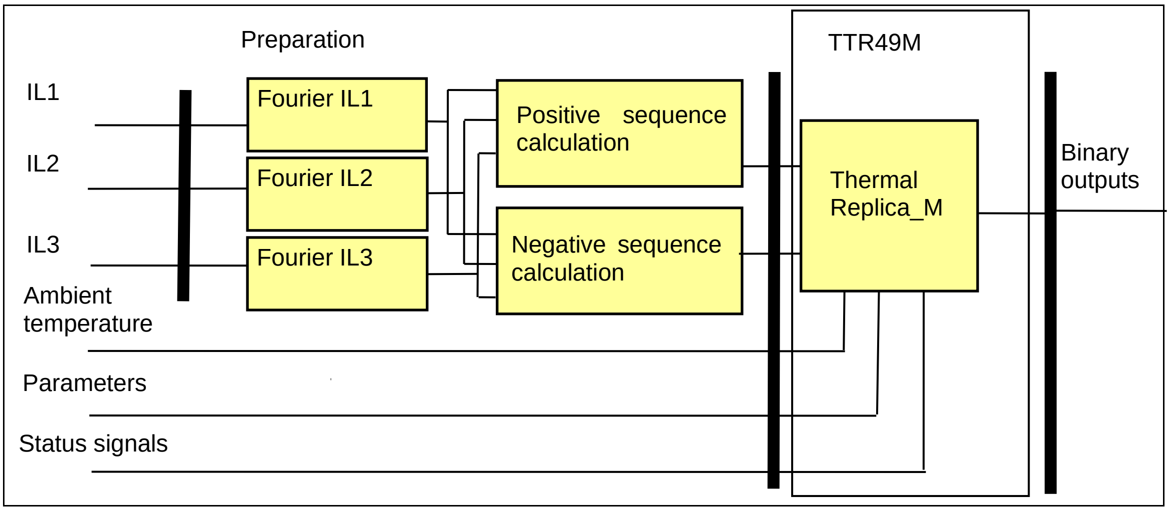


Figure 1-1 Structure of the motor thermal overload protection algorithm

For the preparation phase:
The **inputs** are

- the sampled values of three primary phase currents,

The **outputs** are

- the fundamental Fourier components of the positive and negative sequence currents, calculated using the phase currents.

For the thermal overload function:
The **inputs** are

- the fundamental Fourier components of the positive and negative sequence currents, calculated using the phase currents.
- the signal proportional to the ambient temperature,
- parameters,
- status signals.

The **outputs** are

- the binary output status signals.

The **software modules** of the thermal overload protection function:

Fourier calculations
These modules calculate the basic harmonic component values of the phase currents individually. These modules are not part of the thermal overload function; they belong to the preparatory phase.

Positive sequence calculation

Negative sequence calculation
These modules calculate the positive and negative sequence basic harmonic components of the phase currents. These modules are not part of the thermal overload function; they belong to the preparatory phase.

Thermal replica
This module solves the first order thermal differential equation using a simple step-by-step method and compares the calculated temperature to the values set by parameters.

The following description explains the details of the individual components.

1.3 Fourier calculations (Fourier calculations)

These modules calculate the basic harmonic component values of the phase currents individually. These modules are not part of the thermal overload function; they belong to the preparatory phase.

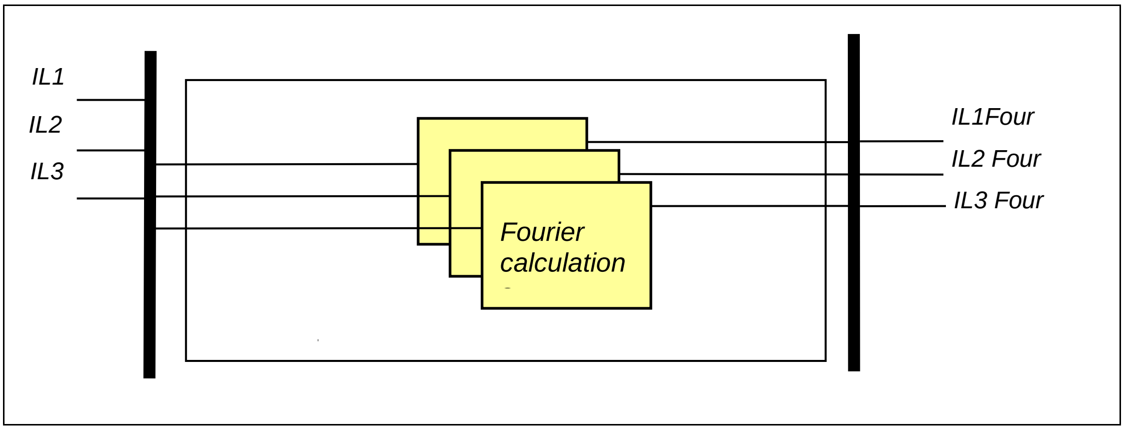


Figure 1-2 Principal scheme of the Fourier calculation

The **inputs** are the sampled values of the three phase currents (IL1, IL2, IL3)

The **outputs** are the basic Fourier components of the analyzed currents (IL1Four, IL2Four, IL3Four).

1.4 Positive sequence calculation (Positive sequence calculation) and negative sequence calculation (Negative sequence calculation)

These modules calculate the positive and negative sequence basic harmonic components of the phase currents. These modules are not part of the thermal overload function; they belong to the preparatory phase.

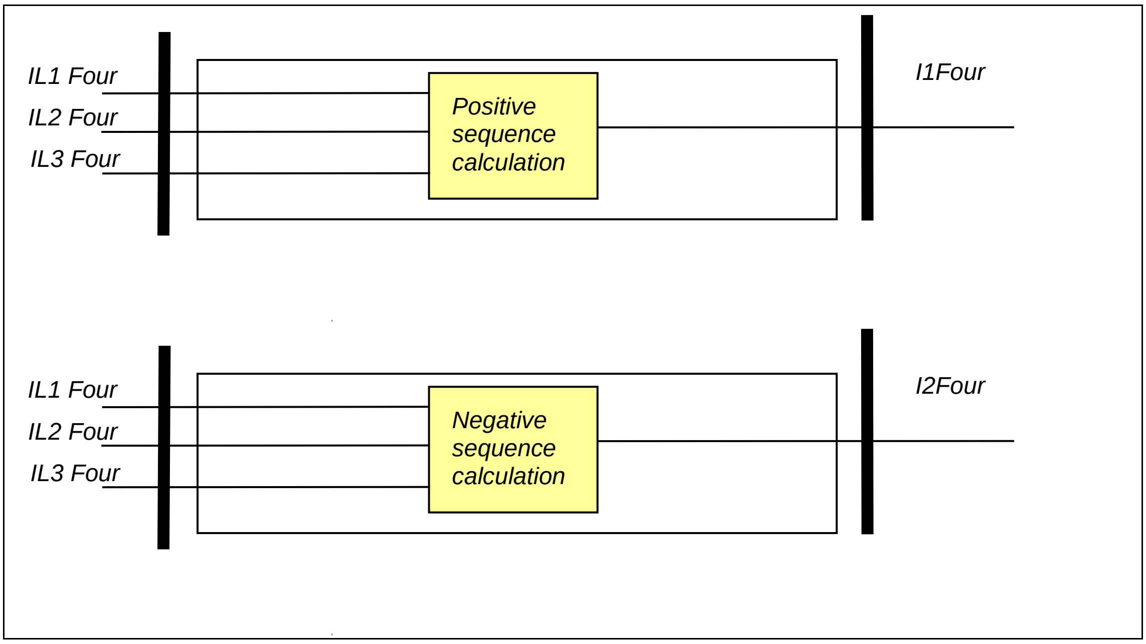


Figure 1-3 *Schema of the positive and negative sequence component calculation*

The **inputs** are the basic Fourier components of the analyzed currents (IL1Four, IL2Four, IL3Four)

The **outputs** are the positive and negative sequence fundamental harmonic Fourier components of the phase currents.

1.5 The temperature calculation and decision (Thermal replica M)

This module solves the first order thermal differential equation using a simple step-by-step method and compares the calculated temperature to the values set by parameters.

The **inputs** are:

- The positive and negative sequence fundamental harmonic Fourier components of the phase currents,
- The value proportional to the ambient temperature (this signal is optional, defined at parameter setting),
- The basic Fourier components of the phase currents (IL1Four, IL2Four, IL3Four). These values support the decision about the running (heating) or still-stand (cooling) state of the motor,
- Binary input status signals,
- Parameters.

The **outputs** are the status signals. These indicate the generated trip command if the temperature is above the current setting value.

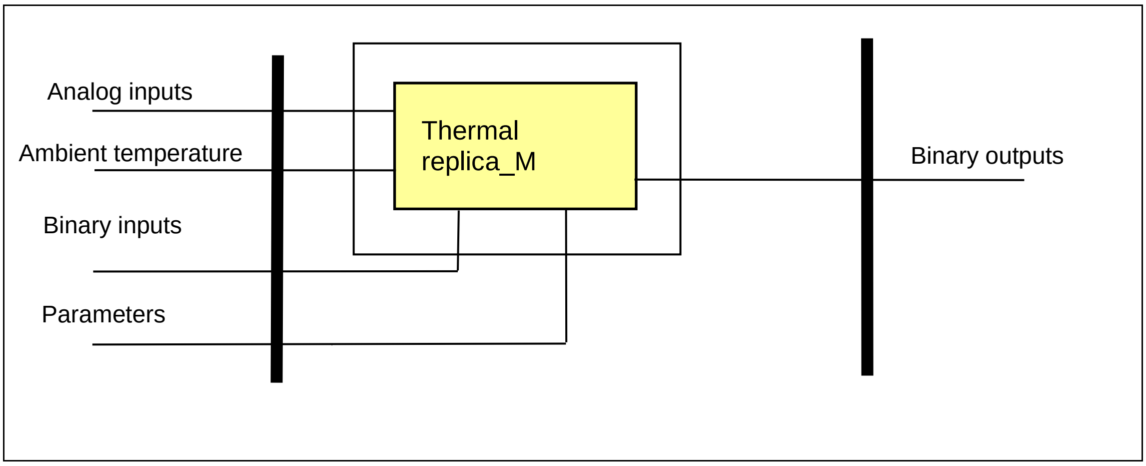


Figure 1-4 Principal scheme of the thermal replica calculation

Enumerated parameter

Parameter name	Title	Selection range	Default
Parameter for mode of operation			
TTR49M_Oper_EPar_	Operation	Off, Pulsed, Locked	Pulsed

Table 1-1 The enumerated parameters of the motor thermal protection function

The meaning of the enumerated values is as follows:

Off	The function is switched off; no output status signals are generated;
Pulsed	The function generates a trip pulse if the calculated temperature exceeds the trip value
Locked	The function generates a trip signal if the calculated temperature exceeds the trip value. It resets only if the temperature cools below the “Unlock temperature”.

Integer parameters

Parameter name	Title	Unit	Min	Max	Step	Default
Alarm Temperature						
TTR49M_Alm_IPar_	Alarm Temperature	deg	60	200	1	80
Trip Temperature						
TTR49M_Trip_IPar_	Trip Temperature	deg	60	200	1	100
Rated Temperature						
TTR49M_Max_IPar_	Rated Temperature	deg	60	200	1	100
Base Temperature						
TTR49M_Ref_IPar_	Base Temperature	deg	0	40	1	25
Unlock Temperature						
TTR49M_Unl_IPar_	Unlock Temperature	deg	20	200	1	60
Ambient Temperature						
TTR49M_Amb_IPar_	Ambient Temperature	deg	0	40	1	25
Startup Temperature						
TTR49M_Str_IPar	Startup Temp.	%	0	60	1	0
Rated LoadCurrent						
TTR49M_Inom_IPar_	Rated LoadCurrent	%	20	150	1	100
Idle Current, below which the “cooling” time constant is valid						
TTR49M_Imin_IPar_	Idle Current	%	1	30	1	5
Time constant						
TTR49M_pT_IPar_	Time constant	min	1	999	1	10
Cooling/Heating						
TTR49M_cpT_IPar_	Cooling/Heating	%	100	400	1	200
Neg.Seq. scale (k)						
TTR49M_NegScale_IPar_	INeg Scale	%	100	500	1	200

Table 1-2 The integer parameters of the motor thermal protection function

Boolean parameter

Boolean parameter	Signal title	Selection range	Default
Parameter for ambient temperature sensor application			
TTR49M_Sens_BPar_	Temperature Sensor	No, Yes	No

Table 1-3 The Boolean parameter of the motor thermal protection function

1.6 Technical summary

1.6.1 Technical data

Function	**Accuracy**
Current in range of 20 - 2000% of In	< ± 1% of In
Operate time at I>1.5*Itrip	<5 %

Table 1-4 *Technical data of the motor thermal protection function*

1.6.2 The parameters

The parameters are summarized in Chapter 1.5.

1.6.3 Binary output signals

The **binary output status signals** of the motor thermal protection function are shown in Table *1-5*.

Binary output signals	**Signal title**	**Explanation**
TTR49M_Alarm_GrI_	Alarm	Alarm signal of the motor thermal protection function
TTR49M_GenTr_GrI_	General Trip	General trip signal of the motor thermal protection function
TTR49M_Lock_GrI_	Reclose locked	Motor restart blocking signal of the motor thermal protection function

Table 1-5 *The binary output status signals of the motor thermal protection function*

1.6.4 Binary input status signals

The motor thermal protection function has two binary input status signals. One of them serves to disable the function; the other one resets the accumulated heat. Resetting serves test purposes only, if the heating calculation needs to start at a clearly defined temperature. Using this signal, the testing engineer need not wait until the cooling reaches the required starting temperature of the subsequent heating test.

Both binary input status signals are defined by the user, applying the graphic equation editor.

The **binary input status signals** of the motor thermal protection function are shown in Table *1-6*.

Binary status signal	Explanation
TTR49M_Blk_GrO_	Output status of a graphic equation defined by the user to disable the motor thermal protection function.
TTR49M_Reset_GrO_	Output status of a graphic equation defined by the user to reset the accumulated heat and set the temperature to the defined value for the subsequent heating test procedure.`
TTR49M_StartUp_GrO_	For motors with heavy starting conditions the presence of this signal decreases the generated heat amount to the half value ($I^2/2$)

Table 1-6 *The binary input signals of the motor thermal protection function*

1.6.5 The function block

The function block of the motor thermal protection function is shown in Figure *1-5*. This block shows all binary input and output status signals that are applicable in the graphic equation editor.

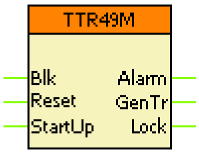


Figure 1-5 *The function block of the motor thermal protection function*