

# Using the Engine Thermal Wizard for Accurate Setting and Commissioning of Motor Protection Relays

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# 1 INTRODUCTION

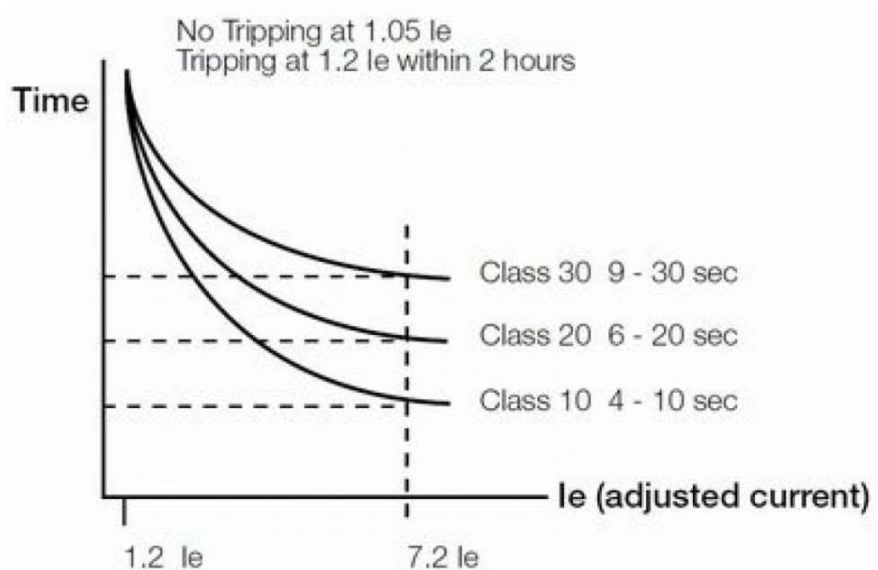
It is quite common that new induction motors and synchronous machines come with datasheets which provide the thermal limit curve(s) of the engine. Sometimes the manufacturer's datasheet even instructs which type of curve should be used. In a worst-case scenario, there is no available information regarding the thermal curves. In such instances, especially when dealing with old devices, it is quite common that old relay settings have just been copied over to the new protection relays during maintenance. In the most challenging situations, the motor thermal replica must be built based on the starting of the motor just to avoid nuisance tripping during starting.

Overload relays typically operate on an inverse time curve where the tripping time decreases as the current increases. Overload relays are rated according to their trip class, which specifies the length of time needed for the relay to react in an overload condition.

In Europe, the shape of the tripping curves of overload relays is defined by ANSI or IEEE standards. In North America, the standard NEMA MG 1 defines four of the most common class types: 5, 10, 20, and 30. Respectively, these will trip within 5, 10, 20, and 30 seconds at 600 % of full motor load currents.

Class 5 is usually used for motors that require extremely fast tripping. Class 10 is commonly used to protect artificially cooled motors, such as submersible pump motors with a low thermal capacity. Class 20 is usually sufficient for general purpose applications. Class 30 is typically required for high-inertia loads to help prevent nuisance tripping.

Figure 1-1. NEMA standard for overload protection.



Even though a motor thermal replica should be set according to the manufacturer's thermal curve presented in the datasheets, this is not always possible. Sometimes the manufacturer has not provided a thermal curve, and other times a proper datasheet is not available. Even in new applications it is not always possible to properly model the motor thermal replica to the relay because the relay settings are not flexible enough to create a good match with the thermal curve presented in the manufacturer's datasheet. Based on this author's experience it is quite common that a thermal replica is set and commissioned based on a single point in the datasheet's thermal curve. Such a method could lead to

the motor being over- or underprotected in certain load conditions or when the engine is in a locked rotor state.

In the simplest protection relays the thermal replica is built based on the nominal current, the pick-up setting, the trip class, and the ambient temperature. In modern relays, however, the most advanced thermal protection also takes note of other things, such as running an overload, locked rotor starts, frequent starting, and the effect of the negative sequence current ( $I_2$ ).

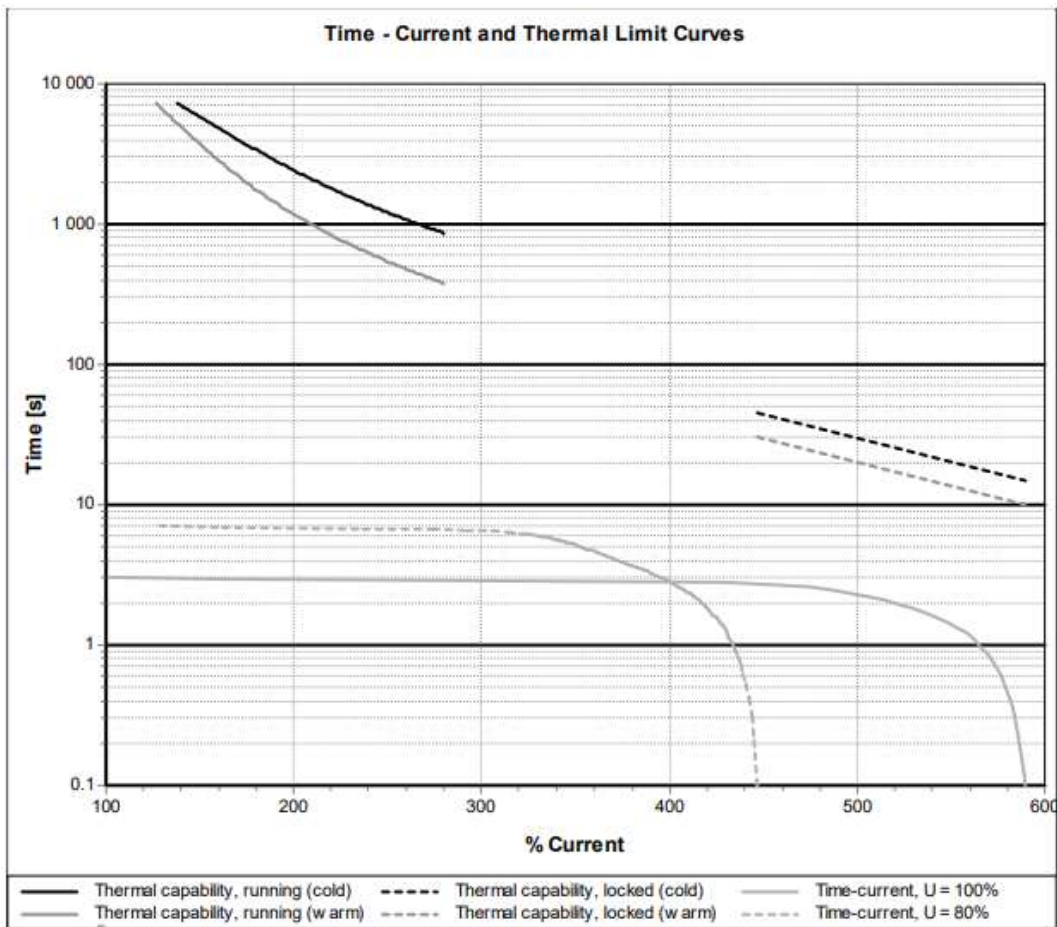
The thermal replica of a regular air-cooled induction motor follows the square of the current ( $I^2$ ), and this works great with most protected engines. However, applying this protection basis on water-cooled synchronous machines does not produce satisfactory results: they follow a different type of thermal curve, and the logarithmic  $I^2$  method cannot mimic it accurately enough.

This paper further examines the differences between the thermal replicas of water-cooled and air-cooled engines. Additionally, a method for creating and testing an unorthodox thermal model with the use of Arcteq's Thermal Wizard software will be presented.

## 2 INVESTIGATING AND MODELLING THE THERMAL REPLICA OF AN INDUCTION MOTOR

The thermal curve provided by a motor manufacturer is usually executed by using one or more time constants. A thermal model with multiple time constants includes separate curves for a hot engine condition and a cold engine condition. This means that once an engine reaches a certain temperature, its condition can be interpreted as “hot” and the hot condition time constant then causes the operating time to approach a trip faster.

Figure 2-1. The thermal curve of a squirrel cage motor with separate curves for hot and cold engine conditions.



When a datasheet of a protected motor includes two thermal curves (as shown, for example, in Figure 2-1 above), the thermal replica of the protection relay should include two separate time constants. These are known as the hot theta and the cold theta.

Most of the protection relay manufacturers provide at least two separate curves for modelling the engine hot and cold conditions. Additionally, the locked rotor condition is covered by using these two curves in applications where the locked rotor condition follows a set  $I^2$  curve and does not considerably differ from the locked rotor region (for example,  $4.0...7.0 \times I_n$ ). Some manufacturers use separate  $k$  factors for regular overload, unbalance, and locked rotor conditions.

The Thermal Wizard software is an easy-to-use tool to help in the modelling of thermal curves in different applications. The software allows users to define whether the protected machine is air- or water-cooled, and to select which types of thermal capacity equations are used depending on the machine's cooling method. Water-cooled machines operate with a single time constant, whereas air-cooled machines can have one or more time constants (depends on the application). A maximum of two separate time constants (hot theta and cold theta) can be configured in the Thermal Wizard.

Figure 2-2. In the Thermal Wizard users can select whether the thermal replica follows the  $I^2$  curve equation (for air-cooled machines) or not (for water-cooled machines).

The screenshot displays the Thermal Wizard configuration window with the following parameters and values:

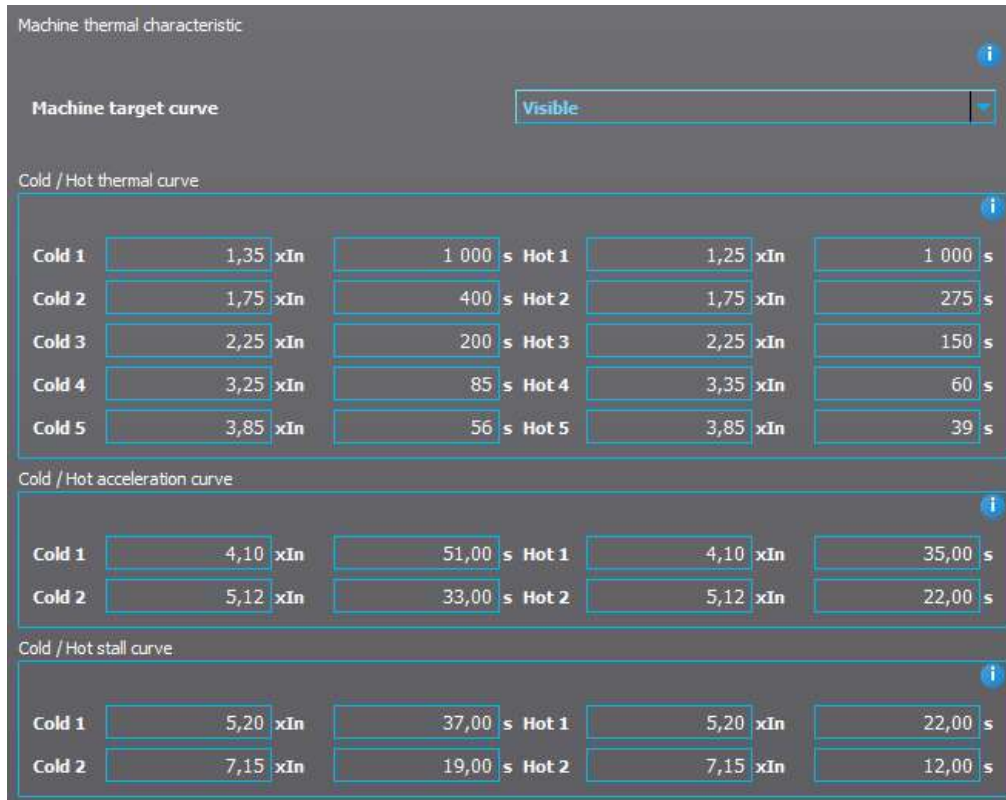
Parameter	Value
Thermal curve selector	$I^2$ curve
Injected current amplitude	400 A (Pri)
Injected I2 component	0 %
Phase CT input selection	CT1
CT ratio	300,0 / 5,0 A
Nominal current	244,0 A (pri)
Pickup current	1,05 pu
Trip level	100,0 %
Machine Cold/Hot limit	80,00 %
Used thermal capacity	0,00 %
NPS biasing in use	Yes
NPS bias factor	2,0
Time constant	Single
Cold curve Tau	8,8 min
Machine running&cooling Tau	10,0 min
Machine stopped Tau	10,0 min
Machine service factor	1,00 xIn

First, let us consider the case of an air-cooled motor. We start by selecting the  $I^2$  curve equation as the basis for the thermal replica (see the first parameter selection box shown in Figure 2-2). Next, we must select the number of time constants to be used. From the motor's datasheet we find that the engine uses two thermal curves to model its thermal behavior and therefore we select "Multiple" for the *Time constant* parameter (also visible in Figure -2).

The parameter *Hot condition theta limit* defines the temperature where the thermal model changes from the cold condition to the hot condition (that is, when we consider the protected motor to turn hot). Please note that the hot condition directly affects the relay's tripping time because the hot condition theta limit is usually configured to act faster than the cold one. However, this is only true for protection relays that have adjustable cold and hot curve theta limits; not all relays have them.

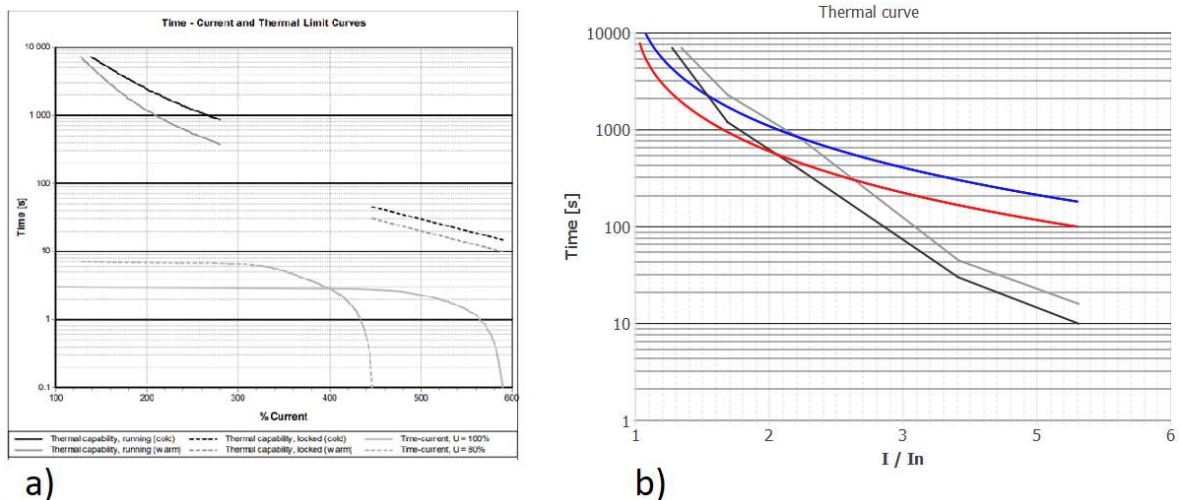
The Thermal Wizard software also has many familiar settings which are based on the motor's name plate values. For example, these settings include the nominal current, the pick-up setting, the service factor, the motor frequency, and the motor nominal starting current. These settings directly affect the shape of the thermal curve as well as the functionality of the protection relay. Please note that when using a protection relay of a brand other than Arcteq, the service factor setting should be set to 1.0 because the effect of the service factor varies between the protection relays of different manufacturers.

Figure 2-3. The hot and cold thermal target curves are set in the Wizard separately through five different setting points. The hot and cold acceleration and stall curves use two setting points.



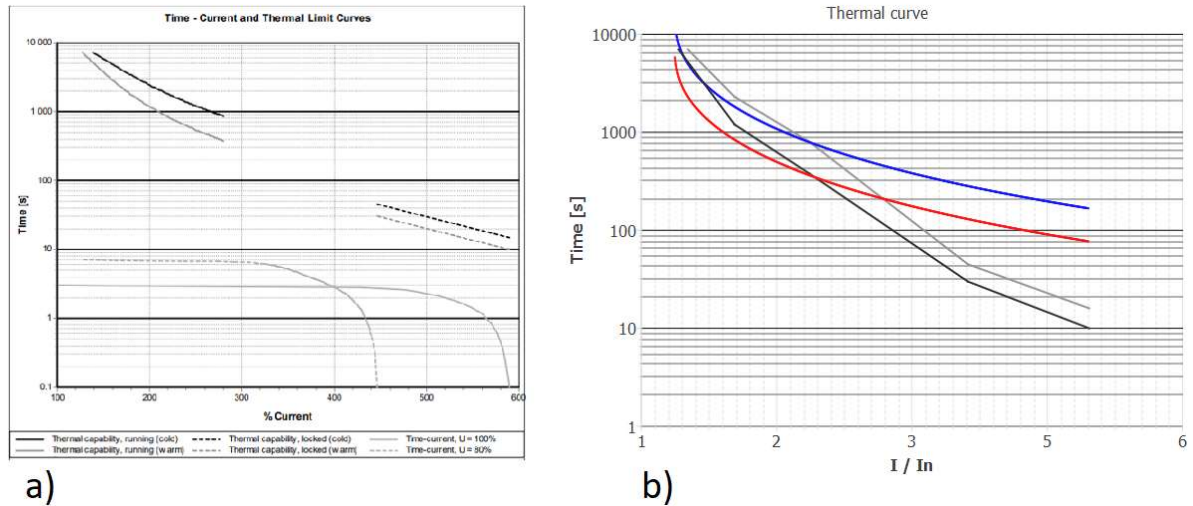
As seen in Figure 2-3 above, the thermal target curve of the protected engine can be conveniently set in the Wizard by using several setting points. Please note that the settings for hot and cold curves are separated for all three curve types: the basic thermal curve, the acceleration curve, and the stall curve. The graph B in Figure 2-4 (below) shows how the visualization of a thermal curve looks in different situations (overloaded motor, acceleration, and locked rotor).

Figure 2-4. A) The thermal characteristic curves of an ABB induction motor, as provided by the motor's datasheet. B) The  $I^2$  protection curve on top of the engine's thermal characteristic curves, as modelled in the protection application.



As Figure 2-4 above shows, adjusting the  $I^2$  relay curve based on a single  $k$  factor does not always give a satisfying result. It is noticeable that the locked rotor area of the curve is located considerably below the protected curve; even the top end of the curve differs from the intended curve.

Figure 2-5. A) The thermal characteristic curves of an ABB induction motor, as provided by the motor's datasheet. B) The  $I^2$  protection curve on top of the engine's thermal characteristic curves, as modelled in the protection application (service factor adjustment is being used).



When the service factor is included in the thermal equation (see Equation 1 below), the user can adjust the curve's top end a little more precisely in  $I^2$  applications. However, even with this adjustment it is still noticeable that the locked rotor state is not correctly protected (see Figure 2-5 above).

$$Trip\ time = LN \frac{I_{EM}^2 - (\sqrt{T_{stat} \times k_{SF}})^2}{I_{EM}^2 - (\sqrt{I_{SET} - k_{SF}})^2} \times \tau \times 60 \quad (1)$$

Different relay manufacturers deal with the thermal replicas in various different ways, and some manufacturers support more functionalities than others. For the products of most manufacturers, the Thermal Wizard is restricted to the above-mentioned functionalities.

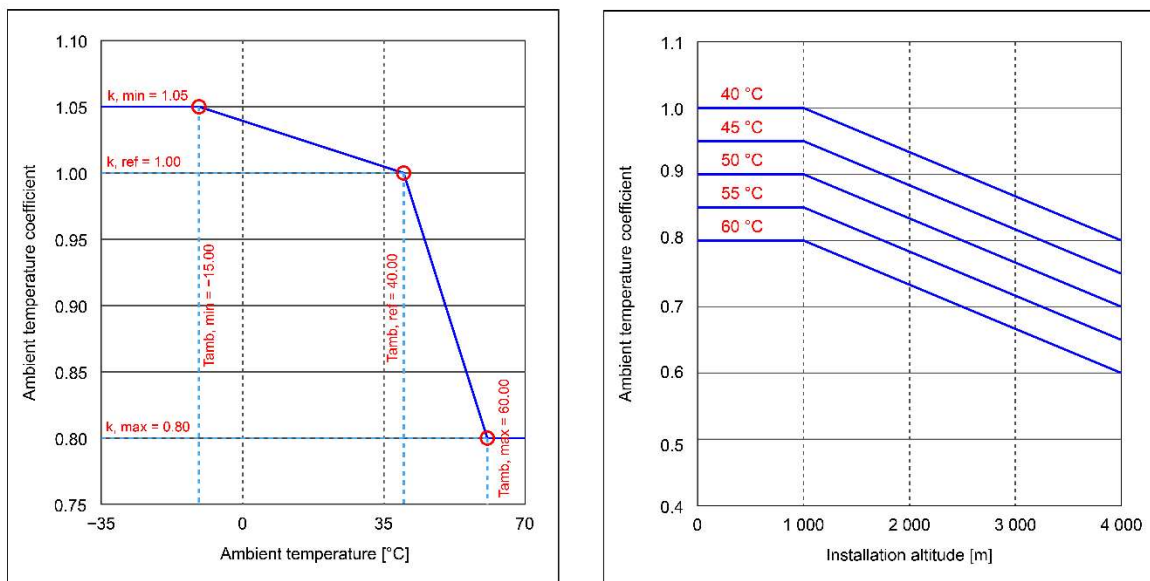


### 3 SETTING AN ARCTEQ RELAY WITH THE THERMAL WIZARD

Negative sequence current ( $I_2$ ) is one extremely essential factor to be considered when using a thermal replica for machine protection. The negative sequence quantities have an opposing rotation direction to that of the power system, and this reversed rotating stator current induces double frequency currents within the rotor structure. This, in turn, causes significant amounts of heating which can then damage the rotor very quickly. In fact, the negative sequence current  $I_2$  heats the protected engine twice as much as the positive sequence current  $I_1$ . When it is time to commission the relay, the Thermal Wizard calculates the actual operating time of the thermal protection, basing the calculation on a specified or injected current and its negative sequence current amplitude (in percentages). Again, not all protection relay manufacturers apply the negative sequence current in their thermal protection algorithms. Additionally, even when the negative sequence current is applied to thermal protection, the exact means by which this is done varies from one manufacturer to another.

There are also a few other factors that significantly affect the heating of the protected motor: the setting of the service factor (that is, the shape of the used thermal curve), the ambient temperature around the engine, and the installation altitude. When the outside ambient temperature increases, the current in the winding of the stator also increases. This causes the motor's temperature to increase earlier than it would have in lower ambient temperatures. The same applies to the increase in the installation altitude: in higher atmospheric pressure the current begins to create a higher thermal impact to the protected object than it would have in lower altitudes. Figure 3-1 below shows how altitude and temperature affect the engine's thermal withstand.

Figure 3-1. Both installation altitude and ambient temperature affect an engine's thermal withstand.



The total current heating the machine is based on the current and the harmonics ( $I_{TRMS}$ ), the negative sequence current ( $I_{2eff}$ ) as well as the ambient temperature and installation altitude ( $k_{AMB}$ ), as shown in Equation 2 below.

$$I_{EM} = \frac{I_{TRMS} + I_{2eff}}{k_{AMB}} \tag{2}$$

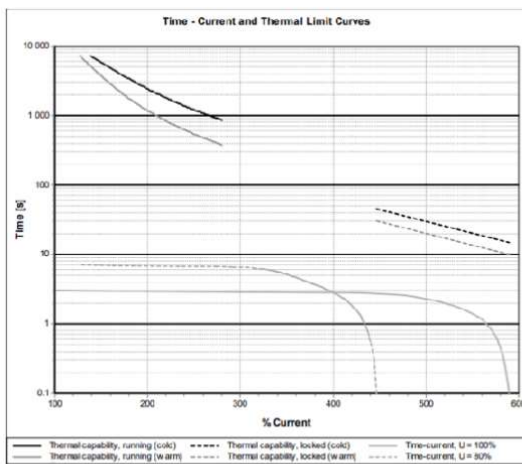


This means that even when the base current is slightly below the pick-up value, thermal protection may still eventually trip if the negative sequence current is present, or if the installation altitude is above 1,000 km, or if the ambient temperature is higher than the normal rated temperature. This, of course, assumes that the relay is otherwise appropriately configured.

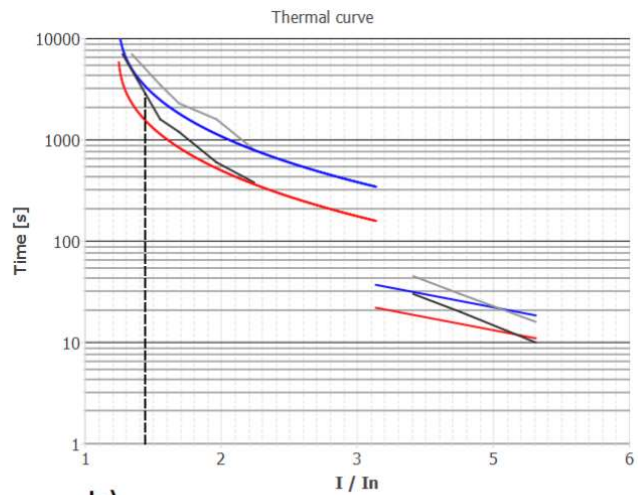
In Arcteq-brand relays the installation altitude is configured separately in the Thermal Wizard. The relay's installation altitude and the outside temperature together determine the actual ambient temperature which is then considered in addition to the relay's measured current. The Wizard also calculates the ambient effect just in case it is needed for commissioning.

As can be seen in Figure 3-2 below (specifically, Graph B), the Wizard setting tool makes it much easier to configure a motor thermal curve replica into a relay. Arcteq's I<sup>2</sup> curve setting for motor thermal relay can be set very accurately when the Wizard tool is properly used.

Figure 3-2. A) The thermal characteristic curves of an ABB induction motor, as provided by the motor's datasheet. B) Arcteq's motor thermal relay has a built-in artificial intelligence that allows the thermal replica of the relay to operate very closely like the motor's actual curve, even in the most complicated applications.



a)

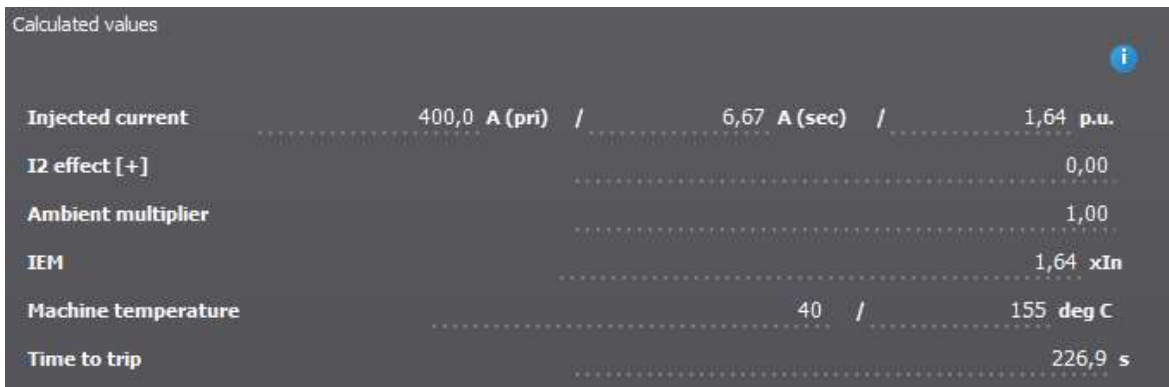


b)

## 4 COMMISSIONING

The Thermal Wizard makes it possible to model a more accurate curve to a relay even in highly demanding applications, thanks to the visual representation of the curve that the tool provides. This is true whether using an Arcteq-brand relay or a relay by another manufacturer. The user also receives immediate feedback from the Wizard as it calculates the injected current's primary, secondary, and per-unit values. The total effect of the negative sequence current is presented separately and combined with the actual IEM (see Equation 1 discussed in the previous chapter). The ambient multiplier increases or decreases the IEM current as well. The ambient coefficient is calculated based on the given outside temperature and installation altitude. Finally, tripping time is calculated based on the given attributes along with the injected current (see Figure 4-1 below).

Figure 4-1. The time to trip is estimated in the Wizard based on the given nameplate values and the injected current.



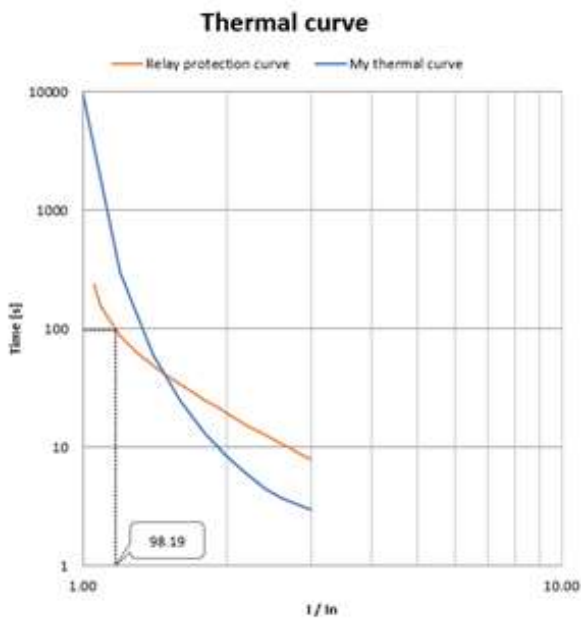
Calculated values		
Injected current	400,0 A (pri) / 6,67 A (sec) /	1,64 p.u.
I2 effect [ + ]		0,00
Ambient multiplier		1,00
IEM		1,64 xIn
Machine temperature	40 / 155 deg C	
Time to trip		226,9 s

Testing the relay's thermal curve with multiple different injection points and schemes gives a better result. It also increases the confidence towards the whole setting of the relay.

## 5 THE THERMAL REPLICA OF A WATER-COOLED SYNCHRONOUS MACHINE (ARCTEQ RELAY)

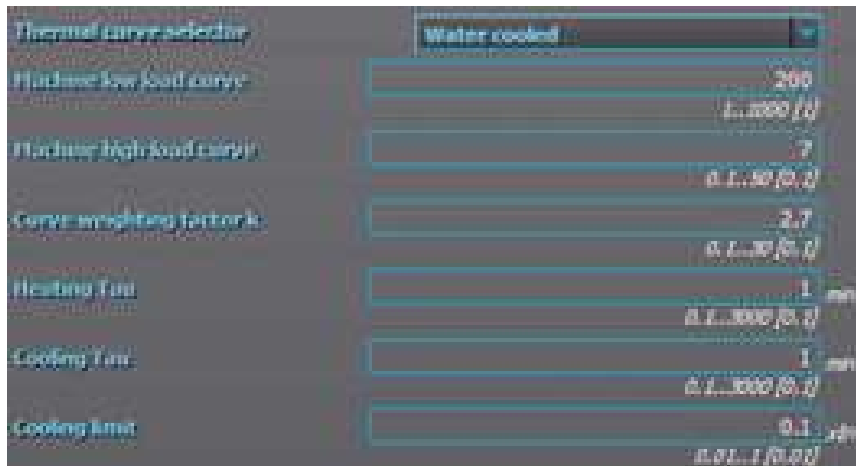
A motor's temperature can be modelled quite accurately with the square of the current ( $I^2$ ) when it comes to air-cooled motors, as was shown with Equation 2 (discussed previously in Chapter 3). However, when protecting water-cooled synchronous machines (such as generators), the situation becomes more challenging because matching the traditional  $I^2$  curve meant for air-cooled machines to the thermal curve of a water-cooled machine is nigh impossible (see Figure 5-1 below).

Figure 5-1. Protecting a water-cooled engine may prove difficult when using traditional protection methods.



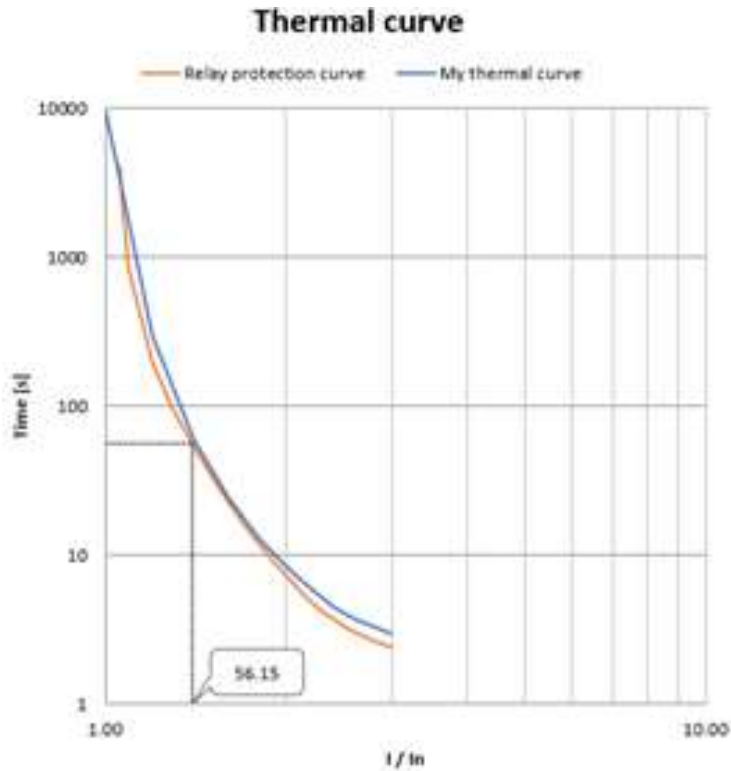
Instead of trying to force the traditional  $I^2$  replica, a new method has been developed to protect synchronous water-cooled machines during overload situations. This new method is called Curve-X and it can be selected either directly in the relay settings, or by using the Thermal Wizard tool.

Figure 5-2. Settings of a water-cooled engine.



When a water-cooled thermal curve is used and both the heating and the cooling time constants are set, the actual thermal curve is adjusted according to the values in the following parameters: *Machine low load curve*, *Machine high load curve*, and *Curve weighting factor* (see Figure 5-2 above).

Figure 5-3. Protecting a water-cooled generator with the new Curve-X algorithm.



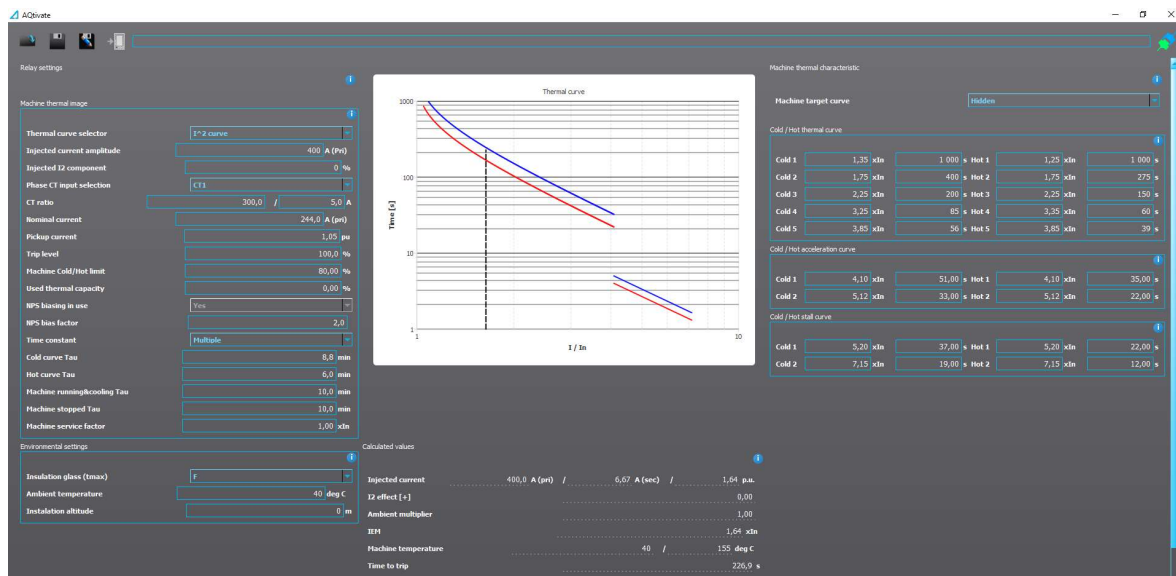
Curve-X method makes it possible to protect a water-cooled synchronous generator far more accurately than trying to build a thermal replica with the I<sup>2</sup> logarithmic calculation meant for air-cooled machines (see Figure 5-3 above). Once the user is satisfied with the adjusted curve, it can be written into the relay with the click of a single button after a connection has been established via one of the relay's Ethernet ports.

## 6 CONCLUSION

The Thermal Wizard setting tool is very useful for educational purposes, especially for learning how to operate a protection relay's more difficult protection functions, such as motor thermal protections. In general, the Wizard makes it easier to commission the I<sup>2</sup>-based thermal protection in various motor relay applications, regardless who the relay's manufacturer is. Additionally, the Wizard tool includes some new aspects that are dependent on the manufacturer, such as the artificial intelligence used to model the thermal characteristics in even the most difficult applications, but first and foremost the tool provides a thermal replica for water-cooled synchronous machines.

The Thermal Wizard also combines the effect of the measured current, its harmonic content, the negative phase sequence current, the ambient temperature, and the installation altitude of the projected object. This, therefore, gives the user a simple tool for more advanced setting and commissioning of motor protection relays.

Figure 6-1. All settings of the Thermal Wizard: on the left are the relay settings (machine thermal image settings, environmental settings); in the middle are the calculated values and the visual representation of the thermal curve; on the right are the machine thermal characteristics.



## 7 REFERENCES

- [1] ABB Ltd., *High voltage engineered induction motors – Technical catalogue*, revision M. 2021.
- [2] *Controllers, Contactors and Overload Relays Rated 600 V*, NEMA ICS 2, 2000.
- [3] *Motors and Generators*, ANSI/NEMA MG-1, 2016.
- [4] Arcteq Relays Ltd., *AQ-M215 Instruction manual*, version 2.04. 2021.