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UNIVERSITY OF VAASA

Ari Orhanen

**Thermal overload protection and automated
protection relay setting value calculations for high
voltage asynchronous motors**

School of Technology and Innovations
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Tekijä:	Ari Orhanen	
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Työn ohjaaja:	DI Veikko Lehesvuo	
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TIIVISTELMÄ:

Suurjännitteiset epätahti- eli induktimoottorit ovat suosittuja teollisuuden eri prosesseissa ja sovelluksissa. Niiden suosion perustana on niiden yksinkertainen toimintatapa ja helppo muokattavuus eri käyttötarkoituksiin. Moottorikoon kasvaessa kasvaa myös moottorin toimintavarmuuden odotus. Moottorin vikaantumista johtuvia kalliita ja pitkäkestoisia prosessien seisahduksia halutaan välttää. Moottorit joutuvat kuitenkin alttiiksi useille eri häiriöille elinkaarensa aikana. Usein häiriötilanteen seurauksena moottoriin aiheutuu suurta termistä rasitusta, mikä edesauttaa moottorin eristeiden ennenaikaista vanhenemista, joka lyhentää moottorin elinikää. Moottorin mahdolliset häiriöt pyritään havaitsemiseen mahdollisimman aikaisessa vaiheessa suojaareleilla, joilla pyritään estämään moottorin vikaantumisia.

Tässä opinnäytetyössä päätavoite on automatisoida suurjännitteisten epätahtimoottoreiden suojaukseen tarkoitettujen suojaaleiden asetteluarvojen laskenta. Nykyisin laskenta vaatii paljon kokemusta asetteluarvojen laskennasta ja aikaa. Ratkaisuna kehitetään laskentatyökalut käyttäen Matlab:n ja Octave:n sovelluksia. Eri laskentatyökalut kehitetään eri ABB yksiköiden käyttöön. Molemmat laskentatyökalut laskevat suojaaleiden asetteluarvot automaattisesti moottorin suorituskykytietojen ja käyttäjän määrittämien arvojen perusteella. Lopuksi sovellukset tuostavat suojaaleen asetteluarvot valmiille raporttipohjalle.

Lisäksi tässä opinnäytetyössä tutkitaan, miten ABB:n moottorisuojaaleiden moottorin termistä ylikuormitussuojausta voitaisiin parantaa. Tutkimuksen lopputuloksena esitetään viisi eri kehitysehdotusta. Ensimmäinen ehdotus pyrkii hyödyntämään nykyistä enemmän RTD-lämpötilamittauksia ja täten tuomaan lisätoiminnallisuuksia nykyisin käytössä olevalle virtapohjaiselle moottorin termiselle ylikuormitussuojaukselle. Toinen ehdotus pyrkii ottamaan huomioon epätahtikoneen jättämän laskettaessa moottorin termistä ylikuormitusta. Kolmas ehdotus sallii suuri-inertisten kuormitusten käynnistyksen entistä paremmin muokkaamalla moottorin termisiä lämpö-
 rajakäyriä. Neljäs ehdotus tarjoaa uuden mahdollisuuden tunnistaa lukkiutuneen moottorin moottorin impedanssista käynnistystilanteessa. Viidentenä ehdotuksena on ottaa käyttöön termi-
 ninen aikavakio, joka ottaa huomioon käyvän moottorin jäähtymisen ylikuormituksen jälkeen.

AVAINSANAT: terminen ylikuormitussuojaus, suojaaleen asetteluarvojen laskenta, suurjännite, epätahtimoottori

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Author:	Ari Orhanen
Thesis title:	Thermal overload protection and automated protection relay setting value calculations for high voltage asynchronous motors
Degree:	Master of Science in Technology
Major of Subject:	Electrical Engineering
Supervisor:	Professor Timo Vekara
Instructor:	M.Sc. (Tech.) Veikko Lehesvuo
Evaluator:	M.Sc. (Tech.) Henrik Tarkkanen
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ABSTRACT:

High voltage asynchronous, i.e. induction, motors are popular in various industrial processes and applications. They are popular because of the simple operating principle and easy formability for various application requirements. As the rated power of a motor increases, so does the expectation of reliability. Thus, costly and prolonged process stoppages due to motor failure should be avoided. However, motors are exposed to many different disturbances during their lifetime. Usually, a disturbance will result in high thermal stress, resulting in damage to motor insulation and shortening motor lifetime. Potential motor disturbances are detected at the earliest possible stage by protection relays, which are used to prevent possible motor failures.

The main focus in this thesis is on automating the protection setting value calculations for high voltage asynchronous motor protection. Nowadays, the calculations require knowledge of setting value calculations and time. As a solution, calculation applications were developed using Matlab and Octave software. Different calculation applications were developed for different ABB units. The calculation applications automatically calculate the protection relay setting values by utilizing the motor performance data and user-defined values. Finally, the applications will store the calculated protection relay setting values on a ready-made report template.

Additionally, this thesis studies how to improve ABB motor protection relays' thermal overload protection. The study presents five different development proposals to improve ABB motor protection relays' motor thermal overload protection model. The first proposal seeks to take advantage of the RTD measurements and bring additional functionality to the current-based thermal overload protection. The second proposal aims to consider the asynchronous machine's slip when calculating the rotor's thermal overload. The third proposal allows starting high inertial loads better by modifying the motor's thermal limit curves. The fourth proposal is to provide a new opportunity to identify a locked-rotor situation during motor start-up from the motor's impedance. The fifth proposal introduces a fourth thermal time constant that considers the motor cooling after overloading the situation when the motor is still running.

KEYWORDS: thermal overload protection, protection relay setting value calculations, high voltage, asynchronous motor

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Symbols, Abbreviations and Terms

Greek symbols

θ	thermal capacity
θ_A	hotspot thermal capacity
θ_B	long-term thermal capacity
θ_{Stop}	initial thermal capacity when cooling begins
τ_{th}	thermal time constant
τ_{normal}	thermal time constant normal
τ_r	rotor thermal time constant
τ_{start}	thermal time constant start
τ_{stop}	thermal time constant stop

Other symbols

C_{th}	thermal capacitance
I	true RMS value of the measured max of phase current
I_2	measured negative sequence current
I_p	a long time prior load before overloading
I_{p2}	prior load NPS component
I_r	current reference, FLC or internal FLC
I_{start}	motor start current
I_{LR}	maximum permitted locked-rotor current
jX_m	shunt exciting impedance
jX_s	stator leakage reactance at rated frequency
jX_r	rotor leakage reactance at rated frequency
k	overload factor
k_r	rotor overload factor
K_2	negative sequence factor
n_c	number of cold starts
n_w	number of warm starts
ρ	weighting factor
R	resistance
R_r	rotor resistance
R_s	stator resistance
R_{th}	thermal resistance
RTD_{center}	RTD thermal capacity used at RTD Bias center
RTD_{TCU}	RTD thermal capacity
s	slip
t	time
t_{LR}	maximum permitted locked-rotor time
t_{start}	motor starting time

T	temperature
T_{actual}	current temperature of the hottest stator RTD
T_{amb}	ambient temperature
T_{max}	RTD Bias maximum setting
T_{min}	RTD Bias minimum setting
U_{TRIP}	Maximum motor temperature defined by motor manufactures

Abbreviations

ABB	ASEA Brown Boveri
AC	alternating current
ANSI	American National Standards Institute
CB	circuit breaker
CT	current transformer
DOL	direct-on-line
DT	definite time
EPRI	Electric Power Research Institute
FLC	full-load current
GE	General Electric
GUI	graphical user interface
HVAC	heating, ventilation, and air conditioning
IDMT	inverse definite minimum time
IEC	International Electrotechnical Commission
IEEE	Institution of Electrical and Electronics Engineers
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NPS	negative phase sequence
RMF	rotating magnetic field
RMS	root-mean-square
RTD	resistance temperature detector
SEL	Schweitzer Engineering Laboratories
SF	service factor (NEMA)
TCU	thermal capacity used
TD	time dial
VT	voltage transformer

Terms

Adiabatic motor starting is a process where heat is not exchanged between the motor and ambient. All the heat generated during starting is stored in different parts of the motor.

Cold curve is a characteristic curve applied in thermal electric relays. It presents the relationship between operation time and current. Steady-state conditions with a no-load current before overload is used as a reference. (International Electrotechnical Commission, 2013, p. 7).

Diabatic motor operation (Non-adiabatic process) is a process where heat is exchanged between the motor and ambient. Motor releases stored heat from parts when a motor is operated near rated current or below.

Factor k is a multiplier used in the IEC standard to obtain the maximum permissible continuous operating current and allow equipment to be thermally protected (International Electrotechnical Commission, 2013, p. 7). It is also known as an overload factor.

High-inertia load is a load that has a moment of inertia that passes typical values. Motors are designed to accelerate the load to operation speed and still have thermal and mechanical capacity under designed limits. (IEEE, 2013, p. 5).

High voltage motor has three-phase AC RMS voltage between 1 kV and 35 kV (International Electrotechnical Commission, 2009).

Hot curve (Warm curve) is a characteristic curve applied in thermal electric relays. It presents the relationship between operation time and current. The thermal effect in a steady-state situation with a specified load current before overload is used as a reference. (International Electrotechnical Commission, 2013, p. 7).

Operation temperature is a motor temperature, which it will reach when run at full-load under normal cooling conditions.

Service factor (SF) is a multiplier to rated horsepower. It defines a permissible horsepower loading under conditions that are defined for service factor. For example, a motor with SF 1.15 can operate with a temperature 10 K higher than a motor with SF 1.1. (IEEE, 2013, p. 6 and Siemens AG, 2006, p. 18).

Thermal aging means that over time, the (insulation) material loses its capacity resist thermal resistance. Every 8–10 K rise in temperature accelerates aging with factor 2.

Thermal conduction is heat transfer between different temperatures inside a material. Heat transfer can also take place between different materials that are contacting each other. Conduction contains two different heat transfer mechanisms, with the interaction between molecules or change of free electrons. Different materials have different thermal conductivity. For example, pure metals have good conductivity. (Pyrhönen, Jokinen, & Hrabovcová, 2014, pp. 534–535).

Thermal convection, heat transfer happens with the help of moving fluid and air. A region with a higher temperature has warmer molecules, which displace the cooler molecules in moving fluid and air. (Pyrhönen et al., 2014, pp. 541–542).

Thermal class defines the maximum allowed heat rise for insulation before insulation damage occurs.

Thermal limit curve (cold) defines the maximum allowed time vs. current percentage when a motor is started from the rated ambient temperature. (IEEE, 2013, p. 7).

Thermal limit curve (hot) defines the maximum allowed time vs percentage of the current when a motor is started from rated operation temperature. (IEEE, 2013, p. 7).

Thermal radiation is electromagnetic radiation. The wavelength varies from visible light to the long wavelength of ultraviolet radiation. Heat is transferred via particle or energy from a radiation source to the surrounding or object. (Pyrhönen et al., 2014, p. 538 and Anderson, 1999, p. 773).

Thermal time constant presents time required for the protected equipment to reach $1 - 1/e \approx 63.2\%$ of its final temperature. Respectively, it can present the time required for protected equipment to cool down to $1/e \approx 36.8\%$ of its final temperature. (International Electrotechnical Commission, 2013, p. 8).

1 Introduction

High voltage asynchronous motors are popular in various industrial processes and applications. Especially squirrel-cage motors are popular because of their simple operating principle and easy formability for different application requirements. As the size of the motor increases, so does the expectation of reliability. High voltage asynchronous motors are quite expensive, but a process stop caused by the faulty motor can be significantly more costly. Thus, prolonged and costly process stoppages due to motor failure should be avoided. However, motors are exposed to many different disturbances and stresses during their lifetime. Usually, a motor's fault will result in high thermal stress, resulting in damage to the motor insulation and thus shortening the motor lifetime.

Potential motor faults are detected at the earliest possible stage by protection relays. Protection relays protect a motor by disconnecting it from a grid as disturbances occur to minimize motor damages. However, protection relays should not operate in the normal operating stage. Protection setting parameters for the protection relay needs to be calculated based on motor and system requirements. Protection setting value calculating process can be time-consuming and requires lots of knowledge.

As a solution, this protection setting value calculation is automated by using Matlab and Octave software. Two calculation applications are developed for different ABB units. Different units have different requirements and preferences for software. The calculation applications automatically calculate the protection relay setting values by utilizing the motor performance data and user-defined values. When the calculation applications have calculated protection setting values for motor, the applications will store the calculated protection relay setting values on a ready-made report template.

Additionally, this thesis studies how to improve ABB motor protection relays' thermal over-load protection. This is accomplished by comparing protection methods used by a few protection relay manufacturers. Different protection relay manufacturers implement motor thermal protection in slightly different ways. The main focus in the

comparison will be on the protection functionalities that are not available in ABB motor protection relays as stand-alone protection functions.

1.1 Research questions

High voltage asynchronous motors are exposed to many different disturbances during their lifetime. Many of those cause thermal overload. The question is how asynchronous motor should be protected against those thermal overloads? The answer might not be exact as different protection relay manufacturers adopt motor thermal overload protection in slightly different ways.

Nowadays, the protection relay setting value calculation for high voltage asynchronous motor requires a lot of knowledge and time. This allows an investigation if this setting calculation can be simplified and automated? Could ABB motor protection relays' thermal overload protection be improved, with the collected information in this thesis?

The following listed research questions are answered in this thesis:

- How should asynchronous motors be protected against thermal overload?
- How different protection relay manufacturers adopt high voltage asynchronous motor thermal overload protection?
- How to automate the protection setting value calculation for ABB motor protection relays?
- Is there a way to improve the motor thermal overload protection in ABB motor protection relays?

1.2 Structure of the thesis and research plan

This thesis contains four topics. The first topic contains a literature review on the basics of asynchronous motor protection theory. The theory begins with an introduction to asynchronous motors and protection systems. Fundamentals of asynchronous motor protection are studied. Further, it is discussed what should be accomplished with

protection and what motor information is available for motor protection? The focus is on motor thermal behavior and thermal protection, including motor starting, locked-rotor and overloading situations. Additionally, other typical protections and settings are introduced as knowledge is needed in the applications that automatically calculate the protection setting values.

The second topic of the thesis contains a comparison of different protection relays manufacturers' ways of adopting motor thermal protection. The way how different protection relay manufacturers adopt the motor thermal protection varies with used protection functions and techniques. Then ABB motor protection relays are introduced together with typical motor protection functions.

The third topic contains the development of two versions of automated motor protection setting calculation applications in Matlab and Octave. The Matlab version allows users to enter and modify motor data and manage protection calculations manually, as it is designed for the customer support of the ABB Distribution Solutions. They will use a standalone executable (.exe file) compiled from the Matlab code. The Octave version automatically retrieves motor data from the motor manufacturer's database. It does not allow users to manage protection calculations.

The fourth topic contains proposals to improve ABB motor thermal protection relays. Five different improvements are introduced. The improvements are based on comparison of different protection relay manufacturers' products. The focus of the improvements is on protection functionalities that are not available as stand-alone protection functions in ABB motor protection relays.

2 Basics

High voltage motors and protection systems include different apparatus and operation principles. This chapter contains basics related to this thesis and the setting calculation applications.

2.1 Asynchronous motors

An asynchronous motor is an alternating current (AC) electric motor, which is also known as an induction motor. Induction motor is a more popular name in spoken language. The induction motor also describes the operation principle of the motor. The energy from stator windings is fed to rotor windings with the help of induction. Asynchronous motors can be classified into two groups depending on the used rotor type. The rotor types are a wound rotor and a squirrel-cage rotor. The asynchronous motor structure, operation principle, heat management and typical faults are described in the next sections.

2.1.1 Construction

An asynchronous motor consists of two main electrical parts: the stator and the rotor. The stator core is a stationary part and it is housed inside a metal motor frame. The rotor is the moving part and it is connected to the shaft. The rotor and the stator are separated from each other with bearings and an air gap. The other parts of the squirrel-cage asynchronous motor are shown in Figure 1.

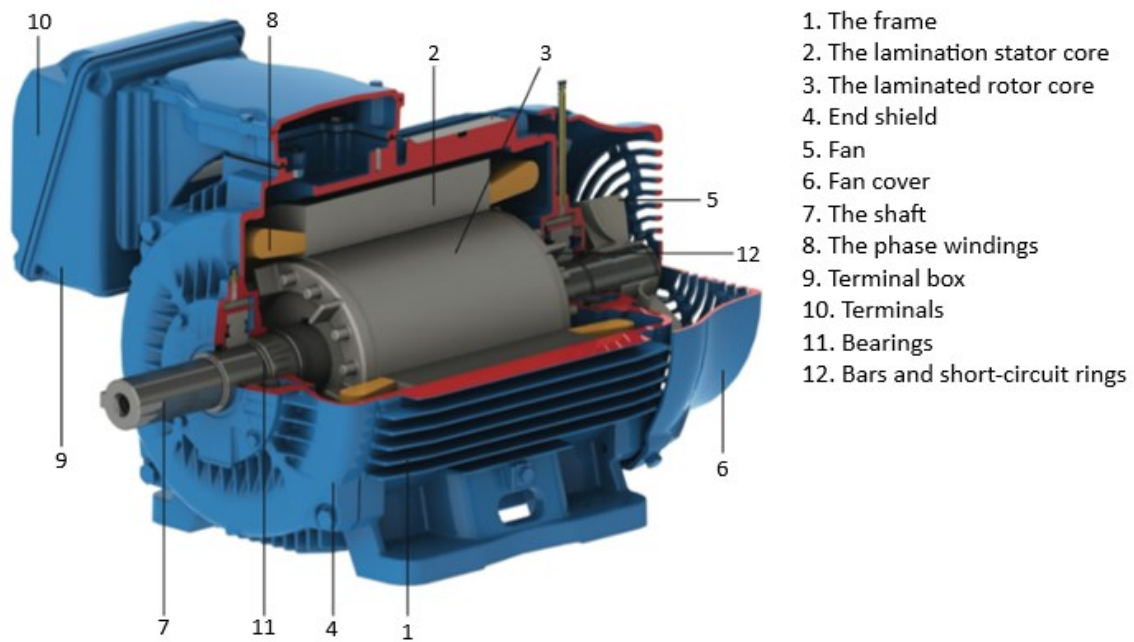


Figure 1. Cross-section of an asynchronous motor (WEG, 2020, p. 13).

The stator's cylindrical magnetic core is made of thin electrical laminated steel plates. The stator core has slots for placing conductors for stator windings. The conductors are made of copper or aluminum. The coils are isolated from the stator core slot walls. (Ong, 1998, pp. 167–168).

There are two types of rotors used in three-phase asynchronous motors, a squirrel cage rotor and a slip ring motor, which is also known as a wound rotor motor. Different rotor types are shown in Figure 2.

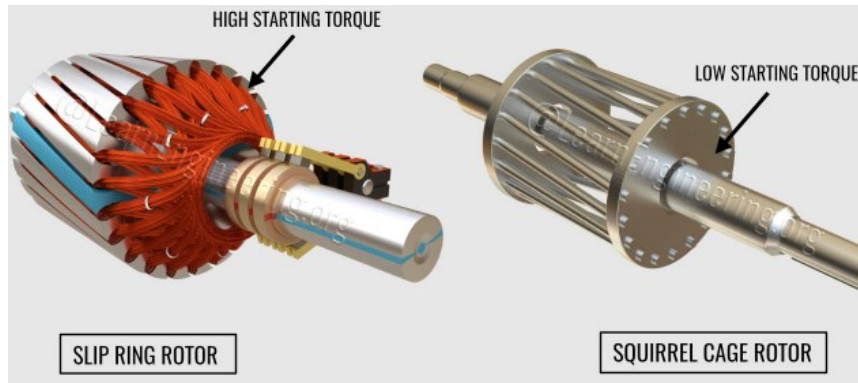


Figure 2. Different asynchronous rotor types, a slip ring rotor and squirrel cage rotor (Baradkar, 2019).

The squirrel cage rotor name describes its construction. It is a cage made with axial bars that are made from copper alloy. The bars are then connected to end-rings on both ends. The end rings are known as short-circuited rings. The cylindrical rotor solid core is made of electrical steel laminations. In a slip ring rotor, the rotor conductors are similar to the stator windings. The conductors are housed in the slots in the laminated core. The conductors are then connected to slip rings or brushes in the same shaft. The slip rings can be connected to an external resistance, which allows obtaining a high torque throughout starting or limited control of the rotor speed. This high starting torque can be seen in Figure 3, where created torque during motor starting with a squirrel cage rotor and a slip ring rotor is shown. (Ong, 1998, p. 168).

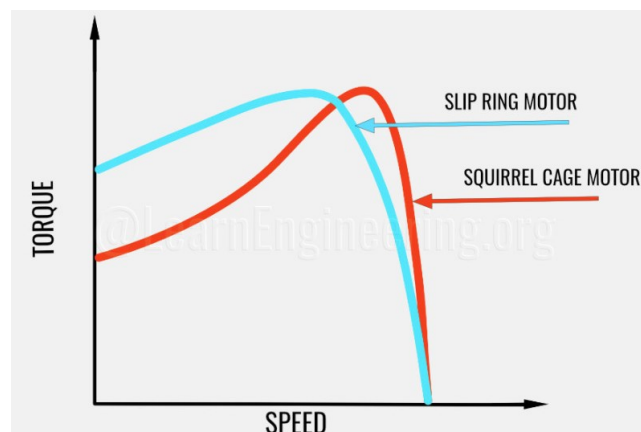


Figure 3. Torque and speed for slip ring motor and squirrel cage motor (Baradkar, 2019).

2.1.2 Operation principle

The electrical motor operation is based on an interaction between the magnetic fields and the currents flowing in the windings or the rotor bars. This basic operation principle applies to every electrical motor. The different motor types and operation modes are separated from each other based on construction, connections, and how voltages and currents are fed to a motor. (Pyrhönen et al., p. 48).

In asynchronous motors, the operating voltage is applied to stator windings via terminals. Applied voltage creates a rotating magnetic field (RMF) to stator windings. The stator windings then both magnetize the motor and induces the operating voltages. Voltages are then induced in the rotor windings or the bars, which then creates currents in rotor bars. Rotor currents then create rotor fluxes, which interact with stator RMF producing torque. (Pyrhönen et al., 2014, pp. 48–49).

Slip is also an essential factor for the operation of asynchronous motors. Slip is defined as the difference between synchronous speed and operating speed. In asynchronous machines, RMF in stator windings rotates at synchronous speed, and the rotor rotates at operating speed. This difference between stator and rotor rotating speed is called to slip. The value for a slip can be given in per unit or percentages. The slip value varies between different motor operation stages, as rotor speed varies between different stages. When a rotor is not rotating, i.e. during the beginning of motor starting, the slip has a high value. Respectively, the rotor is rotating close to the stator's speed, i.e. when a motor is operating normally, the slip is only a few percentages. The asynchronous motor cannot produce torque if there is no slip present, i.e. when the stator and rotor rotate at synchronous speed. Rotating at synchronous speed means that there is no voltage difference between the stator field and rotor bars. If the voltage difference is not present, RMF cannot produce currents to rotor bars.

Traditionally, asynchronous motors are started with direct-on-line (DOL). This means that motor self-starts when full line voltage is applied directly to the stator windings. However,

this starting is very stressful for a motor and a grid. The DOL starting causes a high starting current, which causes thermal stress for a motor. The DOL starting also may cause a 10–20 % reduced voltage to a grid during a motor starting. Different starting methods are used to reduce the stress and voltage drop caused by this motor starting method. ABB Motors and Generators (2010) has listed more different starting methods shown in Appendix 1. Technical note, Starting methods for AC motors.

2.2 Synchronous motors

Synchronous motor's rotor rotates at the same speed as the stator winding RMF is rotating. Synchronous motors differ from asynchronous motors in how the rotor is magnetized. The rotor in a synchronous motor can be magnetized using direct current or by using permanent magnets. When the rotor is magnetized using these methods, there is no need to use air-gap flux to magnetize it and this allows the asynchronous motor to operate without a slip. However, some large synchronous motors need to utilize a slip during motor starting, as they cannot be started to synchronous speed. Those rotors have embedded squirrel-cage damper winding to allow synchronous motor acts as an asynchronous motor during starting. The stator construction and operation are similar in both motor types. Synchronous motors are popular in applications where high power and efficiency are needed as synchronous motors have little better efficiency than asynchronous motors. (Pyrhönen et al., 2014, pp. 388–389).

The developed application can be used also for synchronous motors, excluding that the first version does not yet support the additional protection functions required for synchronous motors.

2.3 Motor protection system

Motor protection relay systems are ensembled from different devices, such as circuit breakers, protection relays, and measuring transformers and sensors. The protection relays' role is to detect faults and quickly and reliably isolate the fault location by opening

the circuit breaker. Protection relays need instrument transformers to measure currents, voltages and frequency. For temperature measurement, some kind of temperature measurement sensor is required. An example of a motor protection system is shown in Figure 4, when the motor will locate in the corresponding location that array indicates. The different techniques and devices are explained in the next sections.

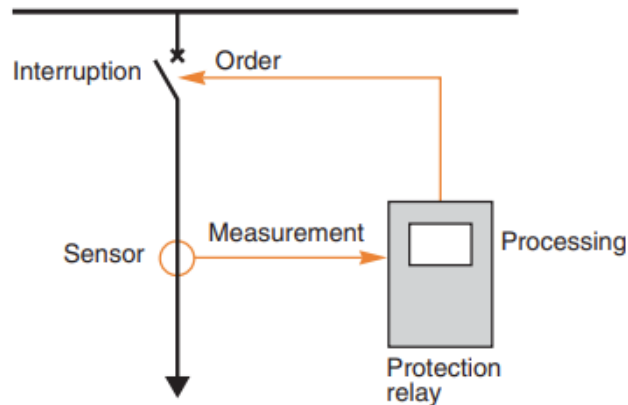


Figure 4. Example of a protection system (Schneider Electric, 2003).

2.3.1 Protection relays

Modern numerical protection relays are compact microprocessor-based devices used in power systems applications to detect unwanted behavior. Protection relays are designed using criteria that describe and shape the primary aims of protection (Blackburn and Domin, 2007, p. 49):

- *Reliability* is a promise that protection works as designed.
- *Selectivity* is to ensure that a system functions with minimum system disconnections.
- *Speed of operation* should be at least for fault duration, ensuing equipment damage and system instability.
- *Simplicity* is to less effort to archive the best protection.
- *Economics* means that best performance with minimum cost.

Protection relay accuracy is also an important quality factor affecting protection relay performance. Standard IEC 60255-1 (Measuring relays and protection, Common requirements) defines protection relay accuracy in three parts: intrinsic accuracy, operation accuracy and overall system accuracy. Intrinsic accuracy defines how well relay accuracy performs compared to reference conditions. Operation accuracy includes intrinsic accuracy and variation due to influence quantities. Overall system accuracy includes operation accuracy and external accuracies affecting performance, i.e., measuring wire impedance and sensor accuracy. Typical relay accuracy tolerance is about 10 %. Standard IEC 60255-1 also defines measurements and formulas for calculating accuracies. (International Electrotechnical Commission, 2009, pp. 40–41 and IEEE, 2013, p. 110).

The basic operation principle is similar in all modern numerical protection relays. Protection relay measures currents and/or voltages from protected systems' primary circuit via CTs (current transformers) and VTs (voltage transformers). Measurements are then connected to relay inputs from the secondary circuit. Relay internal logic handles signal conditioning and converting. The microprocessor calculates protected system status by using numeric data converted from signals. Depending on relay settings, the relay will activate digital outputs and trip and alarm relays, based on calculated system status and relay internal logic and settings. This protection relay internal operation principle can be described as an internal relay block diagram. A simplified version of a modern relay internal block diagram is shown in Figure 5.

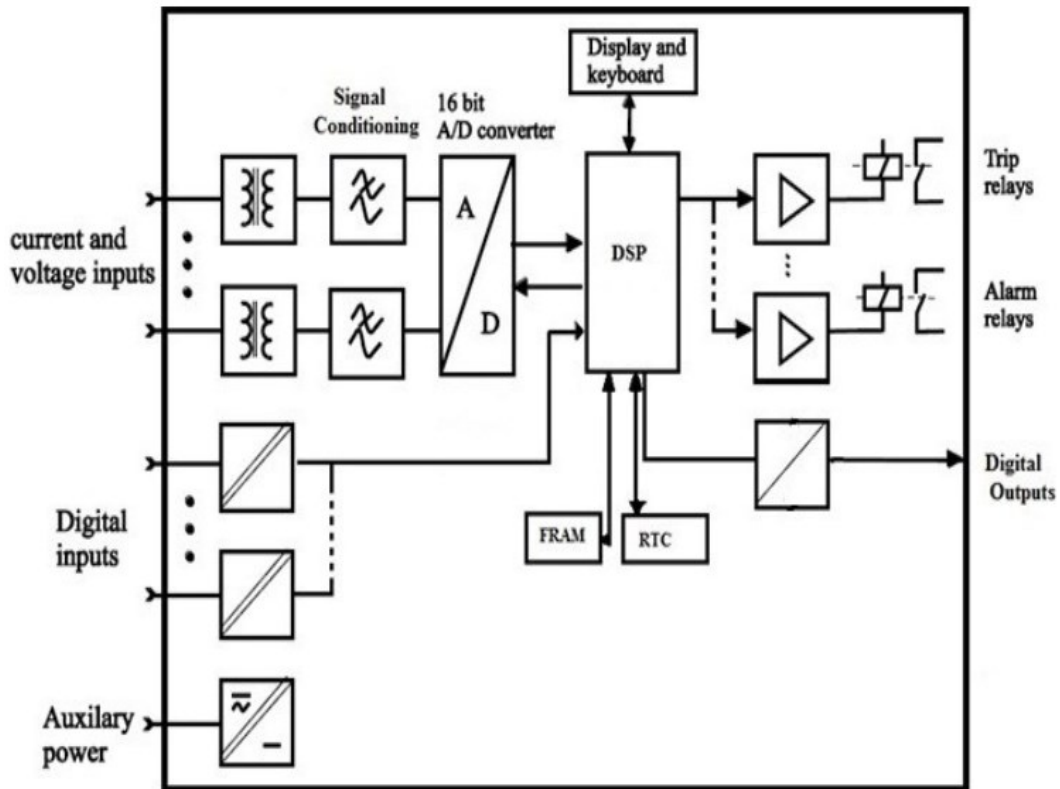


Figure 5. Example architecture of protection relay (Kullkarni and Ugale, 2015, p. 2).

Different applications, such as motors, generators, feeders and transformers, have additional protection relays requirements. Therefore, relays are tailored for various applications. This means that protection relay can have different protection functions and a number of inputs and outputs. Usually, the same manufacturer's protection relays use the same hardware design and software platform for various applications.

2.3.2 Instrument transformers

Instrument transformers are used to isolate an electronic apparatus from high voltage. They should have a reasonable isolation level and current carrying capacity for relays and other measurement apparatus. Typically, rated secondary values for current, voltage and frequency are 5 or 1 A, 100, 110 or 120 V, 50 or 60 Hz. (Elmore, 1994, p. 73).

Current transformer performance is critical for protection relays. Relays can, at maximum, be as accurate as the information fed to them. Current transformer performance

is measured by how well it can reproduce the primary current in secondary without saturation or large errors. In IEC, current transformers are divided into two classes: protection and measurement classes. The protection class of instrument transformers is marked with a letter P. IEC defines maximum combined error accuracy to 5 or 10 % for protection class. The combined error contains errors from current amplitude and angle. In ANSI/IEEE, there are two standard accuracy classes for current transformers: class T and class C. In class T, the accuracy ratio is determined from a manufacturer's test curve and the accuracy is not easy to calculate. In class C, the accuracy ratio can be calculated. ANSI/IEEE defines ratio correction error to a maximum of 10 %. The error value should not be exceeded at any current from 1 to 20 times the rated secondary current. (Elmore, 1994, pp. 73, 74 and 79; Blackburn & Domin, 2007, p. 168).

Sensor technology (Rogowski coil and voltage dividers) are nowadays used in addition to traditional CTs and VTs. They have several advantages compared to conventional CTs and VTs. For example, they do not saturate and have higher accuracy.

2.3.3 Temperature measurement

Thermocouples, thermistors, or temperature detectors are used to obtain temperature information. One typical temperature detector is called a resistance temperature detector (RTD). RTD is a temperature sensor in which resistance change depends on temperature, i.e. RTD can be used in temperature measuring the RTD sensor's resistance. (Beamex, 2020).

One typical RTD temperature sensor used for stator temperature measurement is a platinum-based Pt100 sensor. The number indicates the resistance at 0°C. The Pt100 accuracy is relatively good. For best accuracy classes, the accuracy tolerance is below 0.5 °C in the range of -50 °C to 250 °C. The accuracy depends on the purity of the platinum. Nowadays, there is no problem with getting very pure platinum. (Beamex, 2020).

3 Fundamentals of asynchronous motor thermal protection

In this chapter, different factors affecting motor protection and designing motor protection are described. The chapter starts with an introduction to motor protection. When developing motor protection, it is good to know what kind of information motor manufacturers provide, so motor manufacturers' motor data are also discussed. Motor thermal protection has a central role in this chapter, as most motor hazards are caused due to a motor heating up. The hazards that cause heating are too frequent starting, overloading, cooling problems and supply voltage problems like undervoltage or unbalanced voltages. It is also discussed how motor thermal protection should be applied to avoid damage caused by heat. Finally, at the end of this chapter, typical motor protection functions are described.

3.1 Introduction to motor protection

High voltage motors are highly customized, and much engineering work is done to get an optimal performance to fill the operation requirements. Motors are also used in many different applications and processes, where motor operation demands vary. Every motor is unique, which creates challenges when designing protection for the motor. Motor protection is poorly standardized. ANSI/IEEE has few standards for setting protection. The first one is called (IEEE Std C37.96 IEEE guide for AC motor protection). The second one is called (3004.8-2016 - IEEE Recommended Practice for Motor Protection in Industrial and Commercial Power Systems). IEC also has a couple of standards referring to motor protection. Standard IEC 60255 (Measuring relays and protection equipment) is meant for measuring relays and protection equipment. Whereas standard IEC 60034 part 11 (Rotating electrical machines, Thermal protection) is for thermal protection.

When designing motor protection, the principle is that possible hazards and faults can be detected in the motor before fatal motor failure or accident. Different kinds of manufacturing, assembly or design errors can cause hazards and faults. Furthermore, designed motor protection should not be limiting a motor's normal operation.

A study has shown that the typical annual failure rate of high voltage induction motors is about 3–5 % per year, and in the pulp and paper industry, the annual failure rate can be up to 12 % (Venkataraman, et al., 2005, p. 127). IEEE and EPRI have surveyed motor reliability and major causes of motor failures. The survey results are shown in Appendix 2 called Summary of IEEE and EPRI Motor Reliability Surveys. The motor failures are divided into three different groups: 1. electrical related failures, 2. mechanical associated failures, and 3. environmental, maintenance & other reasons related to failures. Each of the groups presents about one-third of the average failures.

Different typical hazards should be covered when motor protection is designed. Elmore (1994, p. 129) has listed a potential hazard that should be detected in asynchronous motor protection:

1. Phase and earth-faults detection for detecting faults in the windings or associated feeder circuits.
2. Excessive thermal overloads. Continuous or intermittent overload or a locked-rotor condition (motor jamming or failure to start) can cause thermal damage.
3. Reduction or loss of supply voltage can directly affect the applied torque of the connected mechanical load.
4. Phase reversal can be dangerous for the load if the motor is started in the wrong direction.
5. Phase unbalance, as it can create a significant rise in motor temperature.

3.2 Motor data provided by motor manufacturers

Motor manufacturers provide technical information with manufactured motors. The provided information can be used to calculate the protection for the motor.

The motor nameplate contains necessary information about the motor, and it also holds credentials to identify a motor. The nameplate is a metal plate and it is in the motor body. IEC and NEMA motor nameplates vary from each other, i.e., NEMA motor nameplate contains a service factor (SF). An example of a motor nameplate is shown in Figure 6.

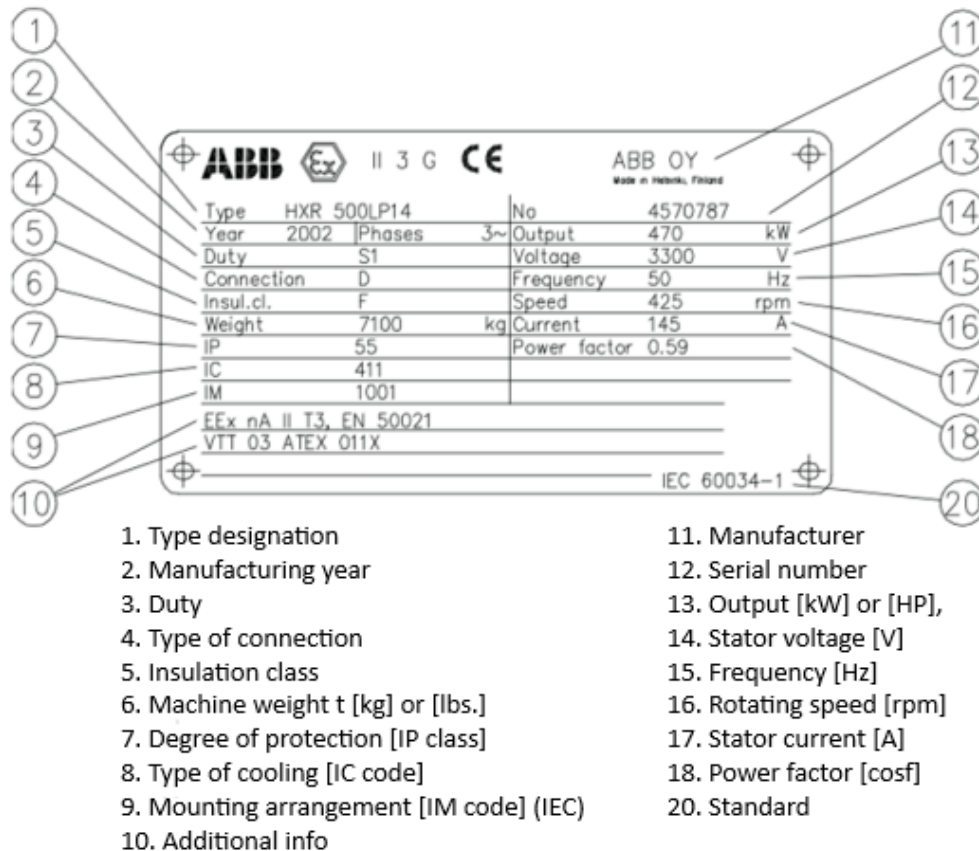


Figure 6. An example of IEC standard DOL starting motor nameplate (ABB oy Motors and Generators, 2015, pp. 20–22).

An example of ABB Motors and generators performance data of the motor is shown in Appendix 3 called Performance data of motor. The performance data is calculated during a motor design process and a motor is manufactured accordingly. The performance data contains information from basic motor data to customer-specific calculations. The basic data includes the same data shown in the motor nameplate. Still, there are also torque and current figures as a function of speed, current and thermal limit curves, and the maximum number of motor starts.

The typical maximum number of motor starts per hour or during another time period is shown. Motor heating and cooling thermal time constant for running and stopped conditions, respectively, are available. Cooling time is used in the thermal model to calculate sufficient motor cooling before new starting. When a motor thermal cooling thermal time constant is not available in motor performance data, some relays can calculate the

cooling thermal time constant with knowledge of the motor state and the temperature RTDs. (IEEE, 2013, p. 121).

3.3 Thermal protection theory

Motors are designed with certain lifetime expectations, but in the end, the actualized lifetime depends on various parameters. One factor affecting motor designed lifetime is the motor design. During design work, parameters must be optimized for starting and operation conditions. Most of the parameters are optimized generally based on experience and specifications. Different stresses, such as the mechanical, electrical and thermal stresses, should also be considered as they affect the motor lifetime expectation by degrading the properties of the insulation (Pyrhönen et al., 2014, p. 506–507). Other factors generated during operating conditions, such as radiation, dust, oil, chemicals, and moisture, will affect motor performance (Pyrhönen et al., 2014, p. 507).

When electricity is converted to mechanical energy, the conversion process generates losses that heat equipment converting the electricity. Motors can absorb a certain thermal energy level caused by copper heat losses (I^2R) and the core losses in iron parts, both in the stator and rotor windings side. Power flow and losses inside induction motors are shown in Figure 7. (Anderson, 1999, p. 772).

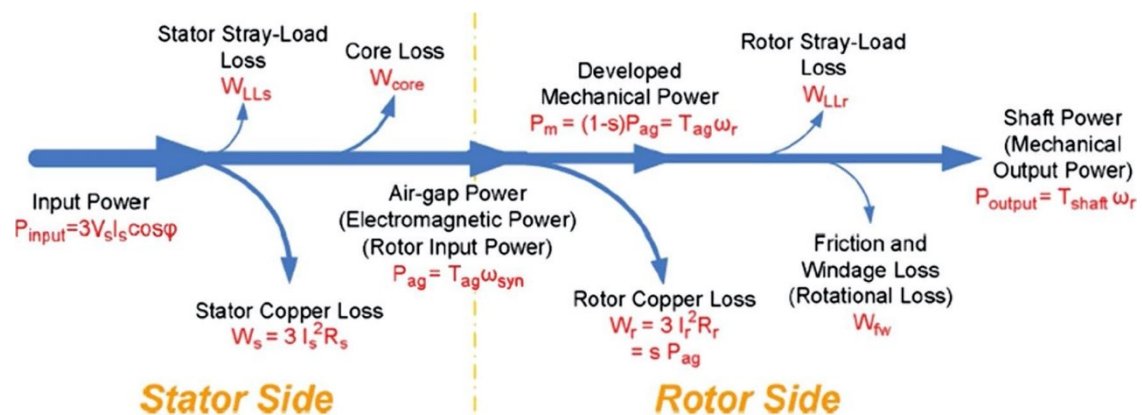


Figure 7. Power flow and losses inside induction motors (Zhang;Du;Habetler & Lu, 2010, p. 35).

The resistance values of the electrical model are the critical factors for heating effects. That is one reason why motors are usually electrically modeled. Figure 8 shows an equivalent circuit for asynchronous motor. The R_s presents stator conductor heating from the stator current, R_r presents rotor conductor heating and $(\frac{1-s}{s})R_r$ is the slip-dependent resistance converting watts to mechanical power. (IEEE, 2013, p. 128).

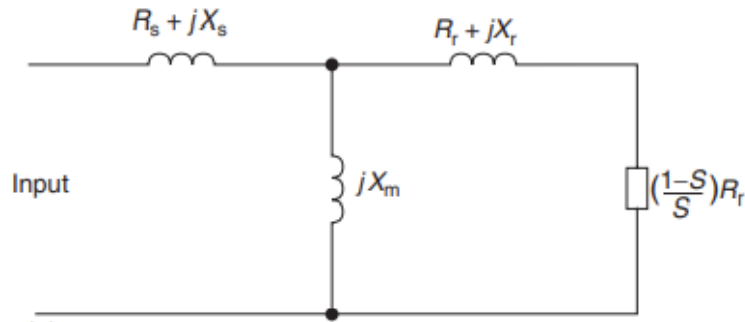


Figure 8. An equivalent circuit for asynchronous motor. R_s is stator resistance, jX_s is stator leakage reactance at rated frequency, R_r is rotor resistance, jX_r is rotor leakage reactance at rated frequency, jX_m is shunt exciting impedance and s is a slip. (Blackburn and Domin, 2007, p. 418).

Motor starting can be assumed to be an adiabatic process, where the generated heat is not exchanged between a system and ambient. During motor starting, it can be expected that all the heat generated by the starting current is stored in the motor metals, which results in a temperature rise in these metals. In the steady-state, heat is then removed by convection to the surrounding atmosphere. This process is called a non-adiabatic process, where heat is exchanged between a motor and ambient. The heat convection can be forced e.g. by blowing air through the air gap. (Anderson, 1999, pp. 772–773).

Motor thermal behavior is shown in Figure 9. The figure shows a motor thermal model. The model shows how positive ($I_1^2 R_1$) and negative sequence currents ($I_2^2 R_2$) cause motor losses). These losses cause motor heating. The generated heat is stored in a motor body and dissipated to surrounding via thermal resistance R_{th} . Motors absorb certain amount of generated heat to a motor body metals. The amount that motors can absorb heat is described as thermal capacitance C_{th} . Thermal capacity is usually given as

thermal capacity used (TCU). TCU varies between different motor states. When TCU reaches U_{TRIP} temperature defined by motor manufactures, there is no more thermal capacity left and a trip signal shall be activated. (Lebenhaft & Zeller, 2008, pp. 1–2).

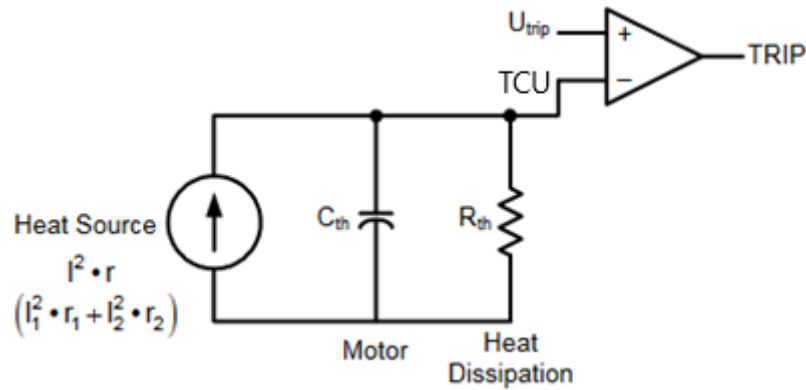


Figure 9. Motor thermal model modified from Lebenhaft and Zeller (2008, pp. 1–2). Heat sources are positive ($I_1^2 R_1$) and negative sequence currents ($I_2^2 R_2$). Absorbed thermal heat in motor body is defined as thermal capacitance C_{th} . Heat is dissipated to surrounding via thermal resistance R_{th} . Trip signal shall be activated if TCU reaches maximum motor temperature U_{TRIP} defined by motor manufacturer.

Some motor applications are more demanding for motor cooling. Standard IEC 60034 part 6 (Rotating electrical machines, Methods of cooling (IC Code)) defines the methods of cooling (IC code) and circulation of coolant in electrical machines. The most common coolants used are air and water.

Following motor operation conditions, currents will affect motor operation temperatures: starting current (locked-rotor current), magnetization current (no-load current), load current, conductor eddy currents, stray loss currents, negative-sequence currents and nonlinear loads. Abnormal voltages and frequency will affect the current magnitudes of the operation condition currents. (IEEE, 2013, p. 59).

Protection relay monitors motor status by measuring different motor variables, such as currents, voltages, frequencies, and temperatures. For example, by monitoring time-

current limit characteristics, protection relay monitors that motor thermal limits are not exceeded.

In IEC applications, standard IEC 60255 part 149 (Measuring relays and protection equipment, Functional requirements for thermal electrical relays) defines minimum requirements for thermal protection. The standard covers thermal protection functions: thermal overload protection, rotor and stator thermal overload protection. The first edition of the standard was published in 2013. The standard canceled and replaced the older IEC 60255 standard part 8 (Electrical relays, Thermal electrical relays), which was released in 1990. (International Electrotechnical Commission, 2013).

Standard IEC 60255 part 149 defines the basic frames for thermal protection functional logic. Protection relay manufacturers can implement this frame. An example of thermal protection functional logic defined in the IEC standard is shown in Figure 10.

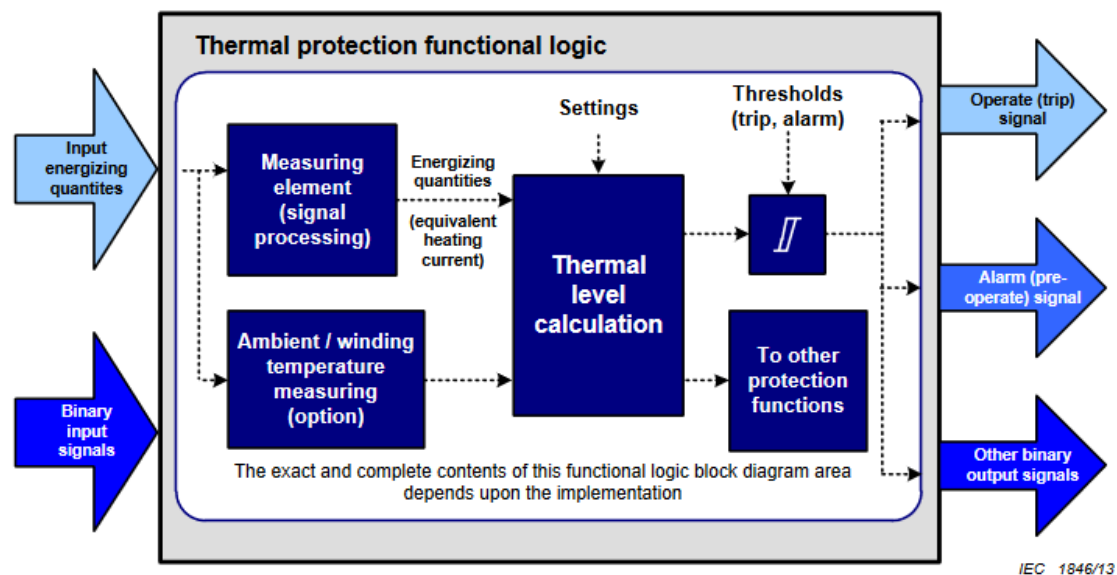


Figure 10. Simplified thermal protection function block diagram (International Electrotechnical Commission, 2013, p. 9).

In Figure 10, input energizing quantities are measured phase currents, positive and negative sequence currents, and temperature. This measured data can be utilized with a

traditional hardwire connection. Another way is using relay communication services, for example, IEC 61850 part 9-2 (Communication networks and systems for power utility automation, Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3) defines sampled measured values over ethernet interface. A binary input signal can be used to reset a functions' thermal memory or change between setting groups for different operation modes. The different operation modes can be used for two-speed motors or star/delta starting motors. (International Electrotechnical Commission, 2013, pp. 9–10).

Protection relay then calculates motor thermal level using measured data. Operation signal, alarm signal or other binary signal is activated when a motor thermal level exceeds user set limits. These limits are set to relay in settings that are based on motor data.

RTD-based measurements can be used to provide additional protection for a motor thermal protection. It allows considering inadequate ventilation or unusual ambient temperatures generated by excessive heating in stator windings. An RTD voting scheme can also be applied if multiple RTDs are available and voting can occur between RTDs measuring similar points. At least two RTDs should exceed the trip threshold. (IEEE, 2013, p. 121).

3.3.1 Thermal limit

Motors are designed to withstand a certain amount of heat rise above ambient temperature at rated load. This allowed heat rise is defined in thermal classes. IEC and NEMA/IEEE Standards define the temperature limits for electrical components. IEC specifies the maximum equipment temperature according to the equipment thermal insulation class, which is designated in standard IEC 60085 (International Electrotechnical Commission, 2013, p. 16). For example, a motor with thermal class B (130 °C) allowed heat rise above designed ambient temperature (40 °C) is 80 K. More thermal classes are shown in Table 1.

Table 1. Thermal classes of insulating materials (Pyrhönen et al., 2014, p. 498).

Thermal class	Previous designation	Hot spot allowance (°C)	Permitted design temperature rise (K) when the ambient temperature is 40 (°C)	Permitted average winding temperature determined by resistance measurement (°C)
90	Y	90		
105	A	105	60	
120	E	120	75	
130	B	130	80	120
155	F	155	100	140
180	H	180	125	165
200		200		
220		220		
250		250		

Manufacturers can design motors using a lower thermal class for temperature rise and a higher temperature class for the insulation system. For example, a motor thermal rise can be according to thermal class B (130 °C), but the insulation system is designed using thermal class F (155 °C). This creates a longer expectation of insulation life. Thermal classes are also designed so that insulation durability is at least according to its class. When the thermal class is determined, the temperature index is rounded down to the nearest thermal class. (Pyrhönen et al., 2014, p. 509).

According to the margins described earlier, motor temperature exceeding thermal limits defined in thermal classes does not cause immediate insulation failure. But it will affect expected insulation lifetime as temperature rise will increase the chemical reaction rate. A good rule of thumb is that when an operating temperature increases by 10 °C expected lifetime of stator insulation is cut in half. An example of temperature and percentages of a lifetime is shown in Figure 11. For instance, if a motor has a thermal class is B (130 °C)

and the motor is operating at 140 °C, it will halve the expected insulation lifetime. (Venkataraman, et al., 2005, p. 130).

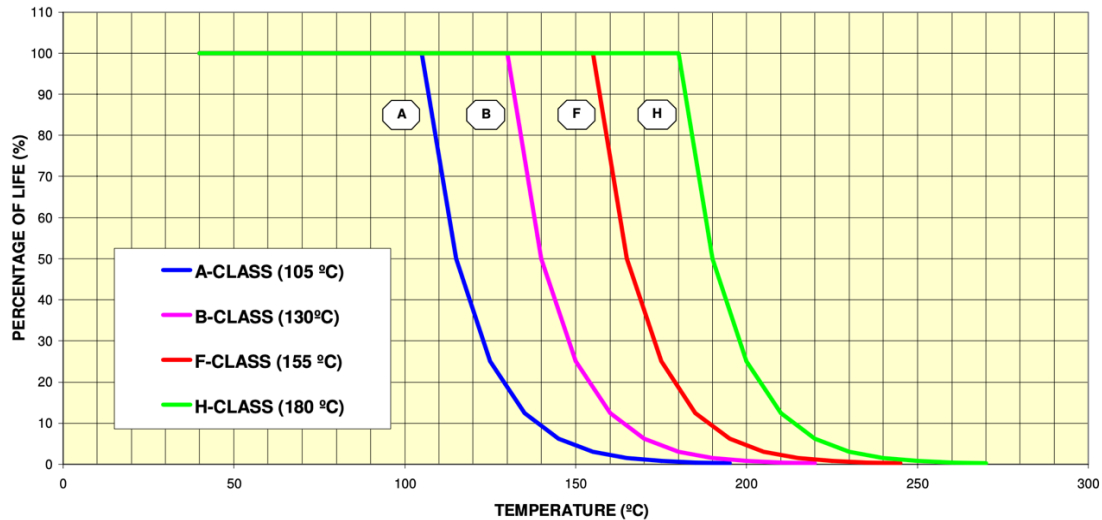


Figure 11. Influence of thermal aging on motor life (Venkataraman, et al., 2005, p. 130).

An ideal way to estimate used motor thermal capacity would be to have a direct accurate temperature measurement and use the aging factor. (Venkataraman, et al., 2005, pp. 130–131).

3.3.2 Thermal limit curves

Thermal limit curves, also known as damage curves, define the maximum permissible safe operation time versus load current for a motor operating in abnormal conditions: locked-rotor, starting and acceleration and running overload at rated operation load and initially at ambient temperature (IEEE, 1996, p. 2). They are usually delivered together with other motor performance data, but this varies between motor manufacturers. Thermal limit curves are presented in a plot where the horizontal axis contains the current value and the vertical axis has time on a logarithmic scale. They are modeled using positive sequence currents from a perfectly balanced supply voltage and motor design (International Electrotechnical Commission, 2013, p. 27). An example of thermal limit curves and motor starting currents in the same plot is presented in Figure 12.

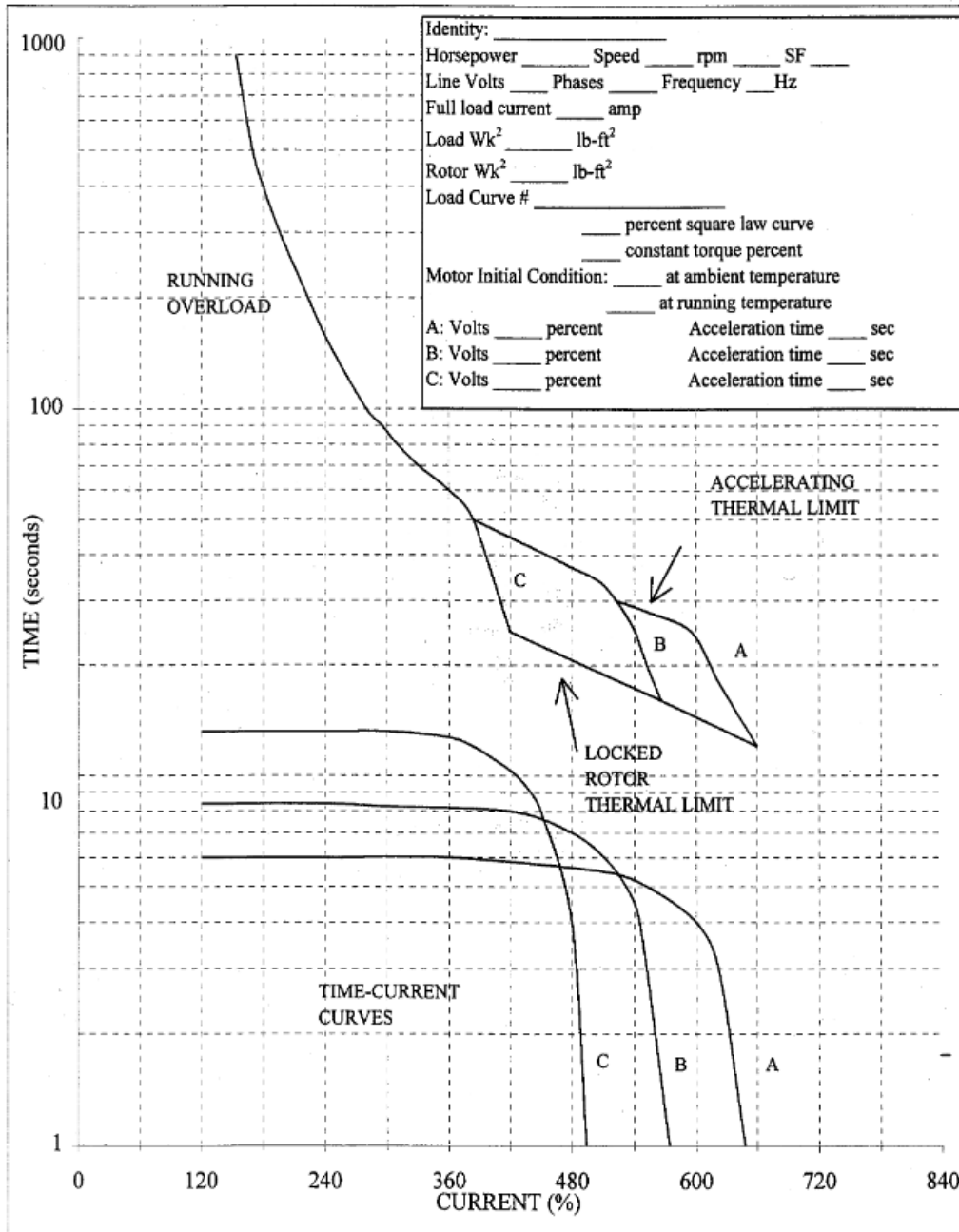


Figure 12. An example of thermal limit curves and motor starting currents (IEEE, 1996, p. 3).

Thermal limit curves contain the shortest safe time for these conditions for the windings, both stator and rotor (IEEE, 1996, p. 2). Thermal limit curves shall be available for rated ambient (cold curve) and rated operating temperature (hot start). The lower part of the motor curves are usually rotor-limited and the upper part of the motor curves are stator-limited (IEEE, 2013, p. 120). Thermal limit curves are provided for cold and hot for medium and large motors.

Locked-rotor

Under a locked-rotor situation, voltage is applied to the stator winding, but rotor speed remains at zero speed. Typically, a locked-rotor situation happens when the applied starting voltage is too low or a machine or load has mechanical malfunctioning. The locked-rotor situation usually causes a high heat rise, as the current in the winding typically is 4–8 times the rated full-load current. High current in stator winding causes high losses. The losses can be 16–64 times the rated losses at high slip. Especially, the rotor will heat up rapidly. The heat loss from the windings is by conduction and radiation. This can be very stressful for the motor as there is usually no ventilation during the locked-rotor condition. (IEEE, 1996, p. 2).

Thermal limit curves shall contain information about maximum safe locked-rotor time without damage. This safe locked-rotor time shall be presented in a curve from about 60 % of the locked-rotor current to the locked-rotor current. (IEEE, 1996, p. 4).

Stator vs. rotor critical motors

Venkataraman et al., (2005, p. 130) declare that a motor is a stator critical when a motor's voltage rating is equal or greater than ten times the motor horsepower rating. Mörsky (1992, p.181) defines it as follows: most of the motors above 15 kW are rotor critical.

Starting and acceleration

During motor starting, the motor starts to accelerate from the locked-rotor condition and the currents in the windings are 4–8 times the full-load current. The starting is stressful for the rotor as the losses are high during starting. The losses are high during high slip values as rotor resistance increases due to a skin effect. The stator and rotor losses are high during the acceleration period as values are still many times the rated values. The temperature increase in this situation is high because of the high losses. The stator and rotor windings can withstand high currents for only a short period. Otherwise, the winding temperatures reach values beyond which insulation or winding damage could occur. (IEEE, 1996, p. 2).

An example of a motor starting from a cold state is shown in Figure 13. The figure represents quite well how stressful starting is for the rotor. The rotor bars' temperature (Bar max) starts to rapidly increase after the motor is started and cooling is also fast after starting is over. The figure also shows how other temperatures develop during motor starting in the rotor slip ring (Ring max) and the stator (St Adiab).

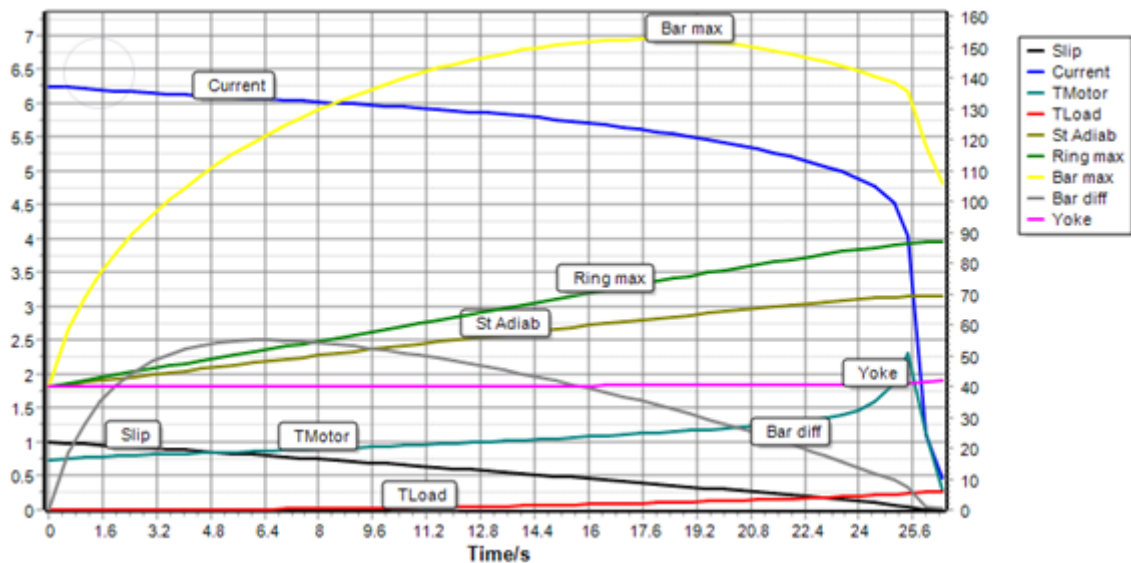


Figure 13. DOL motor starting from a cold state (Z. Kovacs, personal conversation, 30.7.2020).

Thermal limit curves shall contain information about thermal capacity available for specific current value. Available thermal capacity shall be presented in a curve from a locked-rotor current to approximately a current of the breakdown torque point. (IEEE, 1996, p. 4).

Running overload

During overload conditions, motor currents are lower compared to the start, which results in smaller losses. Depending on motor design, the motor can withstand overloads for relatively long periods. Each overload exceeding the thermal limit will cause accelerated aging in thermal insulation. (IEEE, 1996, p. 2).

Thermal limit curves shall contain about thermal capacity available during motor running overload. Available thermal capacity shall be presented in a curve from the full-load

current to approximately the current at the breakdown torque. If the motor has a service factor available, the curve shall be started from the current at service factor. (IEEE, 1996, p. 4).

Motor starting curves

Thermal limit curves shall contain a motor starting time-current curve plotted in the same graph. When the motor is designed to starting in different voltages or lower than rated voltage, the acceleration time-current curves for each voltage shall be plotted to the same thermal limit curves graph. Maximally three different voltage may be plotted in a single graph. (IEEE, 1996, p. 4).

3.3.3 Duty types and applications services

IEC categorizes motors by motor duty types. Motor duty types define how the motor shall be operated. International Electrotechnical Commission (2017, pp. 17–27) defines the following motor duty types:

- S1: Continuous running duty
- S2: Short-time duty
- S3–S8: Periodic duty
- S9: Duty with non-periodic load and speed variations
- S10: Duty with discrete constant loads and speeds.

The most popular duty type is S1. All duty types are designed to operate as duty types define. No extra overloading is suitable, except in duty type S9.

NEMA defines four different designs for motors A, B, C and D. Different designs are separated from each other with the following variables: the amount of slip, starting current, locked-rotor torque and breakdown torque. Different designs are suitable for various applications, like design A is for fans and pumps. Design B is for heating, ventilation, and air conditioning (HVAC) applications with fans, blowers, and pumps. Design C is for positive displacement pumps, conveyors, and design D for cranes and hoists.

Motors can also be classified according to application services. Some applications are essential for a power plant to operate and failure will cause significant production loss. Anderson (1999, p. 789) defines the following as essentials auxiliary motors in a power plant:

- Boiler feeder pumps
- Condensate pumps
- Forced draft fans
- Induced draft fans
- Primary air fans
- Stokers
- Circulating water pumps
- Pulverizer feeders
- Pulverizers
- Excitation drive motors.

Anderson (1999, p. 789) defines as nonessentials auxiliary motors in a power plant:

- Coal handling equipment
- Central coal pulverizers
- Clinker grinders
- Air compressors
- Coal crushers
- Conveyors
- Vent fans
- Service pump.

High inertia loads, such as induced draft fans, usually have a long starting time, which can be greater than motor safe stall time. This creates a challenge for protection to allow motor starting without exceeding safe locked-rotor time if locked-rotor protection is based on I^2t limit principle. Different techniques can be applied to start a high inertia motor. One approach is a reduced starting voltage, which will decrease the starting

current. Another solution will be using a zero-speed switch, which tells the protection relay that the motor has started to accelerate. (Venkataraman, et al., 2005, pp. 139–140).

A third method to allow high inertia motor starting is using a voltage-dependent thermal limit curve. In this method, a motor thermal limit is seen as a function of motor starting acceleration speed. Figure 14 contains an illustration of voltage-dependent thermal limit curves.

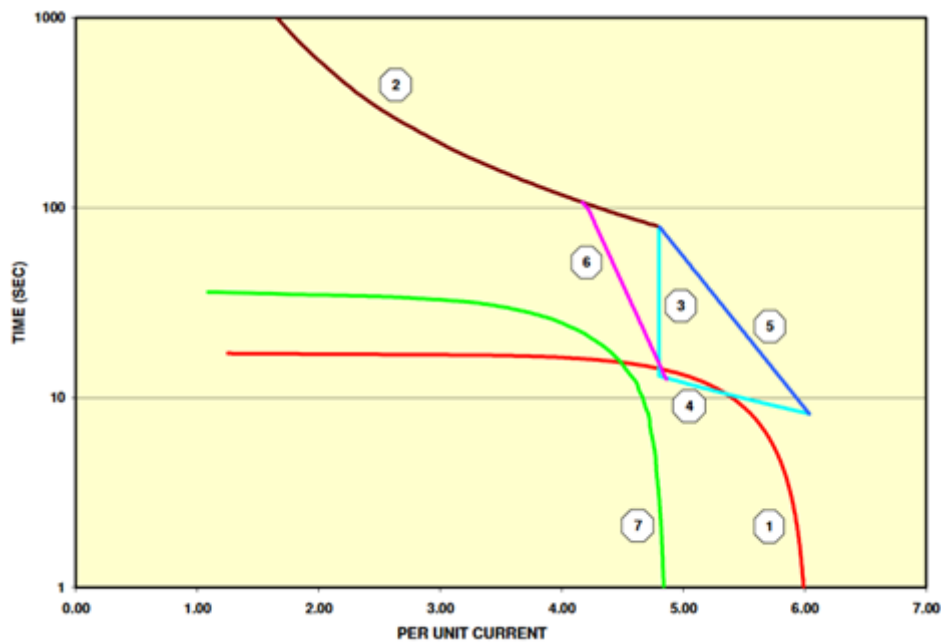


Figure 14. Example of voltage-dependent thermal limit curves (Venkataraman, et al., 2005, p. 139).

In Figure 14, curves 2, 3 and 4 models the typical thermal limit curve and curves 1 and 7 model motor starting time. As seen in the figure, a motor cannot be started with start current 1 as it reaches the locked-rotor limit I^2t . Applying ideology that thermal limit is seen as a function of motor starting acceleration speed, new curve 5 is created. Each point in curve 5 corresponds to a motor start current value and motor speed. If the terminal voltage varies from rated 100 %, i.e., starting with reduced voltage, the new curve 5 will not protect the motor, as the locked-rotor time would be much higher than what

is allowed. Thus, new curve 6 is created to respond to voltage changes during motor starting dynamically. (Venkataraman, et al., 2005, p. 140).

3.3.4 Service factor

NEMA standard does not use motor duty types. However, it defines the service factor as a multiplier, which determines how much motor can handle short periods of overloading. For example, a 100 Hp motor with a service factor of 1.15 can be overloaded short period by 115 Hp. The service factor is used to allow more adjustment to fulfill the horsepower requirements. It also allows motor windings for operating at cooler temperatures at rated load and helps offset unbalanced line voltages. (Csanyi, 2013)

3.3.5 Negative sequence current

Negative-sequence current occurs to motor or system when an unbalance condition exists, stator coil cutout occurs during a repair or there are shorted turns in the stator winding. Unbalance conditions can occur in open-phase situations, single-phase faults or unbalance load. (IEEE, 2013, p. 44).

When the motor is operating normally, the rotor will rotate in the direction of a positive sequence current at near synchronous speed. If an unbalance in stator current occurs, it will create a negative sequence current and flux. Those start to rotate in the opposite direction than the rotor is rotating. Figure 15 illustrates this phenomenon. As those rotating in different directions as the rotor rotates, the effect in the rotor caused by the negative sequence current and flux will be about double the system frequency. This increases heating in the rotor bars as, together with high frequency and skin effect, rotor resistance increases. This extra heat generated by the skin effect is not considered via the thermal limit curve. (Venkataraman, et al., 2005, p. 135).

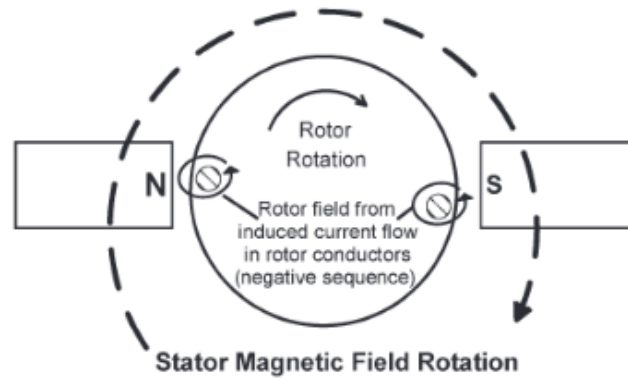


Figure 15. Negative-sequence rotor current from stator flux (Ransom & Hamilton, 2013, p. 2474).

3.4 Motor protection functions and settings

In the following sections, typical motor protection functions and typical protection relay settings are introduced. Protection relay settings should provide optimal protection for the motor. Different standards and literature will be the source for the methods for selecting protection relay settings.

3.4.1 Motor thermal overload protection

Thermal overload protection prevents motor insulation failure by limiting motor-winding temperature and motor current to predetermined values during abnormal motor conditions. There are two main classes of overtemperature thermal protection devices; they can be based on load current or temperature sensing or both. For current sensing, microprocessor-based protection systems can be used to apply motor thermal time constant and for temperature sensing RTDs can be used. The problem is that they cannot alone detect all the abnormal conditions. Current-based sensing cannot detect restricted ventilation and temperature-based sensing can be inadequate, for example, with frequent starting or jogging. (IEEE, 2013, p. 36).

Relay trip curves are set to match the motor thermal limit curves. This approach will protect a motor from overload and starting conditions. Overload pickup is arranged to 110 % of the motor full-load current when a service factor is 1.0. This allows having a

safety margin for protection system inaccuracies and motor won't trip at rated load. If a service factor is 1.15, the overload pickup is set to 120 % of the motor full-load current. The protection system safety margin is now smaller, as motor won't trip for small inaccuracies without heavy overloading. When embedded temperature detectors are used to monitor the motor winding temperature, tripping will be set according to a motor thermal insulation class. (IEEE, 2013, p. 136).

3.4.2 Motor start-up supervision

When the motor is started, the starting acceleration may fail due to the following reasons: mechanical failure of the motor or load bearings, low supply voltage, or an open circuit in one phase of a three-phase voltage supply (IEEE, 2013, p. 28).

Frequent starting and intermittent operations, such as jogging, inching, or spotting, should also be considering. The running period may be too sort for motor cooling from forced convection. Repeated starts may increase used thermal capacity to dangerously high in both stator and rotor unless enough cooling time is not provided between starts. (IEEE, 2013, p. 34).

Usually, time overcurrent-based relays are used for locked-rotor protection. The pickup is set to 150–175 % of motor full-load current and the time-delay setting shall be set with a margin of 2–5 s above motor starting time. When a starting time is in a range of 5–10 s, 2 s margin is satisfactory. When starting time is in a range of 40–50 s, 5 s margin is more suitable. (IEEE, 2013, pp. 114–115).

For high inertia motors, motor starting acceleration can be challenging to achieve before the motor thermal limit is reached. Overcurrent-based protection may need to be combined with speed switches, distance relays or additional rotor thermal protection to protect the high inertia motor during start-up. Speed switches are used to block motor start-up protection if the motor starts to accelerate. This allows a longer starting time than a locked-rotor limit set in motor start-up protection. However, not every motor has the

possibility to install the speed switch. The second way to monitor motor starting acceleration is by calculating motor impedance change during the acceleration. The motor terminal voltage and current can be used to calculate the impedance change using Ohm's law. The calculated impedance contains the real part from the speed-dependent rotor resistance, which can be used to calculate heating in the thermal model, allowing a longer starting acceleration time. Another way to utilizing the impedance change during starting acceleration is by voltage-dependent thermal limit curves. The motor terminal voltage and line current are used to calculate motor speed change due to the impedance change. As the motor thermal impedance changes, the method dynamically chooses correct values for the thermal limit time for any given terminal voltage and line current. (IEEE, 2013, pp. 20, 32).

An example of locked-rotor protection made with impedance relay is shown in Figure 16. Motor impedance is plotted in R-X coordinates. The impedance relay is set to pick up each time the motor is started and reset when a motor begins to accelerate. If the motor fails to accelerate, the impedance relay will stay picked up and allows the timing relay to trip the motor. The impedance relay should trip the motor before a safe locked-rotor limit is reached. (IEEE, 2013, pp. 103–104).

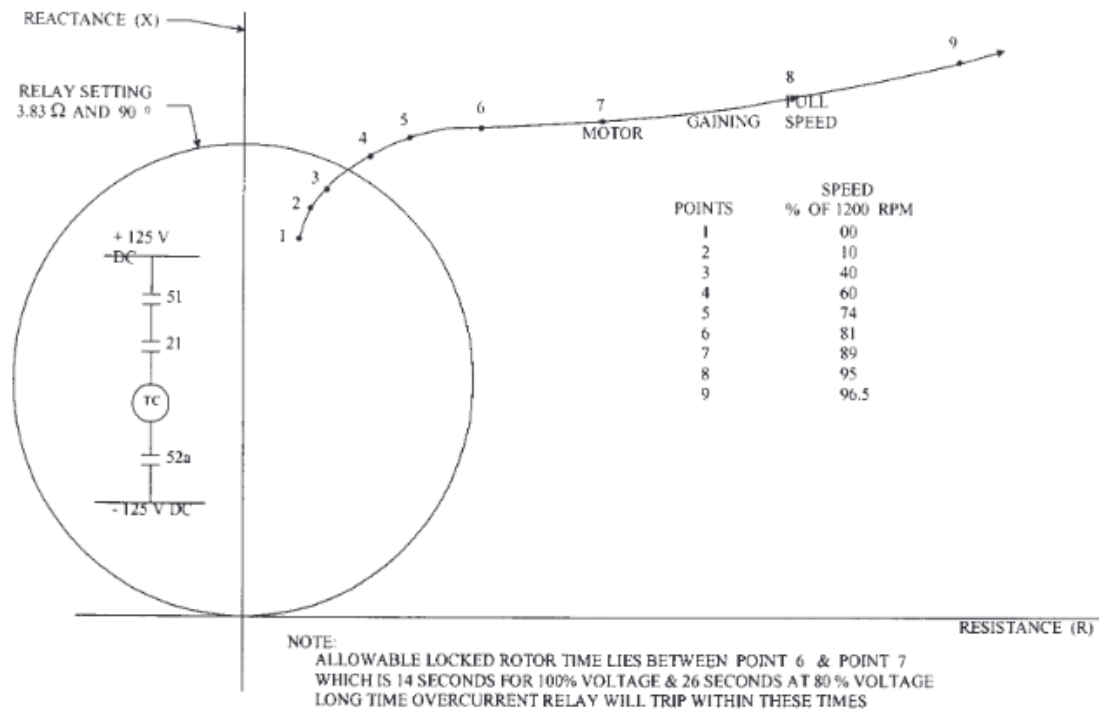


Figure 16. Locked-rotor protection made with impedance relay (IEEE, 2013, p. 103).

3.4.3 Motor phase-overcurrent protection

Phase-overcurrent faults are not so common in motors since almost all the faults quickly generate ground faults. It is, however, a common practice to provide a phase fault protection. This is usually acquired using overcurrent relays or differential relays. These relays will also protect motor feeding cables. (Anderson, 1999, p. 790).

There are two different types of motor drive feeders commonly used with a circuit breaker or a contactor. When using a circuit breaker, instantaneous overcurrent protection is used to give quick protection against phase-to-phase faults in the motor or the motor feeding cable. When using a contactor, the short circuit protection is made with high-voltage fuses and in a relay, this protection is set off. This is because the contactor is not capable of breaking high fault currents.

An instantaneous overcurrent relay can be set to trip at a range of 150 % to 175 % of the motor locked-rotor current to trip instantaneously. It is also essential that overcurrent does not pick up during normal motor starting. (IEEE, 2013, p. 114).

3.4.4 Motor jam protection

Motor jam protection is used when motor stalls and motor speed decreases to zero or at some stable speed level underrated speed. When a motor stalls, the motor current will start to increase rapidly, approaching locked-rotor current. Along with the current increase, the motor impedance starts to approach the locked-rotor impedance. Motor stall can be caused when the load torque exceeds the breakdown torque. The stall occurs when load torque is greater than motor torque supplied. This torque unbalances typically caused by motor terminal voltage reduction or when an excessive mechanical load is applied beyond motor torque capability. (IEEE, 2013, pp. 19–20).

Stall detection is usually provided by using an overcurrent relay. It is traditionally set two times the motor full-load current with a time delay couple of seconds (IEEE, 2013, p. 136).

3.4.5 Motor negative-sequence overcurrent protection

Motor negative-sequence overcurrent protection is used to detect (severe) unbalance caused by losing one phase, unbalanced supply voltage or stator winding inter-turn faults.

The typical pickup setting for a negative sequence is 15 % of the motor full-load current and a recommend time delay of 10 s (IEEE, 2013, p. 106).

3.4.6 Motor phase reversal protection

Phase reversal protection is not a mandatory requirement. It will protect a load and personnel working with a motor from a motor and a load rotating to reverse direction. (Anderson, 1999, p. 794).

3.4.7 Motor voltage protection

Large motors can be started successfully, typically at 70 % to 85 % of rated voltage. However, the reduced voltage may extend motor starting time or prevent the motor from reaching the rated operation speed. This may result in excessive heating in the stator and rotor windings. The undervoltage pickup should be set below the lowest voltage drop during the motor starting acceleration. The undervoltage time delay shall be longer than the voltage drops during the motor starting. (IEEE, 2013, pp. 58, 104).

Typically, undervoltage protection is set at 70 % of the rated voltage, with a time delay, only a couple of seconds. If two-step undervoltage protection is used, the second step is set to 90 % of the rated voltage and the time delay is set to be longer than motor starting time.

Motors can operate in a rated load with a ± 10 percent variation from the nominal voltage in general. When the voltage increases to overvoltage, the magnetizing current also increases, which leads to an eddy current and power factor decrease. Respectively, when the voltage decreases, the current increases. This increases temperature and worst-case lead to a stall. (Zocholl S. E., 2003).

Typically, overvoltage protection is set to 110 % of the rated voltage and time delay is set to only a couple of seconds.

4 Motor thermal overload protection methods used by different protection relay manufacturers

This chapter contains case studies of how different protection relay manufacturers adopt the motor thermal overload protection. Three motor conditions are reviewed: motor overloading, acceleration and locked-rotor. Different manufacturers adopt motor overload protection in slightly different ways. The protection relay manufacturers included in the case studies are Siemens, General Electric and Schweitzer Engineering Laboratories.

4.1 Case study Siemens

Siemens defines separate thermal overload models for the stator and rotor windings. Both thermal models are calculated at the same time. They are independent and they do not interact with each other. Thermal models use a homogeneous motor body for modeling. Thermal models calculate how much thermal capacity is used. (Siemens AG, 2006, pp. 20–22).

The stator thermal model protects motor when motor is overloaded. The stator's thermal model calculates trip time using measured stator winding currents, rated stator winding current reference, factor k , thermal time constant, previous load, and measured ambient or coolant temperature. Factor k defines the continuous maximum overload current by referring to the rated current. The thermal time constant used for stator is a heating thermal time constant. The same thermal time constant is also applied for the cooling thermal time constant when operating with different loads. When motor is shut down, a longer cooling time is used. If measurements from ambient or coolant temperature are available, the thermal model includes information about it for calculation. If temperature measurement is not available, ambient temperature is set equal to 40 °C. (Siemens AG, 2006, p. 20).

Thermal load acts on the rotor during motor starting. However, for the stator, the thermal load during starting is much smaller. The thermal model can be freeze or the starting current can be internally limited to a small value during motor starting to consider the lower thermal load in the stator's thermal model. The stator's thermal model is freeze with motors with a short starting time. The internally limited smaller value is used in the thermal model when motor has a long starting time. The small current value slows down the heat generated by a long start, for example, using 2–2.5 times the motor starting current in the stator thermal model. (Siemens AG, 2006, p. 20).

Siemens relay creates a thermal model for the rotor using restart inhibit function. It prevents motor starting if the motor is started too many times in succession. Only two parameters are required for the rotor's thermal model: the *Rotor overload factor* (k_r) and the *Rotor thermal time constant* (τ_r). Those parameters are not defined in the motor performance data. But the *Rotor overload factor* and the *Rotor thermal time constant* can be found with simple calculations of the parameters that are available in motor performance data: the *number of motor cold starts* (n_c) and *warm starts* (n_w), the *starting time* (t_{start}) and the *starting current* I_{start} . When the *Rotor overload factor* and the *Rotor thermal time constant* are found, those parameters can describe rotor temperature. Another example where those parameters can be used is in the rotor's thermal model threshold level calculation. The threshold level is calculated with the following formula: $(n_c - 1) / n_c$. If the rotor temperature exceeds the threshold level, the rotor must be cooled down below the threshold level before starting the motor. (Siemens AG, 2006, pp. 21–22).

Starting time supervision monitors motor start time is in range and detects locked-rotor condition. The trip occurs if the starting time is longer than defined or starting current exceeds the set limit. For rated and reduced voltage, the trip characteristics have an inverse character that adopts different starting situations. Starting supervision has only three parameters to set: the maximum starting current, the maximum permissible starting time and start detection current. (Siemens AG, 2006, pp. 21, 23).

4.2 Case study General Electric

In General Electric (GE) relay, the thermal model comes from five elements:

- Thermal model curve (overload)
- Overload pickup level
- Unbalance biasing of the motor current while the motor is running
- Motor cooling thermal time constant
- Biasing of the thermal model based on hot/cold information and/or measured stator temperature.

The current base thermal model uses an algorithm that integrates both stator and rotor heating into a single model. The thermal Capacity Used (TCU) register is used for maintaining motor thermal level. (General Electric, 2020, p. 6-10).

GE relay uses an overload curve to protect motor for overload, starting acceleration and locked-rotor. GE relay allows selecting the overload curve from one of the six formats: Motor, FlexCurve A, FlexCurve B, FlexCurve C, FlexCurve D, FlexCurve OL, or IEC. The five first curves can also serve as a voltage-dependent overload curve. The voltage-dependent thermal limit curves help with a high inertia load motor with the stall or locked-rotor condition, starting acceleration and running overload. The voltage-dependent mode shifts the overload curves as the motor speed changes. The change in motor speed is calculated from the motor impedance. (General Electric, 2020, pp. 6-10 and 6-26).

The “Motor” curve is a generic thermal overload curve, and it is created using typical motor thermal limit curves. A time dial (TD) multiplier allows for shifting the original overload curve on the time axis for better response to the protected motor thermal limit curve. (General Electric, 2020, p. 6-11 and 6-15).

The “IEC” curve is built by referring to the old version of a standard IEC 60255-149. The IEC overload curve has characteristics for hot and cold curves defined in the standard.

The hot and cold curve selection is based on motor status and how much thermal capacity is used. The selection criteria for the selected curve are shown in Table 2.

Table 2. Thermal model selection criteria (General Electric, 2020, p. 6-14).

Prior to overload condition		Upon overload condition	Selection of IEC characteristic curve
Motor Status	Thermal Capacity Used	Motor Status	
Stopped	Less than 5%	Starting	Cold
Stopped	Greater than or equal to 5%	Starting	Hot
Running	Less than 5%	Overload	Hot
Running	Greater than or equal to 5%	Overload	Hot

GE guides to set the overload curve lightly under the thermal limit curves. This allows a motor to be tripped before the thermal limit is reached. (General Electric, 2020, pp. 6-10 and 6-11).

The IEC thermal model uses four specific thermal time constants depending on motor status. Motor status is determined from motor full-load current (FLC). The thermal time constants are:

- IEC curve thermal time constant 1
- IEC curve thermal time constant 2
- Cool time thermal constant running
- Cool thermal time constant stopped.

IEC curve thermal time constant 2 is used during motor starting ($I > 2 \cdot k \cdot FLC$). During motor starting, motor is rotor-limited. Respectively, motor is stator-limited during motor overloading. IEC Curve thermal time Constant 1 is used when motor is overloaded ($k \cdot FLC < I < 2 \cdot k \cdot FLC$). Cool thermal time constant running and stopped are used when motor overloading is ended or motor is stopped. (General Electric, 2020, p. 6-15).

FlexCurves are for more demanding applications, where motor thermal damage curves do not match the standard motor thermal limit curves. The thermal limit curve can be linearly discontinuous between the starting (locked-rotor and acceleration) characteristics and running thermal damage curves. FlexCurves A, B, C and D allow programming trip times for pre-determined current levels. FlexCurve OL includes the same programming for trip time, but also it will enable programming operating quantity values as multiple of FLC. (General Electric, 2020, p. 6-16).

GE relay allows to specify a motor overload factor. When a motor load current level exceeds the specified motor overload factor value, the thermal model detects a motor overloading, and the model responds by collecting thermal capacity. To account for inherent load measurement errors caused by CTs and limited relay accuracy, GE guides to set this factor slightly above the motor service factor. Typically, CTs' error and limited relay accuracy can be up to 8–10 %. This inaccuracy is taken in the count by using overload factor 0.1 steps higher than the rated service factor. I.e., if the motor rated service factor is 1 or 1.15, the motor overload factor is guided to set 1.1 or 1.15, respectively. (General Electric, 2020, p. 5-70).

GE relay has separate supervision for motor starting. It has five elements: Thermal Start Inhibit, Maximum Starting Rate, Maximum Cold/Hot Starting Rate, Time Between Starts, and Restart Delay. Thermal inhibit calculates the motor's thermal capacity and allows motor to start if there is enough thermal capacity left. Maximum starting rate and maximum Cold/Hot starting rate work in the same way. Maximum starting rate is used if the maximum allowed number of motor Cold/Hot starts is unknown. They specify a time interval for minimum stop time between two consecutive motor starts. They also count the maximum number of motor starts that can occur at a specified time. Restart delay checks the minimum time after it has been stopped. (General Electric, 2020, pp. 8-5–8-15).

RTDs installed in the stator body can augment the current-based thermal model for calculating the thermal capacity used. RTD Bias allows taking account of unusual high ambient temperature or malfunctioning motor cooling. RTD Bias can also work as additional protection for the thermal limit curve. If the thermal limit curve is selected incorrectly, RTD Bias can take into account the motor's actual thermal capacity. RTD Bias method uses the hottest stator temperature value to estimate RTD thermal capacity and compares it to the current base thermal model. RTD Bias cannot make a trip alone. The motor load current needs to be over the overload limit. If multiple RTDs are available, RTD Bias voting can be used. In the voting feature, the maximum temperature RTD is chosen by voting. RTD values are compared with each other and the highest value is selected. RTD Bias voting also contains a voting band. If the highest value is not inside this band when compared to other RTDs values, it will be discarded and RTD is declared malfunctioning. (General Electric, 2020, pp. 6-22–6-25).

RTD Bias operation temperature curve is visualized in Figure 17. In the figure, the horizontal axis contains the maximum measured stator RTD temperature and the vertical axis contains RTD thermal capacity used. Horizontal axis value for RTD Bias minimum is set to ambient temperature, RTD Bias center point is set to motor rated operation temperature and RTD Bias maximum is set to the maximum insulation isolation temperature.

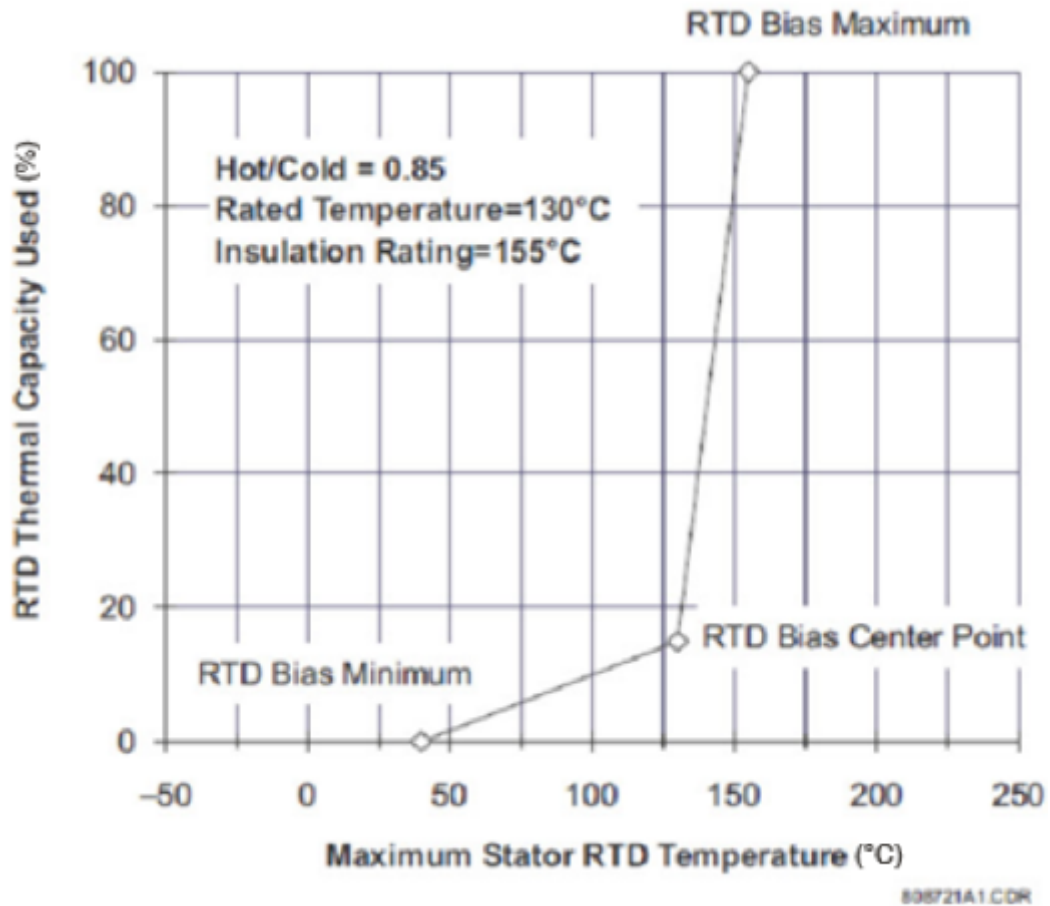


Figure 17. RTD Bias curve (General Electric, 2020, p. 6-24).

In General Electric (2020, p. 6-23) the following Equations 1, 2 and 3 are defined for calculating the RTD Bias thermal capacity used in the points illustrated in Figure 17. The equations use different measured stator temperatures and locked-rotor hot/cold ratio. The first equation defines *RTD Thermal Capacity Used at RTD Bias center* RTD_{center} , when motor is operating at rated load and temperature:

$$RTD_{center} = \left(1 - \frac{hot}{cold} \right) \cdot 100 \%, \quad (1)$$

where *hot* is allowed locked-rotor time for warm motor and *cold* is allowed locked-rotor time for cold motor.

When the measured stator temperature is below RTD_{center} temperature, the second equation is used to calculate the *RTD thermal capacity* RTD_{TCU_1} :

$$RTD_{TCU_1} = \frac{T_{actual} - T_{min}}{T_{center} - T_{min}} \cdot RTD_{center}, \quad (2)$$

where T_{actual} is current temperature of the hottest stator RTD
 T_{min} is *RTD Bias minimum* temperature
 T_{center} is RTD Bias center temperature.

When the measured stator temperature exceeds RTD_{center} point temperature, the third equation is used to calculate the *RTD thermal capacity* RTD_{TCU_2} :

$$RTD_{TCU_2} = \frac{T_{actual} - T_{center}}{T_{max} - T_{center}} \cdot (100 - RTD_{center}) + RTD_{center}, \quad (3)$$

where T_{max} is *RTD Bias maximum* temperature.

4.3 Case study Schweitzer Engineering Laboratories

Schweitzer Engineering Laboratories (SEL) calls their thermal overload protection a thermal overload element. The thermal element protects different motor conditions: locked-rotor, running overload, unbalance current/negative-sequence current heating and repeated or frequent starting. (Schweitzer Engineering Laboratories, 2020, p. 4.5).

The thermal element's parameter setting method is divided into two options: motor rating method and thermal limit curve method. When the motor rating method is used, a thermal limit curve is configured using protected motor parameters. Motor rating methods can also use a slip-dependent thermal model when optional parameters: full-load slip and locked-rotor torque, are set. A thermal limit curve can be selected from one of the 45 pre-defined standard motor overload/locked-rotor curves when a thermal limit

curve method is used. A thermal limit curve method also allows configuring a thermal limit curve with at least 5 or up to 28 user-defined thermal limit points. (Schweitzer Engineering Laboratories, 2020, pp. 4.5, 4.8 and 4.10).

SEL relay has four trip curves for motor thermal limit curves in thermal element configuration: hot and cold stator curves and hot and cold rotor curves. Also, SEL relay uses a separate thermal capacity calculation for the stator and rotor. The stator thermal capacity calculation is built using a service factor and two unnamed motor parameters. The stator model provides overload protection. The rotor thermal capacity calculation is made using a locked-rotor current and time. The rotor model also provides locked-rotor protection. (Schweitzer Engineering Laboratories, 2020, p. H.2).

In SEL relay, the dedicated overload factor parameter by overload factor name is not defined. However, SEL relay allows using the direct motor service factor (SF) parameter in the thermal element. A motor is considered a running overload when the motor full-load current (FLC) is greater than defined in service factor, $FLC \cdot SF$. In SEL it is guided to set this service factor for relay according to motor data. In the ANSI world, if a motor has a service factor of 1.0, a relay service factor should be set to 1.01, but a service factor can be set up to 1.05 if bus voltage fluctuations are a concern. If a motor has a service factor higher than 1.0, SEL guides to use the same value for a relay. For the IEC world, in SEL it is advised to set the service factor between 1.05–1.2. (Schweitzer Engineering Laboratories, 2020, p. 4.6 and Schweitzer Engineering Laboratories, 2008, p. 4).

RTD *Biasing* can operate or the thermal model can also be *Biased*. When used with the thermal model, RTD *Bias* gives an alarm when the two following conditions are met: *RTD % Thermal Capacity* exceeds the thermal element calculated Thermal Capacity Used (TCU) by more than 10 % and the winding temperature rise is higher than 60 K over the ambient temperature. This alarm can indicate that motor cooling is malfunctioning. SEL automatically reduces the RTD trip temperature when the ambient temperature is above 40 °C. (Schweitzer Engineering Laboratories, 2020, pp. 4.42–4.43).

Schweitzer Engineering Laboratories, Inc (2020, p. 4.43) uses the following equation for calculating RTD% thermal capacity:

$$RTD\% \text{ Thermal Capacity} = \frac{\left(\begin{array}{c} \text{Winding RTD} \\ \text{Temperature} \end{array} \right) - \left(\begin{array}{c} \text{Ambient} \\ \text{Temperature} \end{array} \right)}{\left(\begin{array}{c} \text{Winding RTD Trip} \\ \text{Temperature} \end{array} \right) - \left(\begin{array}{c} \text{Ambient} \\ \text{Temperature} \end{array} \right)} \cdot 100 \% \quad (4)$$

RTD% thermal capacity response to winding RTD temperature change will be linear.

4.4 Case study comparison

Each compared relay manufacturer provides thermal overload protection for motor overloading, starting acceleration and locked-rotor conditions. SEL and GE relays provide pre-defined and custom relay trip curves to match motor thermal limit curves. Siemens relay uses few parameters to calculate the relay trip curve.

Additionally, for relay trip curves, relay manufacturers have adopted different protection techniques. Those techniques are compared in Table 3. Siemens relay does not have a solution for starting high-inertia load. GE and SEL relays have their approach for high-inertia loads.

Another observation is that the SEL relay's RTD Bias is not entirely Biased as temperature change is a liner, so it is built using only one slope. Using one slope would mean that if a motor is operating at rated load, *RTD% thermal capacity* sees that motor thermal capacity is almost used. For example, if a motor is operating at rated load. The *Winding RTD Temperature* is according to thermal class B (130 °C) and the *Winding RTD Trip Temperature* is according to thermal class F (155 °C). Using these temperatures would mean that Equation 4 results for *RTD% Thermal Capacity* to be almost 80 %. This means that motor is hard to restart immediately after shutdown if there is no thermal capacity left. As a comparison, the GE relay has two slopes. Having two slopes allows a motor to use

less thermal capacity when motor is running at rated load. Two slopes allow easily to trip motor if RTD temperature rises above rated load temperature or trip temperature.

Table 3. Case study conclusion.

Function of feature	Relay manufacturer		
	Siemens	GE	SEL
Separate thermal model for stator and rotor	Yes	No	Yes
Ambient temperature in thermal model	Yes	Yes	Yes
A slip-dependent thermal model	No	No	Yes
Voltage-dependent thermal model	No	Yes	No
RTD Bias	No	Yes	Yes/No
RTD Bias voting	No	Yes	No

5 ABB Relion® motor protection relays

ABB Relion® protection and control relay series was first introduced in 2007. ABB Relion® protection relay family contains protection relays for different protection applications. ABB Relion® product family has dedicated relays for motor protection applications. Nowadays, the most popular motor protection relays are:

- REM611
- REM615
- REM620
- REM630
- REX640.

REM611 is entry-level protection relay and REX640 is the most high-end with the most capability.

5.1 Thermal overload protection for motors

The thermal overload protection function is called *MPTTR*. It is designed to provide thermal overload protection for electric motors. It responds to short and long time overheating by calculating motor thermal capacity. The motor thermal capacity is calculated based on true root-mean-square (RMS) and negative phase sequence (NPS) values of the measured load currents. The calculated thermal capacity development is saved, and it is used to monitor the motor temperature in the longer run. The protection relay continuously calculates it in the background. When thermal capacity equals 0 %, motor thermal capacity equals ambient temperature. Respectively, when thermal capacity equals 100 %, the motor thermal capacity is close to maximum insulation break down temperature, and the motor trip signal is activated.

Motor manufacturers define a full-load current of the motor at a designed ambient temperature of a typical 40°C. However, a motor's actual ambient temperature can vary from below 20°C to over 65°C. Having ambient temperature below the nominal 40°C allows a

motor to have more thermal capacity, and the motor can be slightly overloaded. Similarly, when the ambient temperature exceeds the nominal 40°C, the motor has less thermal capacity to use, and the motor needs to run below rated values. The ambient temperature can be considered via *MPTTR* function. *MPTTR* can be set to use scaled internal FLC, I_r . The internal FLC is calculated based on the ambient temperature. The ambient temperature for internal FLC calculation can be defined manually or through RTDs. The internal FLC calculations in different ambient temperatures are shown in Table 4. (ABB oy, 2020b, p. 405).

Table 4. Modification of internal FLC (ABB oy, 2020, p. 405).

Ambient Temperature T_{amb} (°C) condition	Internal FLC
<20	$FLC \cdot 1.09$
20 to <40	$FLC \cdot (1.18 - T_{amb} \cdot 0.09/20)$
40	FLC
>40 to 65	$FLC \cdot (1 - \{(T_{amb} - 40)/100\})$
>65	$FLC \cdot 0.75$

Thermal model *MPPTTR* has one thermal time constant. However, the thermal time constant is divided into three settings: *Thermal time constant start*, *Thermal time constant normal* and *Thermal time constant stop*. Each thermal time constant represents a different motor condition. The used thermal time constant depends on the motor current and the setting is automatically changed when the current changes. The dependence of the thermal time constant and motor phase current is shown in Table 5.

Table 5. Thermal time constants (ABB oy, 2020, p. 407).

Thermal time constant τ in use	Motor phase current
Thermal time constant start	Any current whose value is over $2.5 \cdot I_r$
Thermal time constant normal	Any current whose value is over $0.12 \cdot I_r$ and all currents are below $2.5 \cdot I_r$
Thermal time constant stop	All the currents whose values are below $0.12 \cdot I_r$

Relay trip curves are a response to motor thermal limit curves. Relay trip curves have a shorter operation time than defined in thermal limit curves for specific current value. The shortened time ensures that motor trip signal is activated before motor damage. ABB relays have current base relay trip curves. The time t it takes for *MPTTR* function to trip at a specific current value can be calculated using formula ABB oy (2010, p. 6):

$$t = \tau \cdot \ln \left[\frac{\left(\frac{I}{I_r}\right)^2 + K_2 \cdot \left(\frac{I_2}{I_r}\right)^2 - \left(\left(\frac{I_p}{I_r}\right)^2 + K_2 \cdot \left(\frac{I_{p2}}{I_r}\right)^2\right) \cdot p}{\left(\frac{I}{I_r}\right)^2 + K_2 \cdot \left(\frac{I_2}{I_r}\right)^2 - k^2} \right], \quad (5)$$

where τ is thermal time constant

I is the true RMS value of the measured max of phase currents

I_r is current reference, FLC or internal FLC

I_2 is measured negative sequence current

K_2 is negative sequence factor

p is weighting factor setting divided with 100 %

I_p is long time prior load RMS current before overloading

I_{p2} is long time prior load current NPS component before overloading.

MPTTR calculates motor thermal capacity while motor operates. A trip signal is activated if thermal capacity exceeds 100 %. A restart threshold level can be used to prevent motor start. For example, if thermal capacity exceeds the restart threshold level, motor cannot be started before thermal capacity falls below the restart threshold level.

MPTTR has three equations for calculating the thermal capacity. The two first equations are used when the motor is running, and the third equation is used when the motor is at a standstill. The two first thermal capacity equations are also dependent on the overload limit. The overload limit is defined as $k \cdot I_r$. The first *MPTTR* thermal capacity equation, Equation 6 is used when all the motor phase currents are below the overload limit. Equation 7 is used when any of the motor phase currents exceeds the overload limit. In addition, during motor overloading, longer-term thermal capacity θ_B is calculated continuously in the background. When overloading ends, the calculated hot spot thermal capacity θ_A is brought linearly to θ_B with a speed of 1.66 % per second. When motor phase currents are below $0.12 \cdot I_r$, *MPTTR* function sees the motor at a standstill. (ABB oy, 2020b, p. 390).

The equation for calculating *MPTTR* longer-term thermal capacity θ_B when phase currents are below the overload limit and also as a background during overloading (ABB oy, 2010, p. 5):

$$\theta_B = \left[\left(\frac{I}{k \cdot I_r} \right)^2 + K_2 \cdot \left(\frac{I_2}{k \cdot I_r} \right)^2 - \frac{\theta_P}{p\%} \right] \cdot \left(1 - e^{-\frac{t}{\tau}} \right) \cdot p\% + \theta_P, \quad (6)$$

where k is the set value of the overload k factor
 θ_P is the motor thermal capacity prior load
 $p\%$ is the set value of the *Weighting factor*.

The equation for calculating *MPTTR* hot spot thermal capacity θ_A , when at least one of the phase currents are over the overload limit (ABB oy, 2010, p. 5):

$$\theta_A = \left[\left(\frac{I}{k \cdot I_r} \right)^2 + K_2 \cdot \left(\frac{I_2}{k \cdot I_r} \right)^2 - \frac{\theta_P}{100\%} \right] \cdot \left(1 - e^{-\frac{t}{\tau}} \right) \cdot 100\% + \theta_P. \quad (7)$$

When the motor is started from a cold stage, the motor prior load θ_p can be assumed to be zero. That allows simplifying Equations 6 and 7. When motor is started from warm stage, prior load needs to be taken into account. Equation 8 shows how to calculate prior load θ_p (ABB oy, 2010, p. 4):

$$\theta_p = \left[\left(\frac{I_p}{k \cdot I_r} \right)^2 + K_2 \cdot \left(\frac{I_{p2}}{k \cdot I_r} \right)^2 \right] \cdot p\% \quad (8)$$

All the three given Equations 6–8 can be used to calculate motor thermal capacity during motor start-up, running normally and at a standstill. An example of motor thermal capacity calculation during motor start-up and instant shutdown is presented in Figure 18. The horizontal axis is the used thermal capacity and the vertical axis is time.

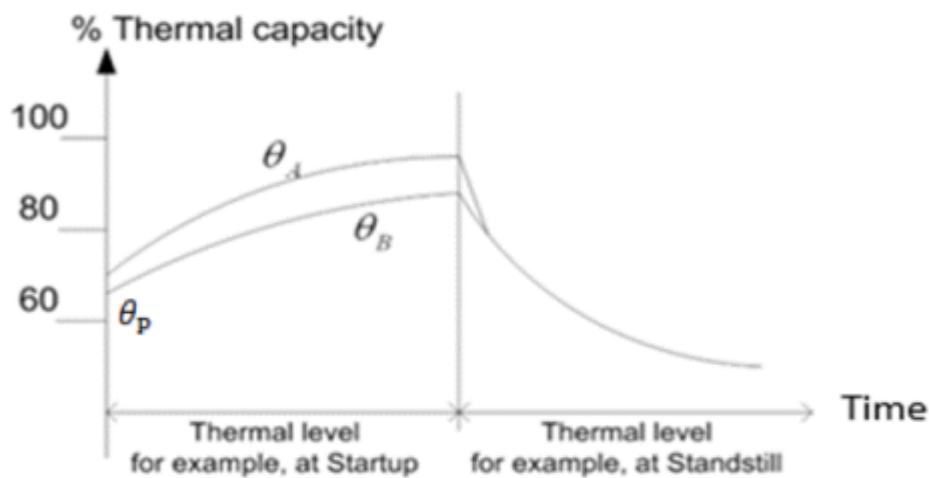


Figure 18. Calculated motor thermal capacity behavior, modified from ABB oy (2020b, p. 407).

5.2 Motor start-up supervision

Motor start-up supervision is called to *STPMSU* function. It is designed for detecting motor starting, too frequent motor starting, protection against excessive starting time and locked-rotor condition during the motor starting. Due to this, motor start-up supervision operates only during motor starting. Thermal stress created by motor starting is maintained within allowed limits. (ABB oy, 2020b, p. 1009).

STTPMSU function has four operation modes: 1. Ilt; 2. Ilt, CB; 3. Ilt & Stall and 4. Ilt & Stall, CB. Operation modes are based on only one operation mode or a combination of operation modes. The ABB oy technical manual (2020b, pp. 1011, 1012 & 1016) defines operation modes:

- In the “Ilt” mode, an operation is based on the calculation of motor thermal stress during starting using equation I^2t . In this mode, motor starting is detected by monitoring true RMS current.
- The “CB” starting is detected in addition to current and CB (circuit breaker) position status. This can be in soft-starting or slip ring motors.
- The “Stall” mode can be used when additionally, a motor speed switch is available. Using “stall” mode, the Lock rotor time -setting is effective.

When using the Ilt mode, motor starting is detected when the motor starting current exceeds the *Start detection A* parameter value. *Str over delay time* defines how long motor currents have to stay below 0.9 times the value set to *Start detection A*, before motor starting is considered as ended. The default value for this setting is 100 ms. This setting is usually used only in special situations. For example, if motor starting includes transitions like, when star/delta starting is used, the setting must be slightly greater than it takes for star-delta change. The Ilt & CB mode is typically used for slip-ring motors, which do not have a precise starting current. Then the *Start detection A* is set equal to the actual starting time. (ABB oy, 2020a, pp. 262–263).

The *STTPMSU* function contains a cumulative starting time counter, where the actual starting time is measured and added to the counter. When the counter value exceeds the setting, further starting is inhibited until the counter drops below the setting. This setting is typically calculated as (ABB oy, 2020b, pp. 1018–1019):

$$\sum t_{\text{start}} = 1.1 \cdot (n - 1) \cdot t + \text{margin}, \quad (9)$$

where n is the maximum number of motor starts
 t motor starting time
 margin is a safety margin.

The counter value is count-down with a settable fixed speed, typically set to be equal to the motor starting time.

5.3 Three-phase non-directional overcurrent protection

Overcurrent protection is used to detect short circuits in the motor or feeder. ABB protection relays have three stages of three-phase non-directional overcurrent protection functions: low stage, high stage and instantaneous stage. Typically, only an instantaneous stage is used. (ABB oy, 2020b, p. 319).

5.4 Motor load jam protection

Motor jam protection is also known as a *JAMPTOC* function. Motor jam protection is used to detect motor stalls during motor normal operation. This protection is blocked during motor starting as the motor start-up supervision function provides protection for locked-rotor at motor start.

The function operates when measured phase currents exceed the breakdown torque level. When the load torque exceeds the breakdown torque, operation speed decreases to zero or some stable level below rated operation speed. During motor jamming, the motor draws high currents, creating excessive heating in the rotor and stator. *Operate delay time* setting is used to trip motor before temperature rise reaches insulation limits. (ABB oy, 2020a, p. 393).

5.5 Negative sequence overcurrent protection for machines

Negative-sequence overcurrent protection is called to *MNSPTOC* function. It detects unbalanced load or phase-to-phase and single-phase faults. The unbalanced load can be caused due to broken conductors, winding interturn faults or unsymmetric supply voltage. Unbalanced loading causes excess heating in the motor. (ABB oy, 2020b, p. 752).

5.6 Phase reversal protection

Phase reversal protection is called to *PREVPTOC* function. It detects motor reversed rotation. The function monitors motor calculated negative-sequence current I_2 and operation is based on definite time characteristics. If motor phases are connected incorrectly, it will create a high I_2 value. (ABB oy, 2020b, p. 770).

5.7 Three-phase undervoltage protection

Three-phase undervoltage protection is called to *PHPTUV* function. The protection is typically done using one or two undervoltage functions. The operation mode characteristics can be according to definite time or inverse definite minimum time. (ABB oy, 2020b, pp. 791 and 793).

5.8 Three-phase overvoltage protection

Three-phase overvoltage protection is called to *PHPTOV* function. The function operates when the voltage exceeds the set value of the *Start value*. The operation mode characteristics can be according to definite time or inverse definite minimum time. (ABB oy, 2020b, p. 793).

6 Automated setting value calculations for high voltage asynchronous motors

The main goal of this thesis is to develop automated protection setting value calculations for high voltage asynchronous motors. This chapter contains information about this development. As a result of the development, two applications were built. The first one is made using Matlab and the second is made using Octave. The chapter starts with an introduction to calculation applications' use cases. Then Matlab and Octave software are introduced. After introductions, the development process is described. Setting values presented in Sections 6.2–6.4 are default example values.

6.1 Introduction to automated protection setting calculation applications

Two different versions of the calculation application are developed in this thesis. Different versions of the applications are designed for different ABB departments based on their needs and the software used. ABB Vaasa uses Matlab and ABB Helsinki uses Octave. ABB Vaasa also needs more customizable functionality and data inputs, as motor protection settings are calculated based on various vendors' motor data. Matlab version can be shared with customers and consults as a compiled standalone executable (.exe) file. ABB Helsinki will calculate protection settings based on their own motors only, so there is no need for customizable functionality and data inputs.

The calculated protection settings will be used in ABB Relion® protection relays. The application should be usable when released, so protection functions available nowadays in Relion® relays will be used. The focus with the applications' are on motor thermal protection as customers have the most problems finding proper setting values for motor thermal protection. Other common motor protection functions are included to speed up the overall protection setting calculation. Nowadays, an excel based tool is used to

calculate motor thermal protection settings. Other protection settings are mostly calculated by hand.

Earth-fault protection and frequency converter applications are not covered in the applications. Earthing systems vary between installations and customers are usually familiar with their earthing systems and earth fault protection. ABB relays do not support installation between a frequency converter and a motor. However, ABB protection relays can be installed before a frequency converter, but it won't change how protection for a motor is done. So, frequency converters are not covered in applications.

6.1.1 Introduction to Matlab

MathWorks Inc. maintains Matlab, and it is one of the most popular software used for engineering and science to program and analyze data. The basic version includes a core Matlab application covering the basic calculation tasks and command window editor, allowing running at Matlab functions, m-files and display results. The basic Matlab core version can be modified to perform more advanced functions by having separately purchased toolboxes. Different toolboxes cover different tasks by having specific solution tailored features. (MathWorks, 2020).

App Designer toolbox is built into a base Matlab core, and it is a toolbox designed for Application building. It was first introduced in Matlab version R2016a, and it replaced the older Guide-toolbox. The Guide-toolbox was like the App Designer toolbox, but it was less feature-rich. (The MathWorks, Inc., 2020, p. 4-2).

App Designer toolbox includes the same calculation functions as the basic Matlab version, and it has a user-friendly environment for application building. The app-building environment consists of code and layout editors. Making changes to another also generates changes to another editor immediately. (The MathWorks, Inc., 2020, p. 1-2).

In this thesis, the Matlab version, 2020b, is used as it is currently the latest version. Matlab includes a feature that allows converting applications made with an older version of Matlab into a newer version of Matlab. This feature is handy as Matlab releases two releases per year. The application developed in this thesis can be converted to a recent Matlab version when released.

6.1.2 Introduction to Octave

Another software called Octave was first conceived in the year 1988. By then, it was developed to have different tools for chemical reaction design problems. The first official 1.0 release was in 1994. Since then, Octave has got more flexible tools for solving numerical problem computations. The language that is used in Octave is mostly compatible with Matlab. (GNU Octave, 2020).

Octave is free software under the GNU General Public License (GNU Octave, 2020). Octave version 5.2.0 is used in this thesis as it is the newest stable release.

6.2 Application code and functionality description

The overall functionality in both software is similar. They calculate protection settings for protection functions base on motor data and store results in a word file. The most significant difference between the applications is that the Matlab version allows manual management of results after calculation and choosing which protection functions are included in calculations. Both applications' code is divided into modules for different protection functions.

Some motor manufacturers provide motor thermal limits and starting curves in an excel file format. In the excel files for start-up current, the first data point can be given for time to equal zero. This would cause an error in calculation or plotting in logarithm graph. Therefore, time value zero is substituted with a value of 0.01.

Motor starting current and allowed numbers of motor starts, and other motor performance data are inserted in the applications' GUI (Graphical user interface) in the Matlab version. In the Octave version, other performance data is inserted into the application with a specific excel file.

The calculation process for both applications is shown in Figure 19. After the motor data is inserted, the first attempt to calculate relay settings is made. Suppose that relay trip curves are not between motor thermal limit curves, starting currents are not in a range or calculated thermal capacity used (TCU) is greater than 100 %. In that case, the *weighting factor* is decreased by 2 %, until curves are in range or the *weighting factor* setting limit (20 %) is reached. If the range is not met, an error is given. Finally, when trip curves are in range or an alarm is given, other protection functions are calculated. In the end, the results are stored on the word report.

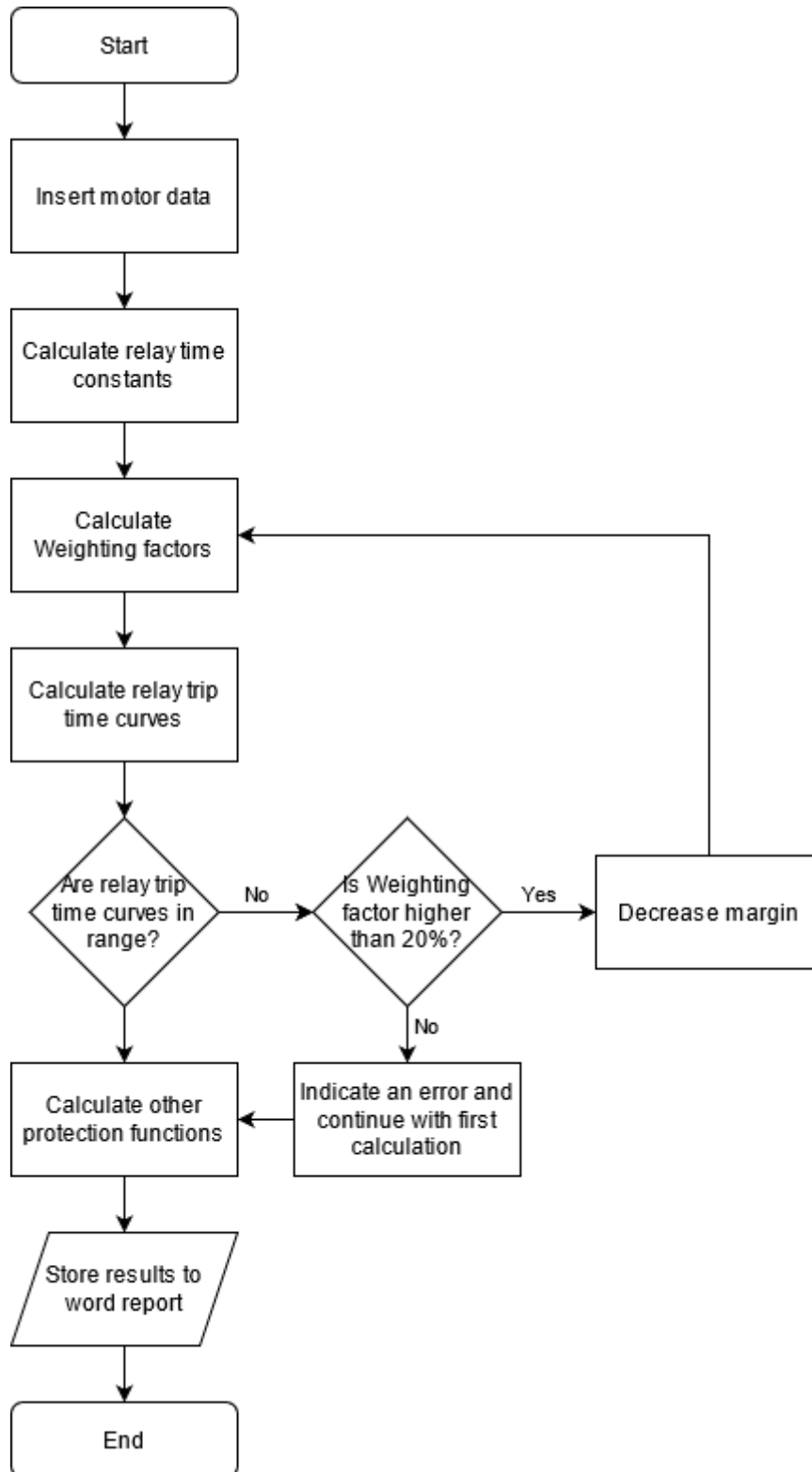


Figure 19. A flowchart represents the calculation process for the applications.

6.2.1 Matlab application code and functionality description

Designing of application GUI was the first step when the Matlab application was started to write. This was due to the limits of the GUI editor. When adding a new element with the GUI editor, the editor automatically generates the component's code. The automatically generated code is added to the end of the code, not to the spot where it belongs in order.

The Matlab application GUI is divided into two panels. The panels are separated from each other by a darker grey line in the middle. An example of the GUI is in Figure 20. The left-hand side panel contains user-editable content, e.g. choosing relay, CT ratios, and motor data. The right-hand side panel is for previewing simulation results, as it includes a preview of thermal limit curves and start simulations.

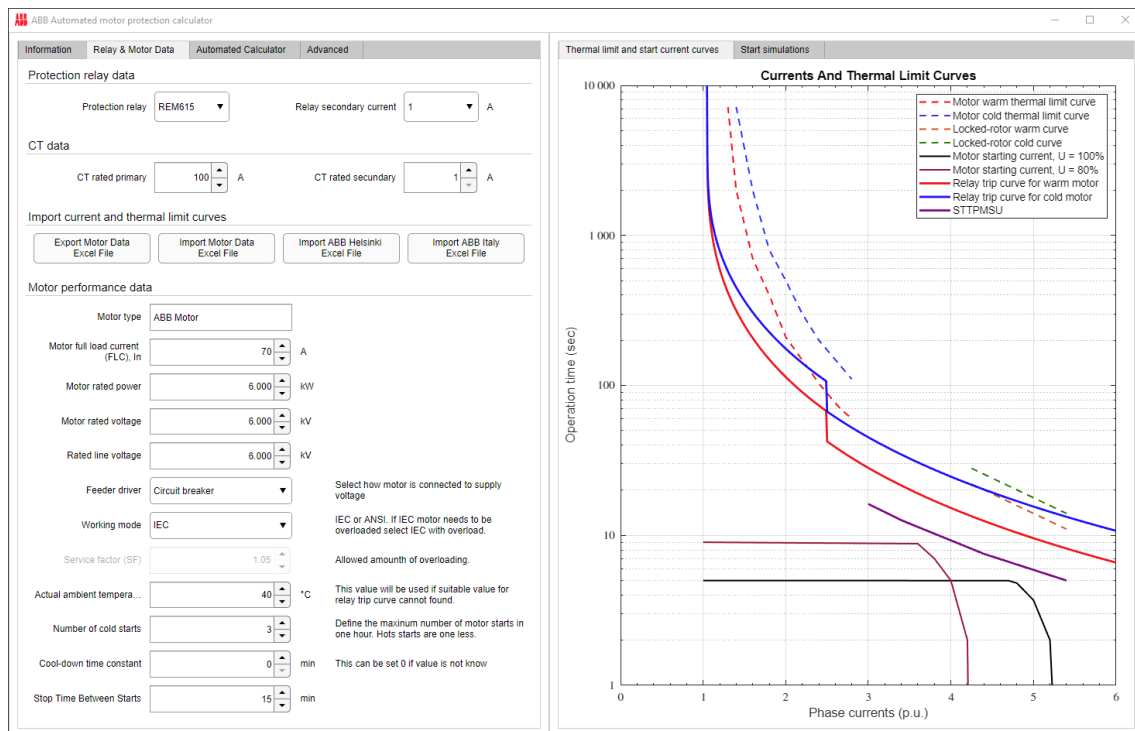


Figure 20. Preview of the Matlab application from relay and data input overview.

The contents are categorized into different pages in the left-hand side panel. The first page is called *Information*. This page contains information on how to get started with the application and find more information about functionalities.

The second page is called *Relay and Motor Data*. The type of protection relay, current transformer (CT), and motor data are settable on this page. Available ABB protection relay types are defined in a drop-down menu. Similarly, a relay-rated secondary current input from CT can be selected from a drop-down menu. When the relay-rated secondary current input is selected, it will automatically select the CT's secondary current value. Primary CT-rated value can be chosen manually from an editable field. Both CT settings will affect to protection relay's internal current calculation. The motor thermal limit and start current curves are then imported to the application from an excel file. Application is made to support factory-delivered excel files from ABB Helsinki and ABB Italy. The application also allows export of an excel template. This allows manually write motor thermal limit and starting curves data to excel file. The last part of this page is a section for necessary motor information. The information in this section is mostly used for generating the report. However, there are also information used in calculations, e.g. motor full-load current and the number of allowed cold starts during a time period. The number of hot starts is assumed to be one start less than cold starts.

The third page is named *Automated Calculator*. This page contains the developed protection setting calculator and an overview of the selectable protection functions. Different functions can be included or excluded from the calculation with checkboxes. When wanted functions are selected, the application can be run by pressing the Calculate button. The calculation results for each function are presented on the functions page.

The fourth page is called *Advanced*. This page contains so-called fine adjustment features. The curve management function allows the user to choose what data is shown in the graphs and manage how motor thermal limits and starting curves data are assigned from

the excel file's data. There is also a possibility to adjust relay trip curves manually from the MPPTR-settings page.

The graphs are shown in the right-hand side panel. The available graphs are motor thermal limits and starting curves, but also relay trip curves. The second page contains starting simulations using rated and reduced voltages.

6.2.2 Octave application code and functionality description

The Octave application has three different files. The files are a calculation script file, an excel file for defining data and the word report file. The calculation script file is the core of the calculation application. The excel file for defining data contains user-editable information, which is then used in calculations and results. This information is e.g. protection relay, CT and motor type. An example of this excel file is shown in Figure 21. Finally, the third file, the Word report file, is used as a template for printing calculation results.

Relay, CT & Motor Data		
Protection relay data		
Protection relay:	REM615	
Relay secondary current:	1	A
CT data		
CT rated primary:	100	A
Motor data		
Motor type:	ABB Motor	
Rated motor power:	12000	kW
Rated motor voltage:	8300	kV
Rated line voltage:	11500	kV
Motor full load current (FLC), In	70	
Service factor (SF):	1,05	
Number of cold starts:	3	
Stop time between starts:	15	Min
Cooling time constant:	0	
Motor drive feeder	Circuit breaker	
Actual ambient temperature	40	

Figure 21. Screen capture from excel motor and relay data definition.

The calculation code itself is written in the same order as it runs. This means that there is no possibility to run only certain parts of the code. The code begins with loading the required pre-installed Octave packages. The packages are `io` and `windows` packages. The `io` package is used for reading data from the user-editable excel file with `xlsread` command and the `windows` package is used for printing results to word file with `actxserver` command.

6.3 Settings for thermal overload protection function

Motor thermal protection is one of the essential functions of motor protection. Settings up values for motor protection can be challenging as motor manufacturers do not necessarily define all the needed parameters. Also, motor warm-up thermal time constant does not correctly express the motor's actual thermal behavior compared to motor thermal limit curves. Nowadays, an excel tool is used to estimate *Thermal time constant start* and *Thermal time constant normal* from motor thermal limit curves. This excel tool has its limits and it requires knowledge and time to find the right values for thermal time constants to protect the motor and still allow the required number of motor starts.

Matlab and Octave applications use the setting calculation equations given in Section 5.1 Thermal overload protection for motors. *MPTTR* can take into account also excessive heat caused by unbalanced stator currents. However, because only part of the customers uses this feature, in the Matlab and Octave applications, the corresponding *MPTTR* parameter is set to zero and protection is based solely on the dedicated unbalance protection function *MNSPTOC*.

MPTTR is designed for motors with an ambient temperature of 40 °C. However, some motor manufactures have motors designed for different ambient temperatures. *MPTTR* can also protect motors with other ambient temperatures than 40 °C, but usually, comments from experts are usually needed in that kind of special case. The applications will ask about the motor's maximum ambient temperature. The given maximum temperature is then compared to the temperatures in Table 4. The same information in Table 4

is used to calculate the internal full-load current. However, suppose the given motor's maximum ambient temperature is other than 40 °C. In that case, the applications will calculate internal FLC as with ambient temperature of 40 °C, but the applications will instruct to contact experts to check the protection.

The user defines *overload factor k* by selecting the motor working mode. Three options are available for working mode: IEC, IEC with overload and ANSI. With IEC mode, the application automatically selects for *overload factor k* value of 1.05. This allows taking into account measurement inaccuracies. IEC with overload and ANSI working modes functions in the same way, as both allow to define *overload factor k* using Service Factor.

The *Weighting factor* defines the ratio of the cold and hot relay trip curves. ABB uses the same *Weighting factor* for running motor overloading (motor load current below $2.5 \cdot I_r$) and for motor starting. As the *Weighting factor* applies in two places, it is calculated from motor thermal limit curves from two places. The first calculation is for rotor from the maximum permitted hot and cold locked-rotor times. The second calculation is for stator and it is calculated from cold and hot thermal limit curves from the closest point to $2.5 \cdot I_r$. The two calculated ratios are then compared, and a higher value is used for the *Weighting factor*. This allows adjusting the relay hot tip time curve below motor hot thermal limit curve for both running overload and starting acceleration conditions.

Thermal time constant start and *Thermal time constant normal* can be calculated from motor thermal limit curves and relay trip curves using Equation 5. Thermal limit curves provide the maximum trip time for a specific current value. Thermal time constants are calculated for a cold relay trip curve. This allows calculating thermal time constants with no prior load or NPS component. The hot relay trip curve is then controlled with the *Weighting factor* setting.

For *Thermal time constant start* calculation, cold locked-rotor current and time values at rated voltage are used. As the cold motor is at ambient temperature, we can assume

prior load current I_p to be zero and not include the negative sequence phase component. Now Equation 5 is modified to give thermal time constants and we got an Equation 10, which is used to calculate the *thermal time constant* τ_{Start} :

$$\tau_{\text{Start}} = \frac{t_{\text{LR}}}{\ln\left(\frac{\frac{I_{\text{LR}}^2}{I_r}}{\frac{I_{\text{LR}}^2}{I_r} - k^2}\right)}. \quad (10)$$

Thermal time constant normal is applied when the motor phase current is between 0.12 and $2.5 \cdot I_r$. A search function is used to find the closest current and time value for $2.5 \cdot I_r$ from motor cold curve. Using the closest current value for $2.5 \cdot I_r$ and setting motor prior load current I_p and NPS component to zero. Now using the cold curve, we can modify Equation 5 and we get Equation 11. Now we can find value for *Thermal time constant normal* τ_{Normal} :

$$\tau_{\text{Normal}} = \frac{t_{2.5}}{\ln\left(\frac{\left(\frac{I_{2.5}}{I_r}\right)^2}{\left(\frac{I_{2.5}}{I_r}\right)^2 - k^2}\right)}. \quad (11)$$

A margin is added for both *the Thermal time constant start* and *Thermal time constant normal* in the applications. The margin sets the *thermal* time constants below the actual calculated value, allowing space between thermal limit curves and relay trip curves. By default, the margin is set to 5 % of the value calculated using Equations 10 and 11.

The relay trip curves are calculated using the calculated thermal time constants. Relay curves for both warm and cold motor are divided into two parts, one part for each thermal time constant. We now use a rated current as a prior load and the NPS component is set to zero for warm relay trip curve calculation. Equation 5 can be modified to calculate a relay trip curve for a warm motor t_{Warm} :

$$t_{\text{Warm}} = \tau \cdot \ln \left(\frac{\left(\frac{I}{I_r}\right)^2 - \left(\frac{I_p}{I_r}\right)^2 \cdot p}{\left(\frac{I}{I_r}\right)^2 - k^2} \right). \quad (12)$$

The equation can be modified for calculating a relay trip curve for a cold motor. A cold motor is defined as motor body temperature equals ambient temperature. This allows now setting the prior load to zero. Now we get an equation to calculate a relay trip curve for a cold motor t_{Cold} :

$$t_{\text{Cold}} = \tau \cdot \ln \left(\frac{\left(\frac{I}{I_r}\right)^2}{\left(\frac{I}{I_r}\right)^2 - k^2} \right). \quad (13)$$

When proper settings are found, an example of the result is shown in Figure 22. Relay trip curves are below motor thermal limit curves and above motor start starting curves. There is also the motor start-up supervision curve (*STTPMSU*), which is described in Section 6.4.

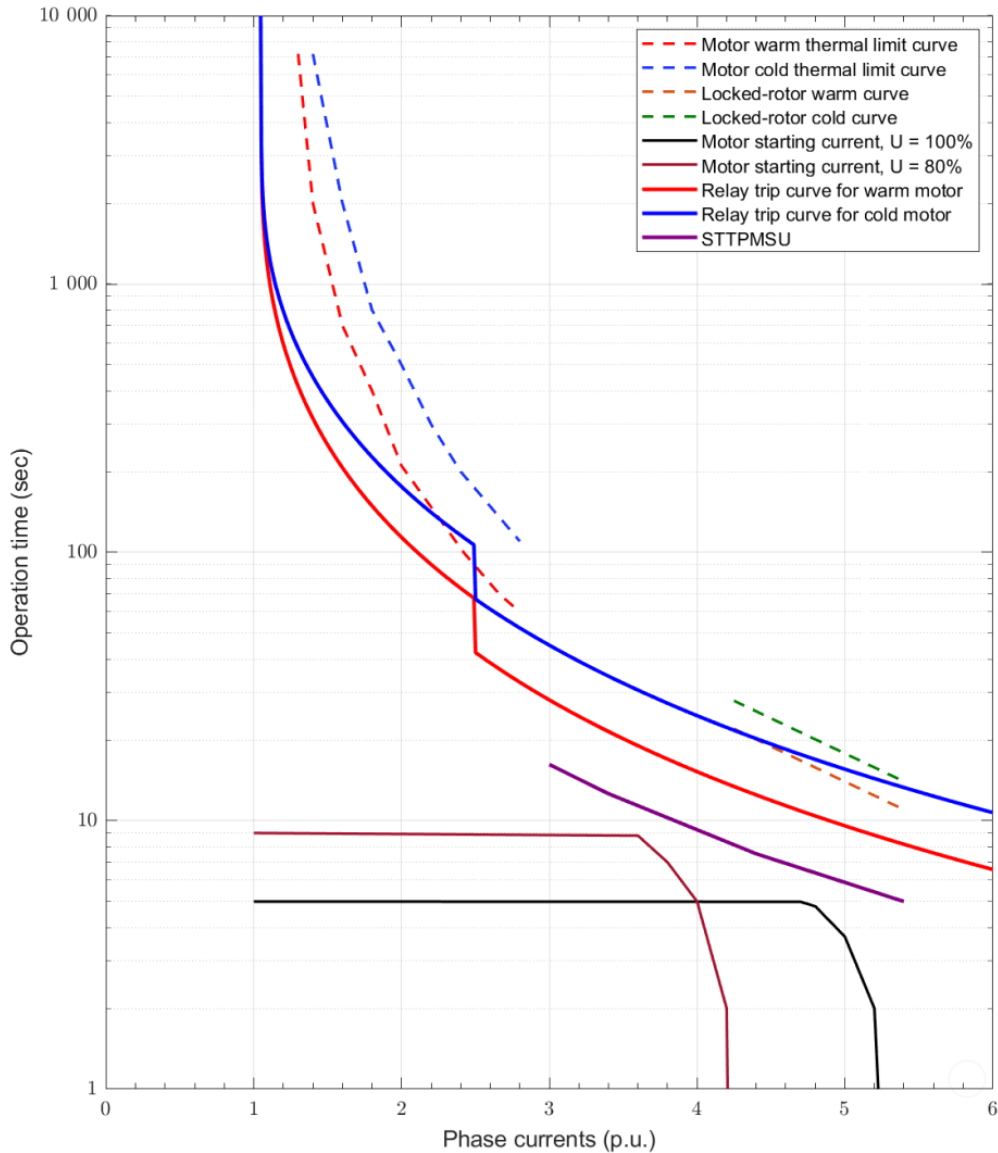


Figure 22. Example of Matlab applications' presentation of motor thermal limits, start currents and relay trip curves.

Motor thermal capacity used at motor starts is calculated after relay trip curves are calculated. Matlab or Octave asks from the user how many cold starts are required. The number of hot starts is calculated to be one less than cold starts. Both applications will calculate motor thermal behavior at rated and reduced voltages.

The thermal capacity based calculations at motor starts are divided technically into two parts into rated and reduced voltage calculations. The first part contains the thermal

capacity based calculation at the first motor start. The first part is always calculated. The second part contains thermal capacity based calculations for possible second and beyond motor starts. The second part is done with the help of a while loop function and maximally, it allows up to ten starts after the first start. The total maximum number of starts is eleven.

In the Matlab application, the user can choose if start stimulations begin from the cold or warm motor condition. In the Octave application, the calculations always begin from the warm state. Typically, start simulations from warm motor conditions with reduced voltage, are harder to allow permitted number of motor starts, as calculated TCU exceeds the set *Reset thermal value* limit easily.

Equations 6 and 7 are used for calculating the motor's thermal capacity level during motor starting acceleration. Motor rated and reduced starting currents from the excel file are used as a reference for measured currents I . For starting from the warm motor condition, Equation 9 is used to calculate motor prior load θ_P with the rated motor current. When calculating in the cold state, we can assume the negative phase sequence (NPS) components and motor prior load θ_P to be zero. We get simplified equations for calculating motor thermal capacity rise per motor starting from the cold state. Equation 14 represents a long term thermal capacity level θ_B :

$$\theta_B = \left[\left(\frac{I}{k \cdot I_r} \right)^2 - \frac{\theta_P}{p\%} \right] \cdot \left(1 - e^{-\frac{t}{\tau}} \right) \cdot p\% + \theta_P \quad (14)$$

and Equation 15 represents a short time hotspot temperature θ_A for the warm motor condition:

$$\theta_A = \left[\left(\frac{I}{k \cdot I_r} \right)^2 - \frac{\theta_P}{100\%} \right] \cdot \left(1 - e^{-\frac{t}{\tau}} \right) \cdot 100\% + \theta_P. \quad (15)$$

A *Thermal alarm* value is set to 95 % for thermal simulations, meaning an alarm is given if an actual motor thermal capacity used value exceeds this value. For restart inhibition, a *Restart thermal value* is used. This value is calculated using a calculated non-adiabatic motor thermal capacity used in a cold motor start. This cold motor thermal capacity used value is subtracted from a thermal alarm value, which now gives a value for the *restart thermal value*.

When motor is stopped, it cools down until it reaches ambient temperature. The stopped motor's cooling time is typically much longer than for a running motor because of reduced cooling. Meaning that there is no forced cooling. Cooling is assumed to be a non-adiabatic process. *Thermal time constant stop* parameter defines the rate of how fast a motor thermal capacity θ cools down. When motor is stopped, *Thermal time constant stop* τ_{Stop} is calculated:

$$\tau_{\text{Stop}} = \left(\frac{-t}{\ln(\theta)} \right). \quad (16)$$

The parameter can easily be determined using a motor cool-down time constant if it is available on the motor datasheet. If it is not available, the user can leave the parameter value to zero in the applications. Then the applications calculate the parameter automatically by solving the *Thermal time constant stop* from Equation 16, which is modified from Equation 6 by setting current references I and NPS components to zero.

Suppose *Thermal time constant stop* is not defined by the user, the applications can calculate it using Equation 16. The applications use one hour for time t in the equation to allow the next motor start after one hour. Thermal capacity θ is calculated using rated starting current and cold locked-rotor ratio. This ratio defines how much thermal capacity is used by one start. The same ratio is also used to calculate *Restart inhibit* level. *Restart inhibit* is calculated reducing thermal capacity used by one start θ from *Alarm thermal value*.

Now when the *Thermal time constant stop* parameter is available, motor thermal capacity θ_{Stop} after a permitted number of motor starts and user defined cooling time is calculated:

$$\theta_{\text{Stop}} = \theta_p \cdot e^{\frac{-t}{\tau_{\text{Stop}}}}. \quad (17)$$

The applications allow a user to define a time between starts. After each permitted motor starts and coolings, motor thermal capacity level calculation is shown in two figures. One figure for rated start current and another for reduced start current. An example of motor thermal capacity based results for rated current is shown in Figure 23.

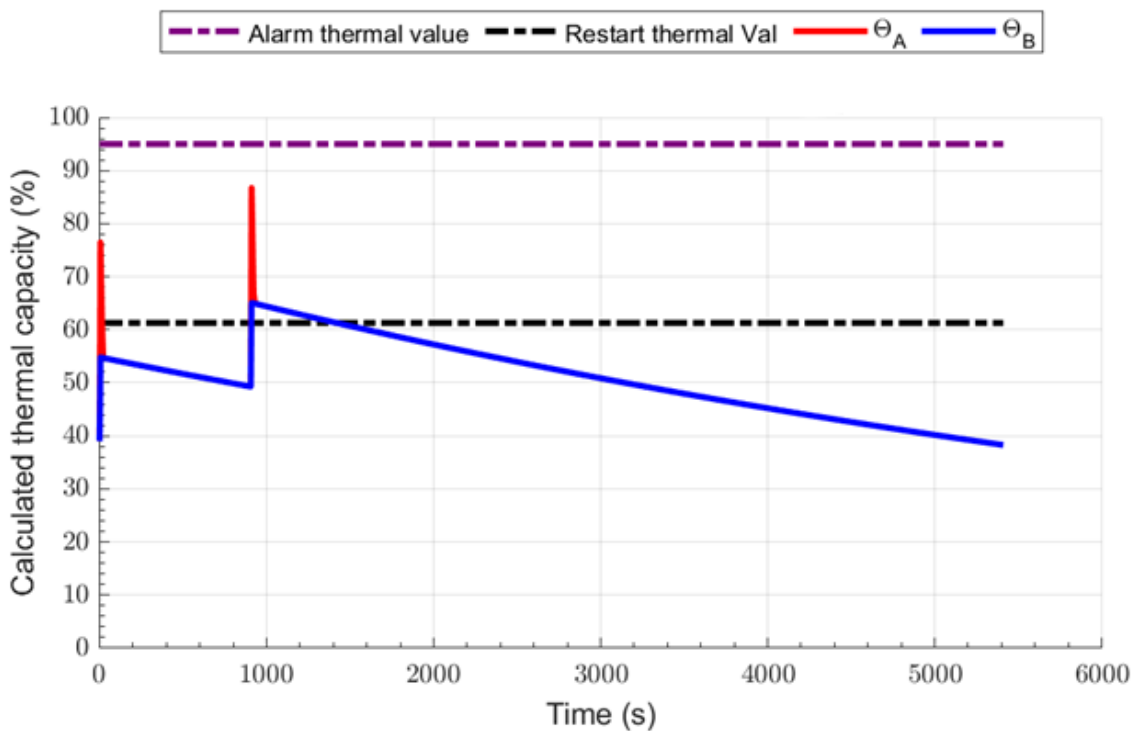


Figure 23. Example of Matlab applications' presentation of motor thermal capacity after two motor starts with previous prior load and one-hour cooling when the motor is stopped.

Both applications are equipped with checkers, which ensure the following conditions:

- Relay trip curves are below motor thermal limit curves. Four points from thermal limits curves are compared to relay trip curves. Two comparisons are from rated cold and warm locked-rotor curves and two comparisons from cold and warm stator thermal limit curves from the closest point to $2.5 \cdot I_r$.
- Motor starting curves are below relay trip curves. Both rated and reduced motor starting curves are compared to relay trip curves. Comparisons are made on a horizontal axis with steps of 0.1 A current value.
- Thermal Capacity Used is below the thermal alarm value in the last allowed reduced voltage motor start. This value is typically closest to the alarm value.

Each condition is checked using subtraction. The subtraction results shall be positive if every condition is inside limits. If any subtraction gives a negative value, applications decrease the *Weighting factor* value by steps of 2 % until each subtraction value is positive or the *Weighting factor* setting limit of 20 % is reached. If decreasing the *Weighting factor* does not help, applications will include an error message to a word result file and Matlab application will also indicate an error in status view. The next step to finding a condition inside the limits would be changing the *Overload factor*. However, it is left out from the first release of the applications.

The target of the applications is to cover the most common and most straightforward asynchronous motors. The applications cannot cover each motor for *MPTTR* protection calculations. The applications' logic would become too complicated or the applications would face the limitations of *MPTTR* protection function. Nowadays, with the first release of the applications, the most problems will occur if the protected motor is designed for ambient temperature other than 40 °C, or the motor has a large number of the required warm starts or the motor requires a long time for cooling between starts. However, the applications will include an error message if the applications notices that they can not cover the protection calculation for motor and then guide to contact protection expert.

6.4 Settings for motor start-up supervision function

The motor start-up supervision function has two parts. It supervises that the maximum starting time cannot be exceeded (prolonged starting time) and it limits the number of consequential start-ups. The applications calculate this prolonged starting time by I^2t , which is also visible in Figure 22. Prolonged starting time is calculated using four points of the rated starting current and reduced voltage starting time. REX640 also has a motor start counter function, which calculates a number of performed motor cold and warm starts. This function is not available in relays REM615, REM620 or REM630, so it is not included in the applications' first release.

Start detection A is used for detecting motor starting. The setting value for it should be around 150 % of the motor rated full-load current. The applications calculate this setting using half of a motor starting current value and the value is multiplied with motor rated full-load current. This value is then divided by the rated CT value.

Motor start-up A is set equal to the highest motor start-up current value at rated voltage. The highest start-up current value is searched from motor excel data with the help of a max function. Max function returns the highest value from the array. Similarly, *Motor start-up time* is searched with the use of max function from motor excel data. *Motor start-up time* is set 10 % higher in calculations than the motor excel data's actual motor starting time. Applications also check that slightly higher *motor start-up time* is still below locked-rotor time. If the locked-rotor time is below the set *motor start-up time*, the setting is reduced until it is below the locked-rotor time. When set *motor start-up time* is higher than the actual motor starting time, but below locked-rotor time, the motor is protected against a locked-rotor and prolonged start.

In the applications, the *Str over delay time* setting is set for 100 ms. This means that the motor starting method is such that the starting current has no transitions (over 100 ms) like in Y/D starter.

The applications do not have an option for speed-switch in the first release, so the *Operation mode* setting is set to Ilt. The speed-switch can be used to monitor rotor rotation. If the speed-switch is available, the rotation information can be used to enable “stall” mode for detecting motor starting.

The *Cumulative time Lim* variable is used to limit cumulative motor starting time. It is calculated using Equation 9, with a safety margin of 10 %. *Counter Red rate* is set to equal motor starting time. For inhibition time between each start, the setting *Restart inhibit time* is used. This setting is set to have the same value as the user has defined for *Stop Time Between Starts* in the applications.

Finally, *Motor standstill A* setting is set to a typical value of 12 % of the motor rated current. When the motor stator current falls below this value, the motor is assumed to be stopped.

6.5 Settings for short-circuit protection function

The short-circuit protection function is used for protecting motor or feeder cable against short circuits. In ABB motor protection relays, the short-circuit protection is called to *PHIPTOC*. Both Matlab and Octave applications have similar functionality. Applications ask if the motor drive’s feeder is a circuit breaker or a contactor. If the contactor is selected, this protection function is set off because contactor can not break a high fault current.

If a circuit breaker is selected, *PHIPTOC* protection function is set on. The *Start value* is set 1.5 times higher than the motor starting current. This prevents *PHIPTOC* function from operating during normal operation. *The operation delay* time is set to 20 ms. *The number of phases* is set to 1 out of 3, so the function will operate if one phase has an active short circuit. *Reset delay time* is set to 20 ms.

6.6 Settings for motor jam protection function

JAMPTOC function provides protection against stall or mechanical jamming when motor is operating in rated conditions. It is blocked during motor starting, as *STTPMSU* function protects motor from locked-rotor during starting. When *STTPMSU* function tells that motor starting is ended, *JAMPTOC* function is activated and *STTPMSU* start-up supervision becomes inactive.

Initially, the defined *Start value* is set to 50 % of the motor starting current. This should not limit normal motor operation. *Operate delay time* is set to 2000 ms. Overall this setting should be smaller than the allowed warm locked-rotor time.

6.7 Settings for negative sequence overcurrent protection function

MNSPTOC function gives protection against broken phase and unbalanced supply conditions. Unbalanced phase voltages create unbalanced phase currents, which create losses and heating.

A typical setting is used for the *Start value* setting. The typical value is 15 % to unbalance of motor rated current. Recommended curve *Inv. Curve B is used for Operation curve type*. The inverse curve is used as it provides selective protection in cases where multiple motors are connected to the same bus. A broken phase situation of any motor might cause too high unbalance in bus voltages (also resulting in a healthy motor to see unbalanced current over setting). A value for *Machine time Mult* is calculated with $175 / I_{\text{Start}}^2$. It should be noted that setting is inside relay setting ranges after calculation. *Current reference* is calculated using motor full-load current divided by rated CT current. (ABB oy, 2020a, p. 264).

6.8 Settings for phase reversal protection function

Motor reverse protection is not mandatory, but some motor applications are critical for motor rotation direction. The motor rotor rotation or load rotation to reverse direction may cause serious damage for the process or person working with the motor.

By default, this function is set off. But if this function is required, settings are based on factory default settings.

6.9 Settings for undervoltage protection function

When an asynchronous motor is started with direct-on-line (DOL) starting, it causes a voltage drop depending required power to start the motor and bus short-circuit power. This should be noted when setting undervoltage protection.

Typically *Start value* for undervoltage protection is set to 70 %. *Operate delay time* is set to 2 s.

6.10 Settings for overvoltage protection function

Typically, the overvoltage protection is set to about 110–120 % of the rated voltage and *Operate delay time* is set to a few seconds. The applications automatically set the *Start value* to 110 % of the rated voltage and *Operate delay time* to 2 s.

6.11 Calculation example for ABB Helsinki asynchronous motor

This section shows the results of the Matlab application automated protection setting calculations. The motor data is available in Appendix 3. Motor performance data.

The motor is a 1200 kW squirrel cage motor used in blower, fan. Insulation is according to Class F (155 °C) and the temperature rise is according to Class B (80 K). The maximum of consequence starts in one hour is set to three for cold and two for hot starts. Motor

rated starting time is five seconds and the starting time is nine seconds with reduced voltage. The maximum stall time at rated voltage is 11 seconds for the warm motor and 14 seconds for the cold motor. The maximum safe stall time for reduced voltage is 22 seconds for the warm motor and 28 seconds for the cold motor. Finally, the motor full-load current (FLC) is 70 A.

In this case, motor data as manufacturer's excel file was not available and therefore it was written to the Matlab excel file template. It is manually written to the Matlab excel file template. Other motor data is written to the user-definable fields, as shown in Figure 24. Also, a protection relay is selected with CTs. Stop time of 15 minutes between starts is used.

Protection relay data	
Protection relay	REM615 ▼
Relay secondary current	1 ▼ A
CT data	
CT rated primary	100 ▲▼ A
CT rated secondary	1 ▲▼ A
Import current and thermal limit curves	
<input type="button" value="Export Motor Data Excel File"/>	<input type="button" value="Import Motor Data Excel File"/>
<input type="button" value="Import ABB Helsinki Excel File"/>	<input type="button" value="Import ABB Italy Excel File"/>
Motor performance data	
Motor type	AMI 450L2P BAH
Motor full load current (FLC), In	70 ▲▼ A
Motor rated power	1200.000 ▲▼ kW
Motor rated voltage	8.300 ▲▼ kV
Rated line voltage	11.500 ▲▼ kV
Feeder driver	Circuit breaker ▼
	Select how motor is connected to supply voltage
Working mode	IEC ▼
	IEC or ANSI. If IEC motor needs to be overloaded select IEC with overload.
Service factor (SF)	1.05 ▲▼
	Allowed amount of overloading.
Actual ambient tempera...	40 ▲▼ °C
	This value will be used if suitable value for relay trip curve cannot found.
Number of cold starts	3 ▲▼
	Define the maximum number of motor starts in one hour. Hots starts are one less.
Cool-down time constant	0 ▲▼ min
	This can be set 0 if value is not know
Stop Time Between Starts	15 ▲▼ min

Figure 24. Matlab data input for automated protection setting calculations.

After importing motor thermal limit and starting curves, relay and CTs data is inserted. Every available protection function is selected to active. Now calculate button is pressed and the application will calculate every setting. When settings are calculated, the results are stored to the word results file. The results file is available in Appendix 4. Word report file.

7 Proposals to thermal overload protection improvement

This thesis's main focus is on automating the protection setting value calculations for high voltage asynchronous motor protection. Additionally, for this, ideas for developing ABB motor protection relays' thermal protection are studied. This chapter contains five development proposals for developing the ABB motor protection relays' motor thermal protection.

7.1 RTD based thermal model

The RTDs allow measuring temperature from the motor ambient or motor temperature in the windings or bearings. Currently, measured temperature information cannot be utilized very well in the relay thermal model. Only ambient temperature can be used for the calculation of relay internal full-load current. The RTD temperature information can also be used to trip if the measured temperature exceeds the set limit.

The starting point for the RTD thermal capacity calculation developments process is using similar approaches that General Electric (2020, pp. 6-22–6-25) and Venkataraman, et al. (2005, pp. 135–136) are using. They are using RTD Biased thermal overload, ANSI device number 49RTD. With RTD Biased thermal overload, stator thermal capacity is calculated with RTDs installed in the stator windings.

An RTD Bias graph is generated in Figure 25. The horizontal axis is set according to stator temperature. The vertical axis contains stator thermal capacity in different temperatures. The numeric points are presenting different motor operation stages. Point 1, motor is stopped, point 2, the motor operates at full-load current and point 3, motor is running overload. Motor should be tripped or an alarm should be generated when the stator thermal capacity is greater than it should be in a specific stator temperature.

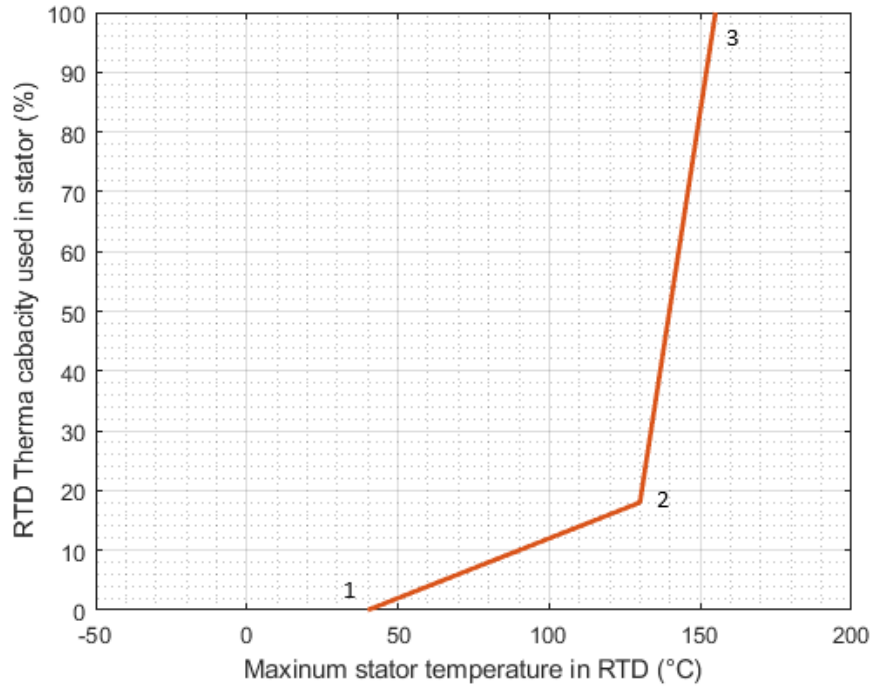


Figure 25. An example of RTD Biased stator thermal capacity curve.

The points defined in Figure 25 represent different stator conditions. The defined points are:

1. Stator is at ambient temperature and thermal capacity is not used. The RTD minimum point is defined by setting the horizontal axis value according to ambient temperature and the vertical axis value to zero.
2. Stator is at rated load. The RTD Bias mid-point is defined by setting the horizontal axis value according to stator's operating temperature. This can be higher if the motor has a service factor. In Figure 25, it is according to thermal class B (80 K) and ambient temperature (40 °C), so total (120 °C). The vertical axis value is set to used stator thermal capacity at full-load current and normal cooling.
3. Stator is overloaded. The horizontal axis, RTD Bias maximum point, is set according to stator's rated insulation class permitted hot spot temperature. In Figure 25, it is according to thermal class F (155 °C). The vertical axis value is set for 100 %.

Measured temperature and RTD Biased information can work as an additional thermal protection function for the current based thermal model. The RTD based thermal

function can work independently or work together with the current based thermal protection. When the RTD Bias thermal function works independently, it can trip or give alarms when the motor temperature exceeds set limits. When RTD Bias thermal function works together with the current based thermal function, it offers several benefits. Examples of those benefits are:

- The first benefit is that this allows checking if relay thermal settings are set correctly. The RTDs allow monitoring motor temperature during different motor operation states. This monitored information can be used, for example, to calculate the actual motor heating or cooling thermal time constants. If these calculated thermal time constants vary from the thermal time constants set to relay, protection relay can notice this when comparing the calculated and set thermal time constants together. Protection relay can be set to adjust the user-set thermal time constant to match the calculated thermal time constants or indicating an alarm.
- The second benefit is that a protection relay can learn the thermal time constants. Suppose the data about the thermal time constants are not available from the motor performance data. In that case, a protection relay can learn the thermal time constants during normal motor operations when the motor load stays constant.
- The third benefit is that it allows adjusting the set thermal time constant during motor's lifetime. Motor internal resistances will vary during its life. This allows the relay to take it into account and change the set thermal time constants.
- The fourth benefit is similar to the first one, as it allows a protection relay to check the motor's actual thermal condition. For example, suppose the motor thermal capacity used is calculated wrongly by the current base thermal model. In that case, the protection relay does not allow motor to restart when the calculated thermal capacity reaches the maximum. Even there is still capacity left. The RTD Bias based thermal function allows of taking this available thermal capacity into account and allowing an extra motor start.

7.2 Slip-dependent thermal model

ABB motor protection relays' current thermal model combines stator and rotor thermal protection. The model lies on the measured stator winding currents. This allows easily to monitor stator thermal behavior. However, for a rotor, this is not ideal. Mostly during motor starting, this approach does not fully cover rotor thermal behavior.

Nowadays, ABB motor protection relays use I^2t for calculating heating effect during motor starting. This works well if motor currents are constant during a locked-rotor condition. With a constant locked-rotor current, it is easy to calculate I^2t heating effect and trip motor when heating reaches a trip threshold temperature. However, this is not accurate as the rotor current depends on the rotor resistance which is proportional to the slip. In addition, the ABB I^2t based protection does not have any thermal memory. I.e. the cumulative effect of repeated starting is ignored. (ABB oy, 2020b, p. 1014).

One approach to tackle this heating problem during motor starting is to use a speed switch, but this requires an extra device. The second approach is to use a slip-dependent thermal model for a rotor. Mr. Stanley Zocholl has patented this kind of slip calculation for motor protection in Patent US7675720B1 (2010) "Motor protection using accurate slip calculations." In the Patent, Zocholl presents a way to estimate slip. The estimation would be by calculating rotor resistances using sampled signals from stator currents and voltages. When the slip and the changing rotor resistances are known, it helps to calculate the rotor heating effect during motor starting.

In parallel with this thesis, ABB has been studying this solution. Using a slip-dependent rotor thermal model allows ABB motor protection relays to have more choices when designing protection for motors with a long starting time. As nowadays, those situations are solved with a speed switch. The slip-dependent approach allows protection for motor where is no speed switch available.

7.3 Voltage-based thermal limit curves

The locked-rotor curve is constructed using I^2t formula when it is presented in motor thermal limit curves. Meaning that different motor starting current magnitudes have an equal threshold for thermal limit. When the starting current magnitude is smaller, for example, due to a lower voltage, the time in I^2t is higher. This I^2t locked-rotor limit is the same for the different starting currents when the rotor is not rotating. Due to that, the locked-rotor limit is more like a line than a curve in the motor thermal limit curves plot.

Venkataraman, et al., (2005, pp. 139–140) presented an idea that after a locked-rotor limit for a specific current value, the motor thermal limit is continuous to the stator thermal limit curve if the rotor is rotating. For example, the thermal limit curve is interpolated to the stator thermal limit curve from the rated locked-rotor limit. This interpolated curve is also called an accelerating thermal limit curve.

In Figure 26, typical motor thermal limit curves and starting currents are presented. However, there are also accelerating thermal limit curves shown. Typically the starting acceleration thermal limit curves are not shown. It should also be noted that starting acceleration thermal limit curves are present in the IEEE 620 standard for Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines (IEEE, 1996, p. 3).

The acceleration thermal limit curves also respond to different starting currents in different voltages by dynamically changing the acceleration thermal limit curve. If the start current curve is not changed, the motor may be damaged. For example, if the motor is started with 80 % of the rated voltage and rated current, starting acceleration thermal limit curve is used. This allows the motor to have a much longer starting time that the I^2t limit would allow.

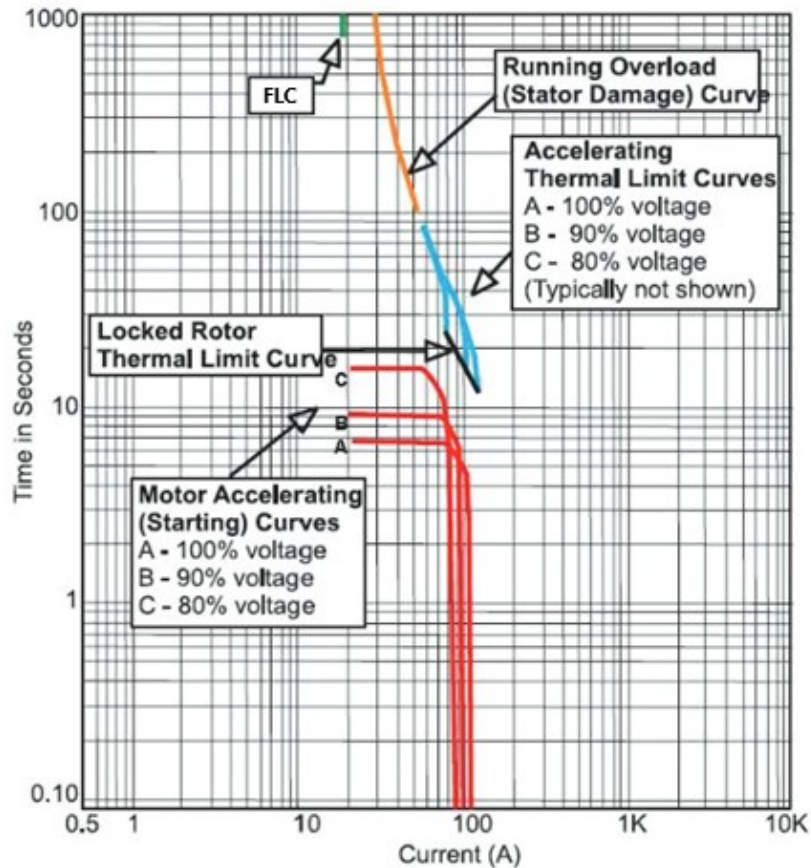


Figure 26. Example of acceleration thermal limit curves (IEEE, 2017, p. 70).

Currently, ABB uses the same relay thermal limit curves to protect both the stator and the rotor. This also covers the locked-rotor, meaning that the motor could be overprotected during the acceleration period in some cases. Using custom acceleration thermal limit curves also allows more time to start high-inertia loads.

ABB has voltage-dependent overcurrent protection function *PHPVOC*, which could be used. However, it does not have thermal memory, i.e. it will reset between starts and it is not available in every motor protection relay.

It should also be noted that custom acceleration thermal limit curves do not help in protection when there is no gap between the stator thermal limit curve and the locked-rotor curve. In that case, a speed switch should be used to detect rotor rotation. (Venkataraman, et al., 2005, p. 139).

7.4 The impedance-based locked-rotor protection

Locked-rotor protection works well when it is based on I^2t thermal limit or a speed switch. However, during a locked-rotor condition, it requires waiting for I^2t to reach the limit. Also, the speed switch is not available for all the motors.

When voltage and current measurements are available, IEEE (2013 p. 103) suggests using a distance (impedance) relay to protect a motor for locked-rotor condition. Motor impedance changes when motor starting is successful. Protection relay can set to trip if the impedance keeps constant during a defined period.

This could be acquired using ABB motor protection relays' three-phase underexcitation protection *UEXPDIS* function and setting an *offset* setting to positive. When the *offset* setting is positive, the resistance values are positive in an impedance circle.

Motor impedance change during motor start-up can be calculated using Ohm's law when motor current and voltage are available. For example, three starts for 10 kV motor with one phase starting current and voltage is shown in Figure 27. Motor impedance change during starting is calculated using Ohm's law. The short time peak at the beginning of the motor start is partial CT saturation. The saturation should be ignored. The impedance stays close to zero during starting. At the end of the starting, the impedance will rise to a rated operation impedance value. Depending on the motor, a good trip threshold level for locked-rotor protection would be around 23–25 s.

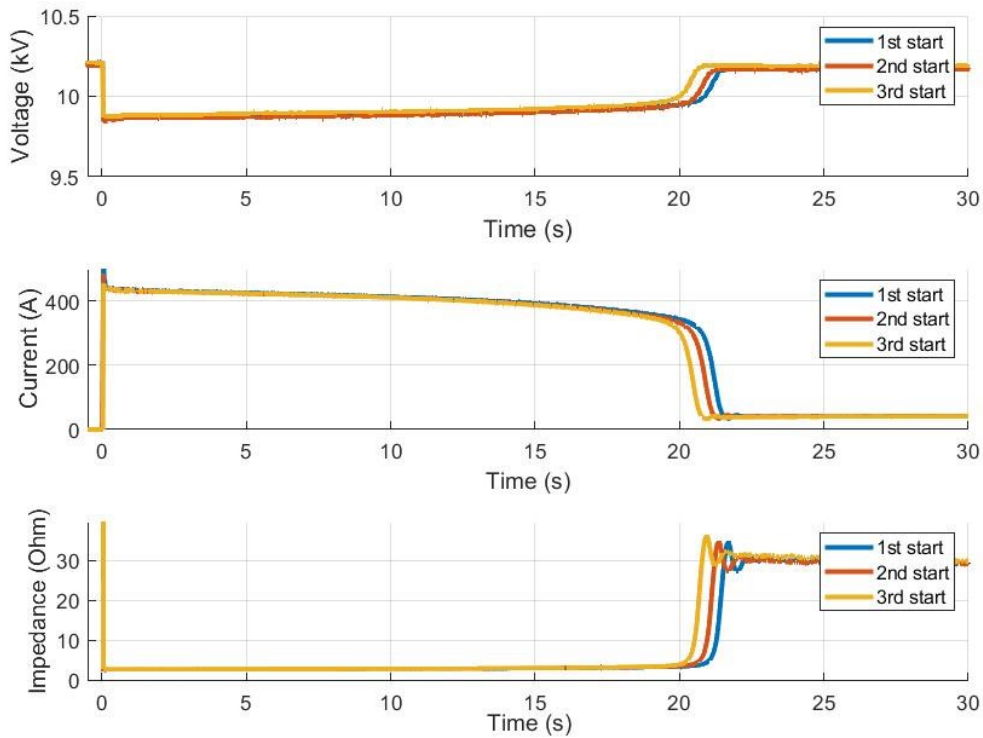


Figure 27. Motor voltage, current and impedance change during three motor startings.

As seen in Figure 27, motor starting time shortens after each motor start. This is due to motor getting warmer and internal resistances are smaller due to heat. This effect also limits the allowed number of motor warm starts. After a proper cooling time, motor starting time will return to normal.

7.5 Cooling thermal time constant running

Nowadays, ABB motor protection relays have three thermal time constants:

- *Thermal time constant normal*, which is used during normal motor operation.
- *Thermal time constant start* is used during motor starting.
- *Thermal time constant stop* is used when a motor is shut down.

ABB motor protection relays are missing one thermal time constant compared to General Electric relays: *Cool thermal time constant running*. This thermal time constant is

used when motor continues operating at rated load after motor overload situation has ended. Motor thermal capacity has increased due to overload situation. After the motor overload situation has ended, thermal capacity starts to decrease until it reaches rated load thermal capacity. This decrease rate GE is described using *Cool thermal time constant running*. Currently, ABB motor protection relays use the *Thermal time constant normal* for this purpose.

When a motor is operating at rated load or below, motor manufacturer's *Heating thermal time constant* applies. This is a thermal time constant for stator heating. But when motor is started or overload, other material constraints must be taken into account. Thus, a relay's thermal time constant must be set typically 15–20% of the stator heating thermal time constant.

Using the same *Thermal time constant normal* for both overload and rated load causes inaccurate thermal modeling after overload situation ends. As this thermal time constant is set smaller than stator heating thermal time constant, relay sees that motor cools down faster than it in reality does. Using 4th thermal time constant would fix this.

When using a *Thermal time constant normal* for both overload and rated load, this inaccuracy is simulated in Figure 28. The *Thermal time constant normal* is calculated using motor and relay data introduced in Section 6.11. The only difference is that the motor in Section 6.11 is in S1 duty type, but the simulated motor is operated in S9 duty type. The other simulation is with the *Heating time constant* available for the same motor in motor performance data. The same value is also available in Appendix 3. Before overloading, motor has been running at rated load in both simulations and thermal capacities are balanced. Motor is overloaded with 1.5 times rated load with 300 s and then the motor is operated at a rated load for 300 s. This is then repeated three times.

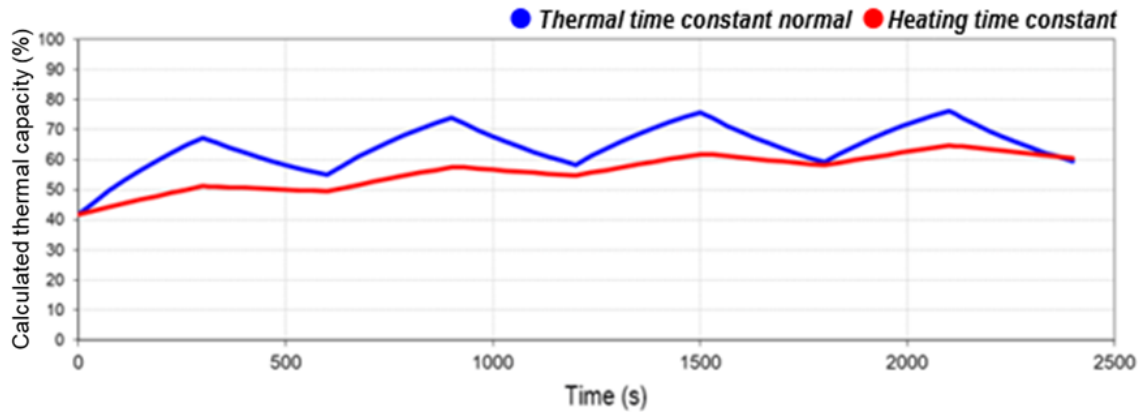


Figure 28. Thermal simulations with two different thermal time constants.

As shown in Figure 28, if using the *Thermal time constant normal* versus the *Heating time constant*, both heating and cooling effects are much faster in *Thermal time constant normal*. This is due to the *Thermal time constant normal* has a smaller value. For heating, the faster thermal capacity rise is reasonable, as the motor is heavily overloaded. But for cooling, this small value allows the motor to cool down much faster than in reality. This allows to thermally overload the motor heavily, which could cause motor damage.

The 4th thermal time constant for cooling during motor operating would cover this situation. It would allow the motor to cool down slower than using the *Thermal time constant normal* for cooling after an overload situation. However, the 4th thermal time constant should have a smaller value than the *Thermal time constant stop* as motor cooling system is still operating.

The 4th thermal time constant calculation is left out of this thesis, as it is only needed when motor is operated other than the S1 duty type and S1 is the most popular operation duty type for high voltage asynchronous motors. It is not needed in the duty type S1 motors, as S1 motors run at a constant speed and no overloading is allowed. Motor speed could change during operation with other duty types, which would cause different heating and cooling effects were the 4th thermal time constant would be needed.

8 Conclusions and Summary

This thesis contained two studies to answer the research questions. The first study was how the protection relay setting value calculation process for high voltage asynchronous motors could be automated to require less knowledge of protection engineering and take less time. The second study was how ABB made motor protection relays' thermal overload protection could be improved.

The first study was started with a literature review. The literature review was essential as setting automation cannot be designed without good knowledge and understanding of how motor should be correctly protected. The focus was on thermal protection, including starting, locked-rotor and overloading situations.

As a solution, two calculation applications were developed. Two applications were developed because different ABB units have different requirements and different software in use. The Matlab application was made for ABB Distribution Solutions in Vaasa and Octave application was made for ABB Motor and Generators in Helsinki. In Vaasa, ABB Distribution Solutions, protection relay customer support will use a standalone executable (.exe file) compiled from the Matlab code. ABB Helsinki will use the Octave version to calculate protection relay settings values for their motors.

Both calculation applications work in the same way. They calculate protection relay setting values automatically by utilizing the motor performance data and user-defined values. Finally, the applications will store the calculated protection relay setting values on a ready-made word report template.

This thesis focuses on motor thermal protection because it is usually challenging to calculate protection values for it. Other essential motor protection functions like earth-fault protection and motor differential protection were left out of this thesis. They were left out because earth-fault protection depends on so much installation and setting differential protection does not require so much knowledge.

There were challenges when coding the Matlab application. The App-designer interface is not designed for that complicated and big applications. Also, App-designer is still quite a new product, so I faced several bugs during coding the Matlab application. Some bugs caused a lot of extra work as the bugs caused project file corruption and I needed to restart the coding from scratch. Copying the corrupted code didn't work, as Matlab requires manually adding the GUI elements and then assigning the code to the elements.

The Octave application also required a lot of work. It was challenging to have the same functionality in the Octave application as in the Matlab application. Octave has its own syntax for functions, while some are close to Matlab's syntaxes, but many were different.

There is a lot of further development for both Matlab and Octave applications. For example, adding more protection functions to applications. Usually, high voltage motors have differential protection, but it is not available in REM615, REM620 or REM630, so it was left out from the first releases. In future, these will be implemented to applications in the later versions. Also, other new protection function can be added to applications when they are released.

For the Matlab version, the final goal will be to convert the application to Matlab Web App. That would allow running the application only using a web browser. That means that there is no need to download Windows Exe files.

The second part of this thesis was to study how ABB made motor protection relays could be improved. The focus was on motor thermal protection. The study's reason was that different protection relay manufacturers implemented high-voltage asynchronous motor thermal overload protection in slightly different ways.

The study was done by comparing three protection relay manufacturers. That resulted in a few functions to protect the motor from thermal overloads during running and

starting conditions. The study resulted in five development proposals for ABB to improve motor protection relays' motor thermal overload protection model:

1. The first proposal seeks to take advantage of the RTD measurements and bring additional functionality to the current-based thermal overload protection.
2. The second proposal aims to consider the asynchronous machine's slip when calculating the rotor's thermal overload.
3. The third proposal allows starting high inertial loads better by modifying the motor's thermal limit curves.
4. The fourth proposal is to provide a new opportunity to identify a locked-rotor during motor start-up from the motor's impedance.
5. The fifth proposal introduces a 4th thermal time constant that considers motor cooling after an overloading situation ends and motor continues operating.

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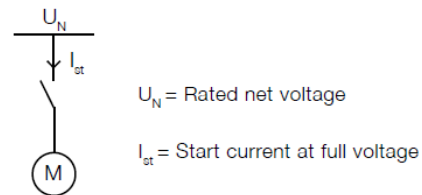
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Appendixes

Appendix 1. Technical note, starting methods for AC motors modified from ABB Motors and Generators, (2010).

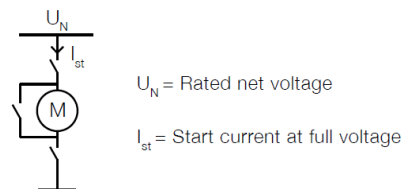
Direct-on-line (DOL) start

In this method, the motor is connected directly on-line by means of circuit breaker or contactor. The starting current can vary typically from 3 to 7 times the motor nominal current. This method is the simplest, cheapest and most common starting method.



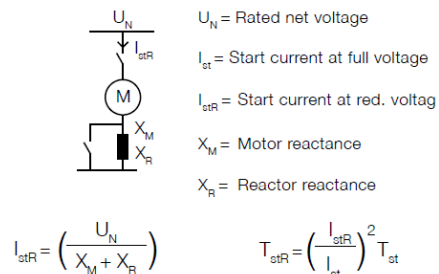
Star-Delta (Y/D) starting

In this method, motor is started in Y-connection, which reduces the starting current about 1/3 of the DOL-starting. Then motor is switched to D-connection. This method is mostly used in low voltage motors. From start-up detection and supervision point of view, the switching time from Y to D must be considered as it causes interruption in the starting current.



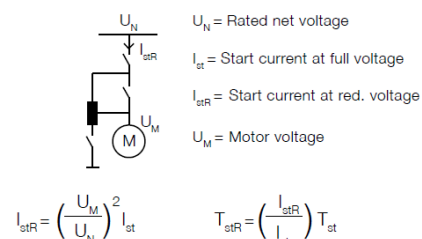
Reactor start

In this method, a series reactor is used at starting for limiting the start-up current. Then the reactor is bypassed.



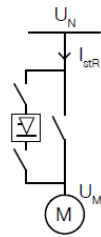
Auto transformer start

In this method, the motor is started with reduced voltage using an auto-transformer. Next, the auto-transformer star-point breaker or contactor is opened. Finally, the auto-transformer is by-passed.



Soft starters

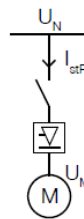
In this method, the motor is started using a soft starter which progressively increase the motor voltage. After reaching desired speed, the soft starter is by-passed.



U_N = Rated net voltage
 I_{stR} = Start current at red. voltage
 U_M = Motor voltage

Frequency converter

In this method, the frequency converter enables low starting current as the motor can produce rated torque at rated current from zero to full speed. The frequency converter is designed for continuous feeding of motors.

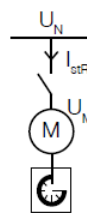


U_N = Rated net voltage
 I_{stR} = Start current at red. voltage
 U_M = Motor voltage

Note that protection relay almost always must measure currents before the frequency converter. This is because relays typically cannot cope the variable frequency in the motor current.

Rheostat starting used with slip ring motors

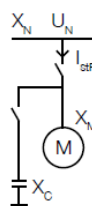
In this method, resistance of the rotor circuit is adjusted during the motor start-up. As a result, motor start-up current can stay below the motor full-load current during entire starting process.



U_N = Rated net voltage
 I_{stR} = Start current at red. voltage
 U_M = Motor voltage

Capacitor start

In this method, it is possible to start motor with full starting torque without of disturbing the network. Capacitor bank is used to store power required for magnetization. After start, bank is uncoupled. The disadvantages in this method is high cost and the large space requirement for the capacitor bank.



U_N = Rated net voltage
 I_{stR} = Start current w/capacitor
 X_N = Net reactance
 X_C = Capacitor bank reactance
 X_M = Motor short circuit reactance

$$I_{stR} = \frac{U_N}{\sqrt{3} \left(X_N + \frac{X_C X_M}{X_C + X_M} \right)}$$


$$T_{stR} = \frac{\frac{X_C X_M}{X_C + X_M}}{X_N + \frac{X_C X_M}{X_C + X_M}} T_{st}$$

Appendix 2. Summary of IEEE and EPRI Motor Reliability Surveys

Table 6. Summary of IEEE and EPRI Motor Reliability Surveys (Venkataraman, et al., 2005, p. 127).

IEEE STUDY		EPRI STUDY		AVERAGE
FAILURE CONTRIBUTOR	%	FAILED COMPONENT	%	%
Persistent Overload	4.20%	Stator Ground Insulation	23.00	Electrical Related Failures
Normal Deterioration	26.40%	Turn Insulation	4.00	
		Bracing	3.00	
		Core	1.00	
		Cage	5.00	
Electrical Related Total	30.60%	Electrical Related Total	36.00%	
High Vibration	15.50%	Sleeve Bearings	16.00	Mechanical Related Failures
Poor Lubrication	15.20%	Antifriction Bearings	8.00	
		Trust Bearings	5.00	
		Rotor Shaft	2.00	
		Rotor Core	1.00	
Mechanical Related Total	30.70%	Mechanical Related Total	32.00%	
High Ambient Temp.	3	Bearing Seals	6.00	Environmental, Maintenance & Other Reasons Related Failures
Abnormal Moisture	5.8	Oil Leakage	3.00	
Abnormal Voltage	1.5	Frame	1.00	
Abnormal Frequency	0.6	Wedges	1.00	
Abrasive Chemicals	4.2			
Poor Ventilation Cooling	3.9			
Other Reasons	19.7	Other Components	21.00	
Environmental Related & Other Reasons: Total	38.70%	Maintenance Related & Other Parts: Total	32.00%	

Appendix 3. Motor performance data (ABB oy, 2018).


ABB Oy Motors & Generators	Classifying code or document type				
	PERFORMANCE DATA OF MOTOR				
Department/Author	Date of issue	Lang.	Rev. date	Our ref.	
Customer ref.	Saving Ident		Rev./Changed by		Pages 1/4

Driven machine: Blower, fan

Motor type code	AMI 450L2P BAH			
Motor type	Squirrel cage motor			
Mounting designation	IM 1001			
Protected by enclosure	IP 55			
Method of cooling	IC 31			
Insulation	Class F			
Standards	IEC			
Cooling air flow, min.	1.6 m ³ /s			
Ambient temperature, max.	55 °C			
Altitude, max.	1000 m.a.s.l.			
Duty type	S1			
Temp. rise	Class B (RES)			
Connection of stator winding	Star			
Rated output	1200 kW			
Voltage	11500 V ±5 %			
Frequency	50 Hz			
Speed	2977 rpm			
Current	70 A			
Relat. starting current ¹⁾	5.4 (5.9)			
Relat. starting torque	0.60			
Relat. maximum torque	2.3			
No load current	15 A			
Rated torque	3849 Nm			
Load characteristics	Load %	Current A	Efficiency %	Power Factor
	100	70	96.1	0.90
	75	53	96.3	0.89
	50	37	96.0	0.85
Direction of rotation	Counter-clockwise			
Inertia rotor / load	Approx. 14 kgm ² / 17 kgm ²			
Bearings	Antifriction			
Maximum stalling time	14 / 11 s (cold/warm, U=100%) 28 / 22 s (cold/warm, U=80%)			
Starting time	5 s (U=100%) 9 s (U=80 %)			
Number of consec. starts	3 / 2 (cold/warm)			
Maximum number of starts	1000 / year			
Warm-up time constant	25 min			
Cool-down time constant	150 min			

This performance data is final and the Motor will be manufactured accordingly. All Motor data is subject to tolerances in accordance with IEC. ¹⁾ Guaranteed values in parenthesis. Efficiency based on typical additional load losses acc. measurements. ABB Oy, Motors & Generators

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ABB Oy Motors & Generators		Classifying code or document type PERFORMANCE DATA OF MOTOR				
Department/Author	Date of issue	Lang.	Rev. date	Our ref.		
Customer ref.	Saving Ident		Rev./Changed by		Pages 2/4	

Motor type code: AMI 450L2P BAH

Rated output	1200 kW	Power Factor	0.90
Voltage	11500 V ±5 %	Rated torque	3849 Nm
Frequency	50 Hz	Relat. starting current	5.4
Speed	2977 rpm	Relat. starting torque	0.60
Current	70 A	Relat. maximum torque	2.3

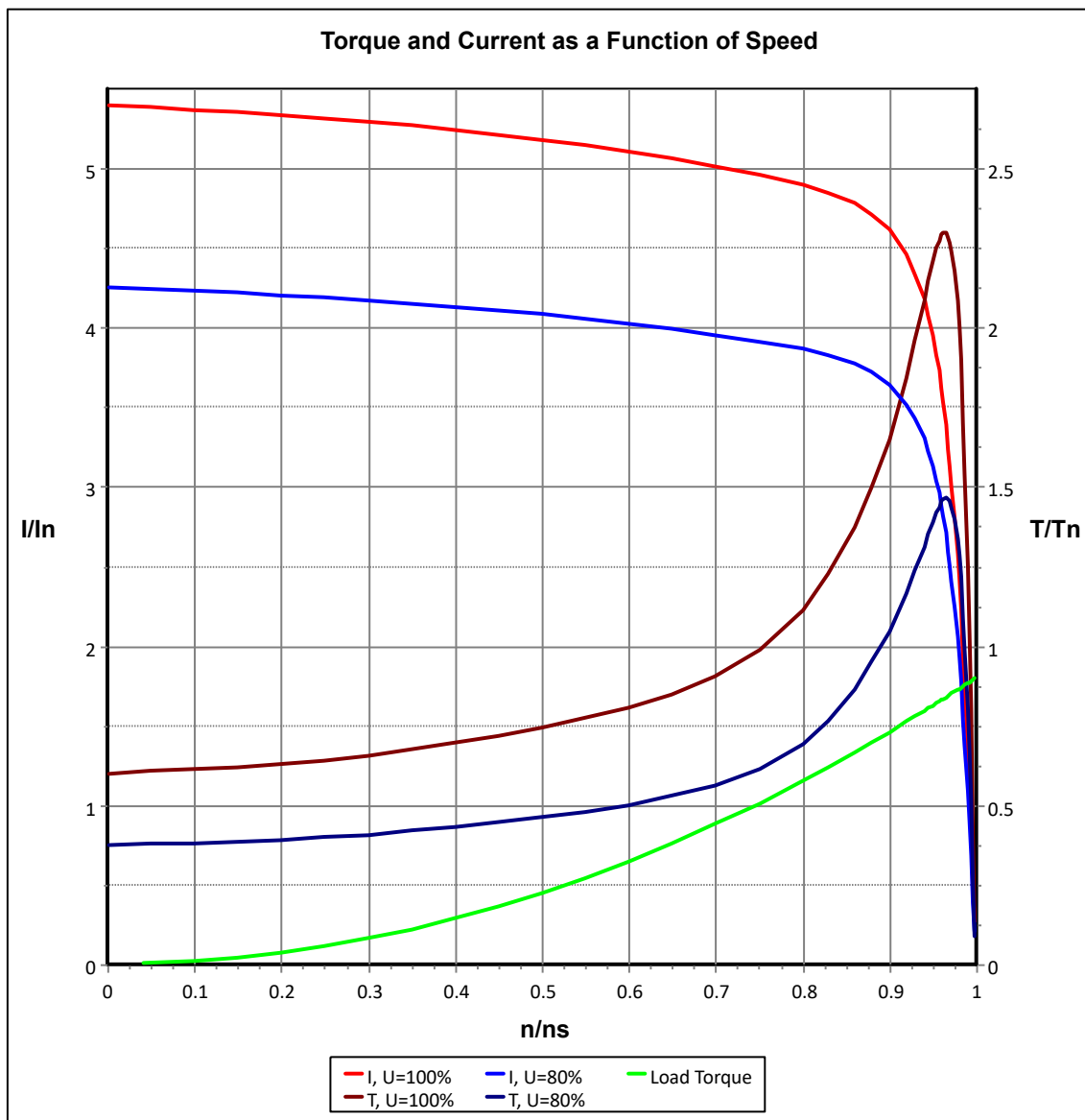



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ABB Oy Motors & Generators		Classifying code or document type PERFORMANCE DATA OF MOTOR				
Department/Author	Date of issue	Lang.	Rev. date	Our ref.		
Customer ref.	Saving Ident		Rev./Changed by		Pages 3/4	

Motor type code: AMI 450L2P BAH

Rated output	1200 kW	Power Factor	0.90
Voltage	11500 V \pm 5 %	Rated torque	3849 Nm
Frequency	50 Hz	Relat. starting current	5.4
Speed	2977 rpm	Relat. starting torque	0.60
Current	70 A	Relat. maximum torque	2.3

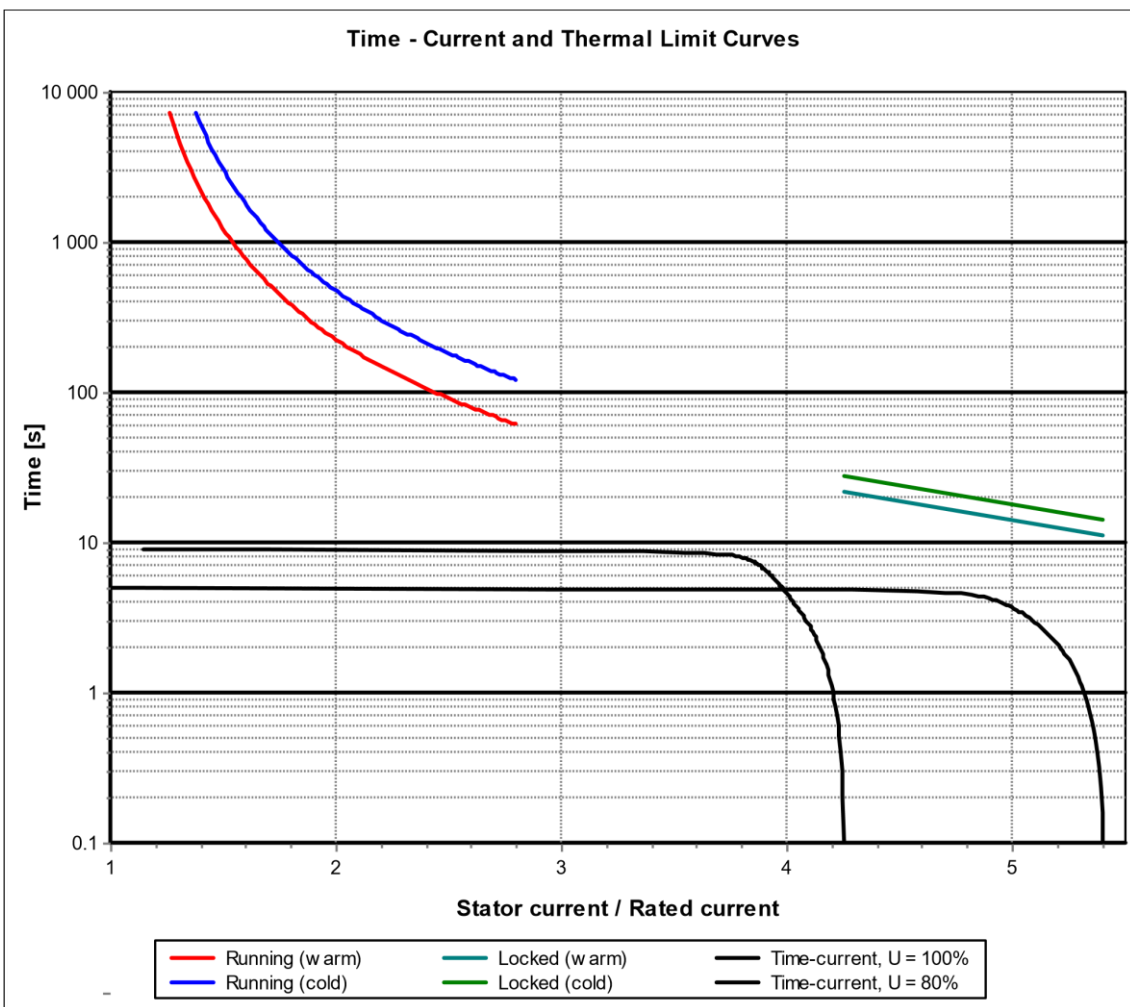



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ABB Oy Motors & Generators		Classifying code or document type PERFORMANCE DATA OF MOTOR				
Department/Author	Date of issue	Lang.	Rev. date	Our ref.		
Customer ref.	Saving Ident		Rev./Changed by		Pages 4/4	

Motor type code: AMI 450L2P BAH

Rated output	1200 kW	Power Factor	0.90
Voltage	11500 V ±5 %	Rated torque	3849 Nm
Frequency	50 Hz	Relat. starting current	5.4
Speed	2977 rpm	Relat. starting torque	0.60
Current	70 A	Relat. maximum torque	2.3

Airgap torque at start from standstill

$$T_e(t) = M_0(1 + e^{-t/\tau_1} e^{-t/\tau_2}) - M_1 (\cos(\omega t - \varphi) e^{-t/\tau_1} + \cos(\omega t + \varphi) e^{-t/\tau_2})$$

$$M_0 = 0.58 ; M_1 = 4.25 ; \tau_1 = 2.6 \text{ s} ; \tau_2 = 0.0195 \text{ s} ; \varphi = 1.43 \text{ rad}$$

Maximum value of torque 4.63 * TN, when t = 94.5 ms ($\omega = 2\pi f$, f = supply freq.)

Airgap torque at 3-phase short circuit at terminals

$$T_e(t) = M_0 e^{-t/\tau_0} - M_1 e^{-t/\tau_1} \sin \omega t$$

$$M_0 = -0.573 ; \tau_0 = 0.0324 \text{ s} ; M_1 = 5.6 ; \tau_1 = 0.0334 \text{ s} ; \omega = 307 \text{ rad/s}$$

Maximum value of torque -5.31 * TN, when t = 5 ms

Airgap torque at 2-phase short circuit at terminals

$$T_e(t) = M_{00} (1 - e^{-t/\tau_0}) + (M_0 + M_2 e^{-t/\tau_2}) \sin 2\omega t - M_1 e^{-t/\tau_1} \sin \omega t$$

$$M_{00} = 0.798 ; M_0 = 1.4 ; M_1 = 5.86 ; M_2 = 1.5 ; \tau_0 = 0.125 \text{ s} ; \tau_1 = 0.0407 \text{ s} ; \tau_2 = 0.0674 \text{ s} ;$$

$$\omega = 312 \text{ rad/s}$$

Maximum value of torque -6.92 * TN, when t = 6.5 ms

Airgap torque at high speed automatic reclosing

$$T_e(t) = M_0 e^{-t/\tau_0} + (M_1 e^{-t/\tau_1} + M_2 e^{-t/\tau_2}) \cos(\omega t - \varphi) + M_{00}$$

$$M_0 = -8.98 ; M_1 = 6.07 ; M_2 = 0 ; M_{00} = 0.536 ; \tau_0 = 0.028 \text{ s} ; \tau_1 = 0.0628 \text{ s} ; \tau_2 = 10 \text{ s} ;$$

$$\varphi = -0.565 \text{ rad} ; \omega = 294 \text{ rad/s}$$

High speed automatic reclosing time t = 0.2 s

Maximum value of torque -11.9 * TN, when t = 7 ms

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Appendix 4. Word report file



Relay setting recommendations

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1. Information

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2. Motor and protection relay data

Motor type	AMI 450L2P BAH
Rated output	1200 kW
Rated voltage	8.3 kV
Full-load current (FLC), In	70 A
Start-up current	5 A
Start-up time	5 s
Required starts	3 Hot / 2 Cold
CT	100 / 1 A

3. SETTING RECOMMENDATIONS

3.1 Thermal overload protection MPTTR

The *MPTTR* function block provides thermal overload protection for motor. There is no information about the load connected to the motor. Settings are based on motor thermal limit curves, allowing at least 3 cold and 2 hot starts when start time is 9s.

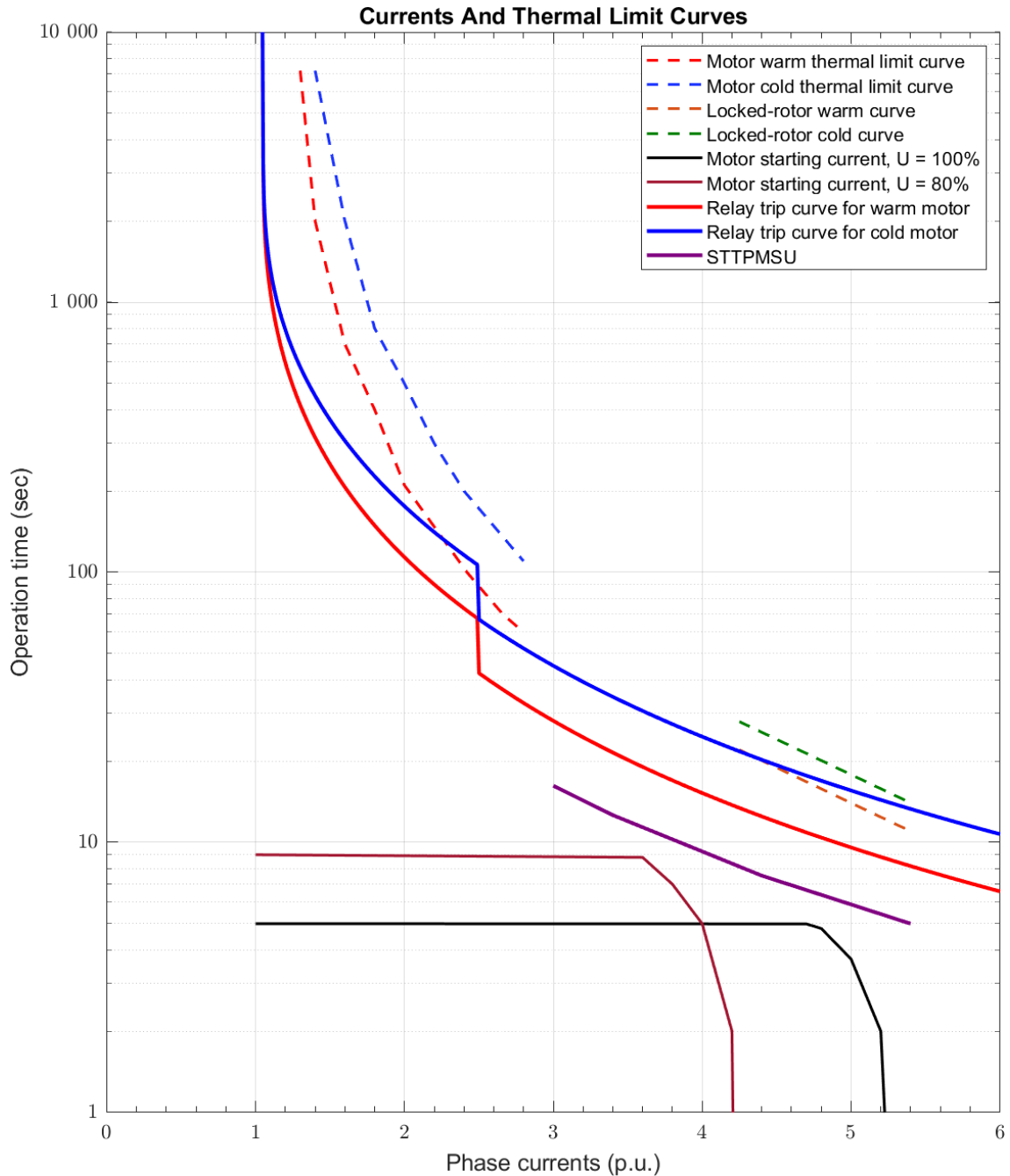
MPTTR Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Overload factor	1.05	Includes inaccuracies
Alarm thermal value	95 %	Typical setting for thermal alarm
Restart thermal Val	61.3 %	
Negative Seq factor	0	Factory default
Weighting factor p	43 %	
Time constant normal	345 s	
Time constant start	345 s	
Time constant stop	8483 s	
Env temperature mode	FLC Only	Used when no RTD sensor for ambient temperature is available.
Env temperature Set	0 °C	

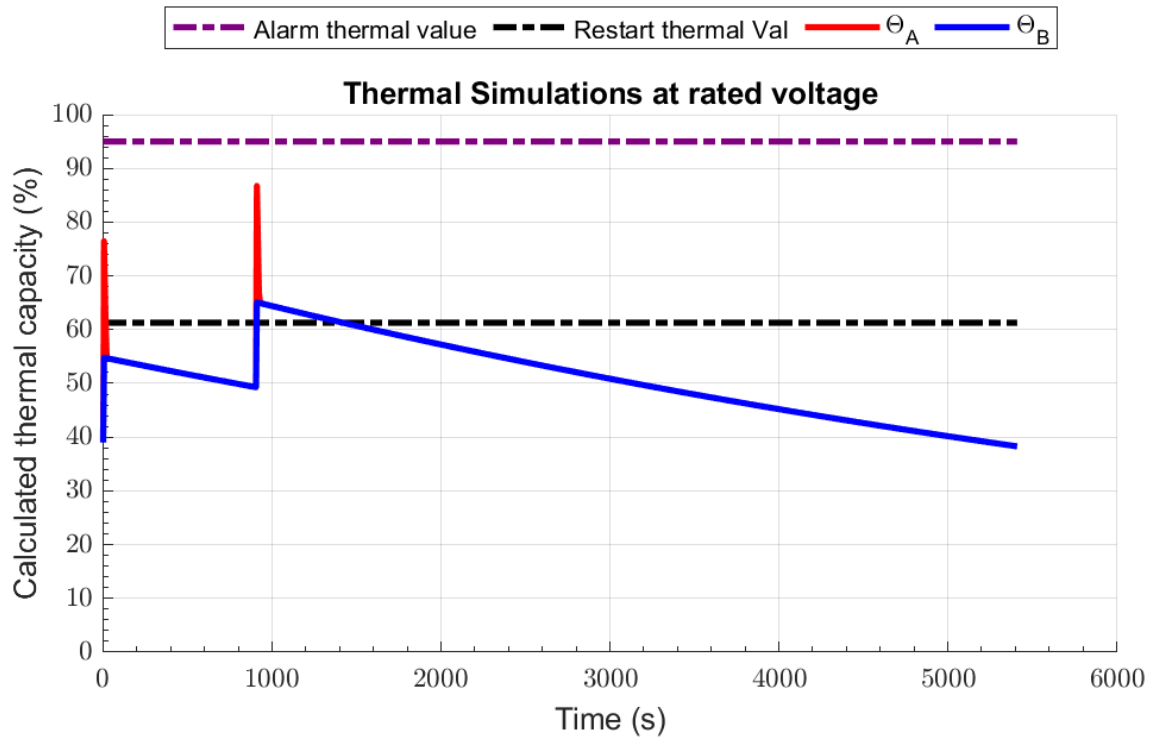
MPTTR Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	
Current reference	0.7 x I _n	Full-load current / CTs
Initial thermal Val	74 %	Factory default

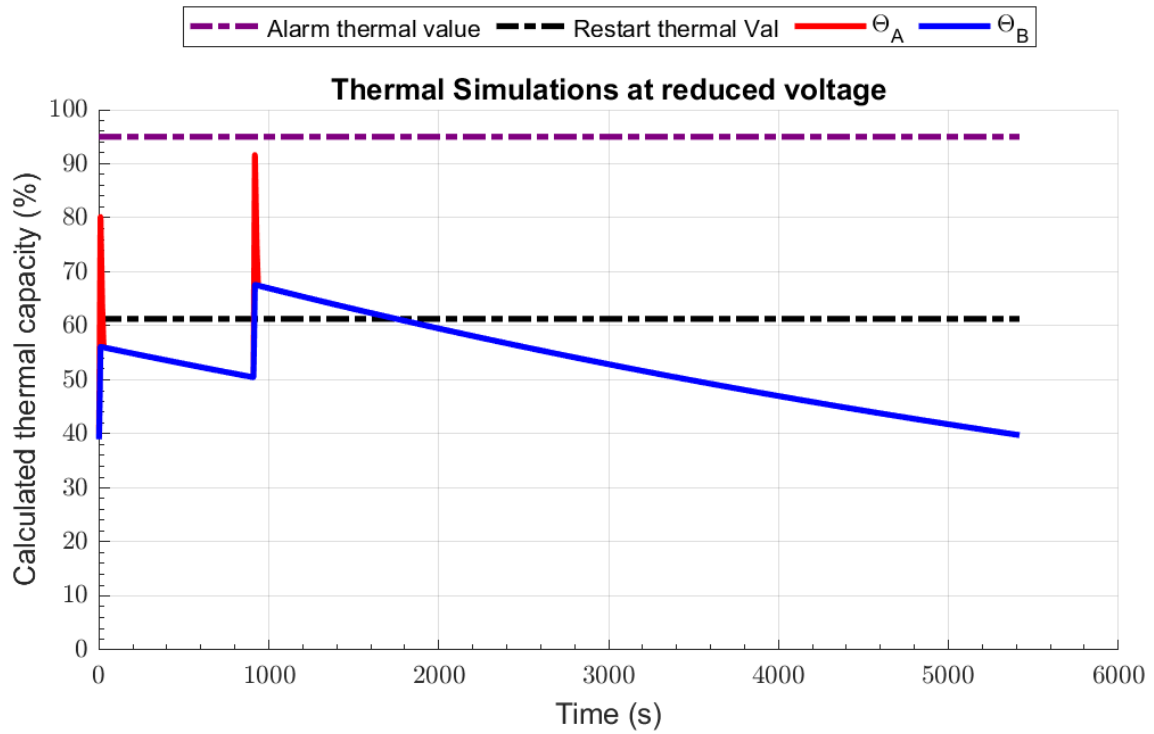
In the next figure, the relay time-current characteristic (trip curve) is given. The “Relay Warm Curve” correspond situation at where motor has been running with rated current before overloading. Also, the Motor Start-up supervision (STTPMSU) function block curve is shown here.



These settings allow required number of consecutive starts. The next figure shows thermal simulation of 2 consecutive starts for a warm motor at rated voltage. Time between starts is 15 minutes.



These settings allow required number of consecutive starts. The next figure shows thermal simulation of 2 consecutive starts for a warm motor at reduced voltage. Time between starts is 15 minutes.



3.2. Motor start-up supervision STTPMSU

This function block has two protection purposes. It supervises, that the maximum starting time cannot be exceeded (prolonged starting time) and it limits the number of sequential start-ups. In the motor start-up, the relay continuously calculates the product of squared phase current and time from the beginning of the start-up. This value is compared to the settings. Relay trips if $I_{L_{\max}}^2 \times t \geq (\text{Start current})^2 \times (\text{Start time})$

After motor start-up, the cumulative start-up counter is increased with the measured actual motor start-up time. When the counter exceeds the set time limit the function block inhibits restarting (this does not trip the motor, only prevents restarting). Only after some time (determined with the countdown rate –setting) the relay will allow new restart.

STTPMSU Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Start detection A	1.5 x I _n	For detecting motor start-up 1.5 x full-load current
Motor start-up A	3.78 x I _n	Start current 5.0 x full-load current / CTs
Motor start-up time	5 s	Trip time for STTPMSU, should be less than locked-rotor time
Lock rotor time		This setting is not used when the operation mode is "Ilt".
Str over delay time	100 s	Factory default

STTPMSU Non-group settings

Setting parameter	Setting value	Comment
Operation	On	
Operation mode	lIt	
Counter Red rate	5 sec/h	Cumulative counter reduction, Existing setting.
Cumulative time Lim	11 sec	Cum.counter time limit
Emg start Red rate	20 %	Factory default
Restart inhibit time	15 min	Time delay between consecutive starts. Not defined by motor manufacturer
Motor standstill A	0.08 x In	Detection of motor stop About 0.12xFull-load current / CTs

3.3 Short-circuit protection PHIPTOC

This function block is used to give protection against short-circuit in the motor feeder and motor.

PHIPTOC Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Start value	5.67 x In	
Start value Mult	1	
Operate delay time	20 ms	

PHIPTOC Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	
Num of start phases	1 out of 3	
Reset delay time	20 ms	

3.4 Motor jam protection JAMPTOC

This function block is used to detect a running motor jamming situation. During motor start, this function is blocked by the STTPMSU function.

JAMPTOC Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	
Start value	1.89 x I _n	
Operate delay time	2000 ms	
Reset delay time	100 ms	

3.5 Negative-sequence overcurrent protection MNSPTOC

The MNSPTOC function block provides phase unbalance protection. The function calculates negative phase sequence current. The operation time can be definite or inverse time. Only one MNSPTOC function is needed.

MNSPTOV Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Start value	0.11 x In	
Operating curve type	Inv. Curve B	
Machine time Mult	6.0	
At the moment all other settings as factory default		

MNSPTOV Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	
Current reference	0.7 x In	
At the moment all other settings as factory default		

3.6 Phase reversal protection PREVPTOC

This function block is used for preventing motor to run in incorrect directions.

PREVPTOP Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Start value	0.52	
Operate delay time	100	

PREVPTOP Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	

3.7 Undervoltage protection PHPTUV

When using only one stage of undervoltage protection, the protection is typically set 70 % of the rated voltage and short-operation time.

PHPTUV Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Start value	0.51 x In	
Time multiplier	1	
Operate delay time	1000 ms	
Operating curve type	IEC Def. Time	

PHPTUV Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	
All settings not mentioned here should have factory default values.		

3.8 Overvoltage protection PHPTOV

Typically, the overvoltage protection is set to about 110...120% of the rated voltage, and the operate time to a few seconds. The protection must be coordinated with the incoming/bus overvoltage protection.

PHPTOV Group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Start value	0.79 x In	
Time multiplier	1	
Operate delay time	5000 ms	
Operating curve type	IEC Def. Time	

PHPTOV Non-group settings

<i>Setting parameter</i>	<i>Setting value</i>	<i>Comment</i>
Operation	On	
All settings not mentioned here should have factory default values.		

