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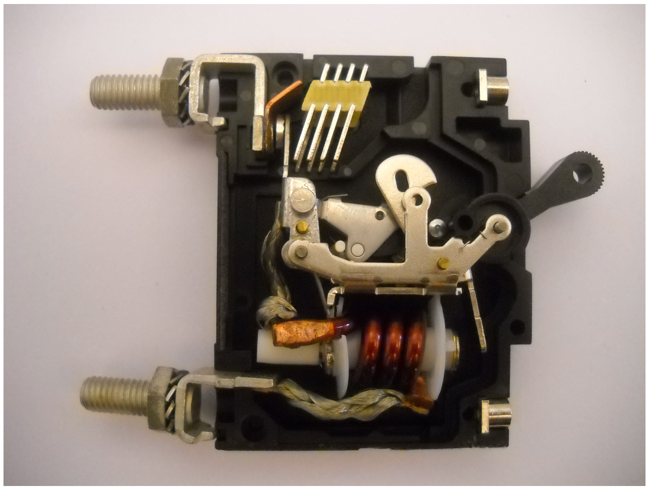

Circuit breakers, Melting fuses and Electronic fuses

Analysis and Design rules for use in Telecom power applications

Master of Science Thesis in the Master Degree Program Electric Power Engineering

JOHANNES ANDERSSON
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Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Photo of a circuit breaker

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Abstract

Selecting and dimensioning the best circuit protection for an application can be very hard. To make this easier for the employees at Ericsson Power Solutions a guideline has been developed. Questions the employees had regarding circuit protection have been answered. Manufacturers have been consulted and IEC and UL standards have briefly been investigated. A guideline consisting of derating rules for melting fuses and hydraulic magnetic circuit breakers has been developed. Considerations have been made in order for the guideline to be of help when designing circuit protection at Ericsson Power Solutions. One of the main issues has been to determine which current is to be derated since the current often includes ripple. How to investigate if a circuit breaker will endure a pulse was unclear and has now been clarified also both reoccurring and single pulses can now be dealt with. Altitude derating is required above a certain altitude. A general model for temperature influence on trip time for magnetic hydraulic circuit breakers has been determined. Finally, one melting fuse and one circuit breaker were designed according to the guideline. The result was close to the ratings of the protections used today but none the less slightly changed.

Keywords: Circuit protection, Fuseology, Melting fuses, Circuit breakers, Electronic fuses, Electronic circuit breakers, Design rules.

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The work has been carried out at Ericsson Power Solutions at Lindholmen, Sweden.

List of abbreviations

BFU	Battery Fuse Unit
CB	Circuit Breaker
DU	Digital Unit
EPS	Ericsson Power Solutions
HOD	High Ohmic Distribution
LOD	Low Ohmic Distribution
MHCB	Magnetic Hydraulic Circuit Breaker
IEC	The International Electrotechnical Commission
PCB	Printed Circuit Board
PCF	Power Connection Filter
PCU	Power Connection Unit
PDU	Power Distribution Unit
PSU	Power Supply Unit
RBS	Radio Base Station
RU	Radio Unit
SCU	Support Control Unit
SHU	Support system Hub Unit
UL	Underwriters Laboratories

List of definitions

Ambient temperature The temperature in direct connection with (immediately surrounding) the circuit protector

Current pulse Any type of transient current that may occur (surge, inrush current, start-up current etc)

Derating The practice of using an electronic device in a narrower environmental and/or operating envelope than its manufacturer designated limits.

Fuse element The wire supposed to melt inside a melting fuse

Maximum operating current The maximum current that can occur in a system, during a long time continuous operation. Current pulses are not included. (For example during low voltage and maximum load operation.) Do not confuse with breaking capacity.

Over current Any current in excess of the maximum operating current

Rated value (nominal value) A limiting value of a component, stated by the manufacturer.

Short circuit current A fault current caused by a short circuit in the system

System lifetime The expected lifetime of a system or device

Trip time The time it takes for a circuit protection to trip if a fault current occurs

List of notations

d_a	Altitude derating
d_p	Derating pulse factor
d_s	Standard steady state derating
d_t	Temperature derating
I^2t_{calc}	The calculated energy of a current pulse
I^2t_{fuse}	The energy required to melt the fuse element, stated by the manufacturer
I_{fuse}	Rated current value of a melting fuse
I_{op}	Operating current
$I_{op.max}$	Maximum operating current in the circuit
I_r	Rated current of the protective device
I_{trip}	Tripping current of the protective devicet
I_Z	Current-carrying capacity of a conductor in continuous service
T	Temperature
t	Time

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1 Introduction

The primary goal of this master thesis is to present a guideline to be of help when selecting an appropriate circuit protection for telecom power applications at Ericsson Power Solutions. Different derating factors as well as different types of protection need to be considered when choosing the circuit protection. To match today's use of circuit protection at Ericsson Power Solutions, melting fuses, circuit breakers and electronic fuses will be revised.

1.1 Background

Circuit protection is needed in many different applications all around us. The primary object is to prevent electrical distribution systems from catching fire when faults occur, but there are also other reasons to why circuits are protected. One advantage is that when faults occur in parts of a larger system, a tripped circuit protection stops the propagation of the fault and other parts will remain unaffected. Another reason is to protect the feeding power system from overload.

1.2 Problem

At present, Ericsson Power Solutions not only designs circuit protection for use within their own system designs but also recommends protective solutions for their customers. As a help, they use only a small part of a guideline concerning electronic components which consists of nothing more than derating values for each circuit protection type, together with specifications from manufacturers and individual knowledge. If two individuals are to select a circuit protection for a specific application, there is an imminent risk that the choices will be different depending on their individual knowledge which results in inconsistency within the applications. In addition to that, the choice is often time consuming and the selected circuit protection may not be as optimized as it could be. Much experience lie within the company and its employees, but what they lack is a conjoint document of how circuit protection is best designed to fit in the specific application.

The assignment is therefore to develop a guideline to be of help when designing circuit protection within Ericsson Power Solutions. Besides selecting the optimal protection for an application, the guideline will also include standards and design rules from manufacturers.

1.3 Purpose

The primary purpose of this thesis is to save time and money for Ericsson Power Solutions by investigating circuit protection derivation and constructing a general model, a guideline, for how the protection is to be selected and used within the company.

A secondary purpose is to get basic knowledge of the products developed at Ericsson Power Solutions and learn how to drive a smaller project with time and quality demands. Another objective is to acquire knowledge about different circuit protection types and how they are used within telecom power applications.

1.4 Previous work

When designing circuit protection the only written help that exists within Ericsson Power Solutions is an internal document referred to as "Design guidelines for electric components"[1] which states current derating for melting fuses, circuit breakers and other components. Some of the circuit protection manufacturers have their own guidelines to be of help when to choose from their specific circuit protection.

1.5 Area of investigation

Three different types of circuit protection are being investigated, melting fuses, circuit breakers and electronic fuses. However within Ericsson Power Solutions the type of circuit breakers used are magnetic hydraulic circuit breakers. Therefore thermal circuit breakers are only mentioned briefly in the section concerning circuit breakers in the existing theory. No notice has been taken to thermal circuit breakers in the guideline.

1.6 Report structure

The structure of the report is as follows: After this introduction the theory underlying the guideline is described, first a section about circuit protection and the general characteristic parameters of them. The different types of circuit protections will then be compared to give an overview of the advantages and disadvantages with each protection in comparison to the others. After this the applications at Ericsson Power Solutions in which circuit protection plays a part in regard to safety issues. This is to provide an insight of how and why circuit protection is used. Also a brief section regarding standards for melting fuses and circuit breakers will be presented. After the preliminary theory a chapter with an explanation of the approach to the problem follows. The section Analysis and Results will explain how the guideline was developed, considerations and decisions that have been made together with the results of what was included or left out in the guideline. Further on the guideline is tested by two examples of circuit protection design. Finally the results are discussed and some conclusions have been made.

2 Existing theory

When selecting suitable circuit protection there are several different parameters that need to be considered. This chapter is intended to provide a general description of the subject as well as background information to the contents in this report. In this thesis, three different types of fuses are discussed and compared; melting fuses, circuit breakers and electronic fuses. There will be a description of each type as well as important differences between them. Also a review of the parameters of the circuit protectors in consideration will follow.

This chapter will also give the reader some information of where and when circuit protection have to be taken into consideration at Ericsson Power Solutions. In a large telecom power application there are several electrical devices in need of protection. Some of the devices might have built in protection while some need external protection, e.g. by circuit protection on a higher level. Ericsson Power Solutions also distribute services which care for power systems in call-offices and provides auxiliary equipment to base stations, services where circuit protection are needed, or at least recommended to the customer.

In the world of telecommunication as well as for circuit protection in general, there are standards and regulations that needs to be considered. Where and how the application will be used are as important as which circuit protector that will be used. A short description of some important European and North American standards will be presented together with differences between them.

2.1 Melting fuses

The first type of fuse developed was of a melting kind. The word *fuse* comes from the Latin word to melt, *fusus*. As Thomas Edison developed his electric light circuit in the late 1870's, he needed a protective mechanism "to provide against accidental crossing of the conductors leading from the mains".[2] Edison used a simple wire fuse in a wood-block holder. In 1890 Edison patented an enclosed fuse "to prevent or diminish the liability to surface creeping of lightning or other powerful current". [3]

The general idea of a melting fuse is (as the name reveals) to melt and make a galvanic break. A metal wire with smaller cross-section compared to the surrounding conduction line is placed in series with the conductor, see Figure 2.1.

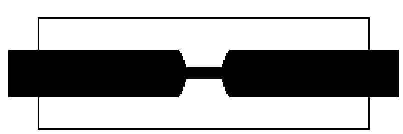


Figure 2.1: Cross section of a melting fuse

If the current increases, the resistance in the small wire results in excessive power dissipation. This energy (described as I^2t) will eventually cause the smaller wire to melt. As the melting starts, the current in the line will create an arc in the gap between the not yet melted parts. Due to the heat dissipation in the arc it will continue to grow in length as the fuse wire melts. The gap will increase until the distance is too large for the energy that created the arc. Not until the arc has been extinct, the fuse will stop to conduct. If the current, ergo the energy is too high, the arc will continue to conduct and the current will rush. Because of this, there is an upper limit for how high over-current that can be allowed. More about this in subsection 2.1.6 dealing with Breaking capacity.

When using an alternating current (AC), the reversion of current(zero passage) benefits the extinction of the arc. To be able to protect both from transients and constant over currents, there are many varieties and layout's of melting fuses. Different thickness of the wire and solder joints that melts at different fault currents can help to design a melting fuse that fits the needs of a specific circuit. [4] [5]

Selecting the proper fuse can be very difficult and when designing a fuse several important parameters have to be considered. Here follows a section to give a basic understanding of important fuse characteristics.

2.1.1 Current rating

The current rating is the current-carrying capacity of a fuse. It is established by the manufacturer and based on a controlled set of test conditions.

To compensate for the differences between the agency approved tests procedure (which determines the current rating during optimized conditions) and the typical application with fluctuating currents and varied temperature, it is recommended to derate the rated current of a melting fuse. Normally the derating value is 75-80% but this varies between manufacturers and type of melting fuse. To apply the current derating, equation 2.1 is to be used.

$$I_{fuse} \geq \frac{I_{op}}{d_s} \tag{2.1}$$

I_{fuse}	Rated current value of a melting fuse
I_{op}	Operating current
d_s	Standard steady state derating

To avoid nuisance tripping and to adequately protect the circuit, the rated current must be higher than the operating current, but at the same time lower than the lowest fault current. Temperature variations are not included in this derating but must also be considered. [5] [6]

2.1.2 Ambient temperature derating

Since the operation of a melting fuse is to melt, it becomes sensitive to temperature variations. Even small variations in the ambient temperature conditions can greatly affect the foreseen tripping time or lifetime. The current derating mentioned above at 75-80% of rated current is at 25 °C ambient temperature. This means that if the ambient temperature differs from 25 °C, it has to be accounted for when selecting a melting fuse. The temperature derating is made in addition to the derating of the rated current according to equation 2.2.

$$I_{fuse} \geq \frac{I_{op}}{d_s d_t} \tag{2.2}$$

d_t Temperature derating

As for the current derating, different melting fuses have different needs of temperature derating. Specifications from the manufacturer describe how different fuses are affected by temperature changes. In Figure 2.2 below an example of temperature derating of two different melting fuses are presented. [5] [6]

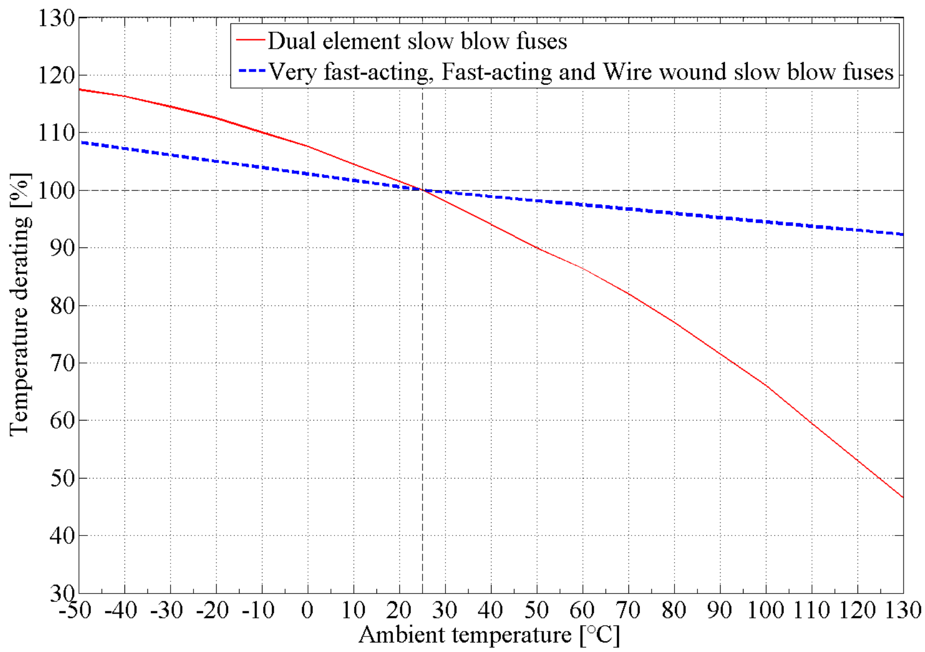


Figure 2.2: Temperature derating of melting fuses.

2.1.3 Environmental considerations

If the fuse is to be operated at high altitudes, the characteristics of a melting fuse are changed since the conditions are changed in thinner air. Quenching of the arc and cooling gets affected since thinner air has poorer heat transportation. In addition to current and temperature derating, altitude derating has to be made if the fuse shall operate over 2000m above sea level according to equation 2.3. [7]

$$I_{fuse} \geq \frac{I_{op}}{d_s d_t d_a} \tag{2.3}$$

d_a Altitude derating

2.1.4 Current pulses and lifetime considerations

A melting fuse can not solely be selected by looking at the rated current and ambient temperature; current pulses also have to be taken into account. Current pulses is a general term and the pulses it refer to can be transients, inrush currents, surge currents or start-up currents. How high current pulses the fuse withstands without tripping is also known as the let-through energy and is described as the nominal melting energy I^2t $[A^2s]$. The I^2t value is seperated from the current rating in the fuse specification from the manufacturer, and can be selected partially independent of the current level. I^2t is obtained by integrating the current pulse and have to be matched with the fuse specification for current pulses.

When the fuse has been subjected to a current pulse the characteristic of the material is slightly changed. It is therefore important to consider how many times the fuse will be exposed to the current pulse and derate for this according to equation 2.4.

$$I^2t_{fuse} \geq \frac{I^2t_{calc}}{d_p} \tag{2.4}$$

I^2t_{fuse} The energy required to melt the fuse element, stated by the manufacturer
I^2t_{calc} The calculated energy of a current pulse
d_p Derating pulse factor

Shown in Figure 2.3 is a typical curve of additional derating depending on how many times the fuse will be exposed to a certain current pulse. Sometimes the manufacturer provides a table instead, see Table 2.1. [5] [6]

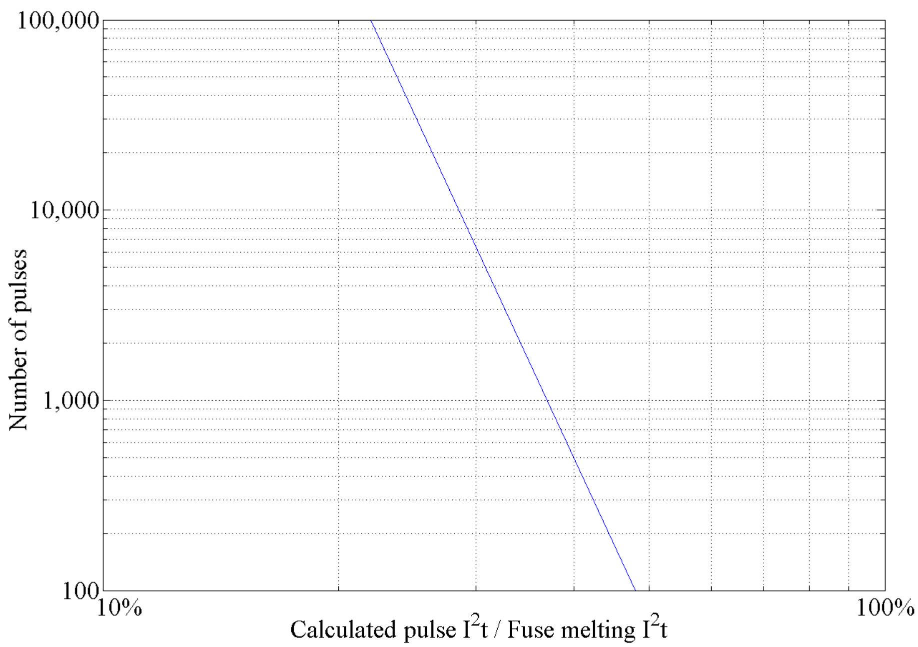


Figure 2.3: Derating depending on the number of pulses the fuse will be exposed to.

Table 2.1: Derating depending on the number of pulses the fuse will be exposed to.

Number of pulses	$\mathbf{d_p}$[%]
1	100%
100	48%
1 000	38%
10 000	29%
100 000	22%

2.1.5 Trip time

The trip time is the time it takes for the fuse element to melt. The trip time differs with fault current. A time-current curve (some times referred to as *time delay curve* or *fuse characteristics*) shows how quickly a melting fuse trip at different current levels. Time-current curves are not included in the fuse specification but are normally provided by the manufacturer as help when selecting the proper fuse. Figure 2.4 is a typical example of this and includes several time-current curves.

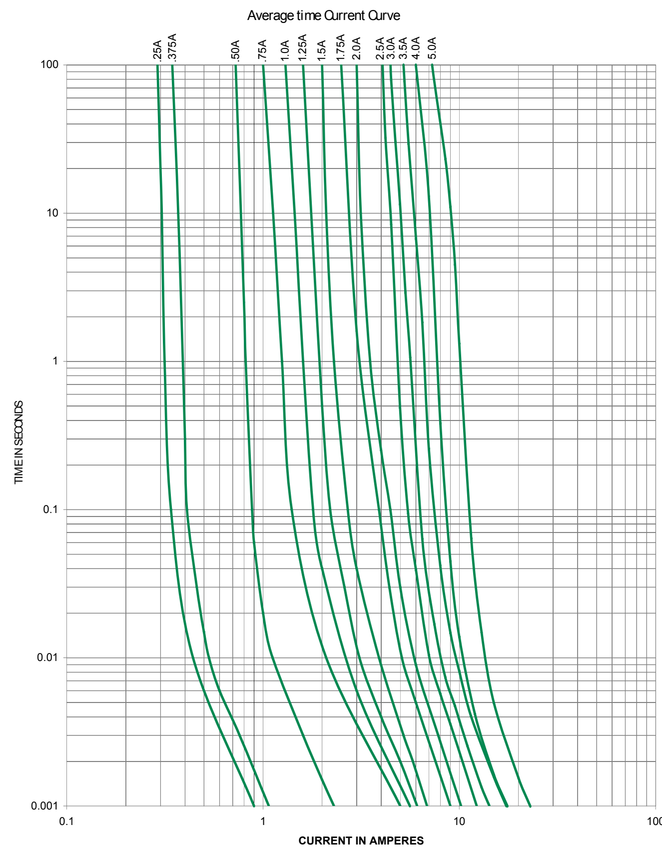


Figure 2.4: A time-current curves for melting fuses. Figure reproduced with the courtesy of Littelfuse Inc.

Two fuses can have the same rating but still have different time-current curves. There are three different categories of fuses, very fast acting, fast acting and time delay (also known as anti-surge). The time delay fuses has an additional thermal inertia which allows large start-up currents or other pulses without tripping. [5] [6]

2.1.6 Breaking capacity

The breaking capacity (some time referred to as *short circuit rating* or *interrupting rating*) is the maximum current a melting fuse is able to safely interrupt.

If a fault current higher than the breaking capacity occurs, the arc will not quench and the current will rush. The breaking capacity depends on a number of factors; including fuse construction, type of current (AC or DC) and circuit operating voltage. [5] [6]

2.1.7 Voltage rating

The voltage rating of a melting fuse indicates at what value the fuse can be trusted to safely interrupt fault currents in a circuit. Though melting fuses are sensitive to changes in current rather than voltage the operating voltage must be equal to or less than the rated voltage. The fuse will regardless of the voltage, remain intact as long as the current stay below the rated current. It is not until the fuse wire actually melts that the voltage has effect. If the voltage is too high the available power caused by the voltage between the open fuse terminals may cause an arc restrike and thereby a fire hazard. This is why a melting fuse can be used at any voltage level from zero to the rated voltage, without compromising its features. [5] [6]

2.1.8 Resistance and voltage drop

The resistance of the fuse often is an insignificant part of the total circuit resistance. However, the resistance of a fuse which is rated at fractions of ampere can be several ohms. Therefore this should be taken into consideration when using a fuse with low current rating, especially in circuits with low operating voltage. It is possible to reduce the resistance of a fuse, but this will result in a higher manufacturing cost. [5] [6]

2.2 Circuit breakers

A simple circuit breaker was developed by Edison as early as 1878 when he worked on his electric light circuit. Even though he did not use his mechanical breaker in his commercial circuit, the function was based on the same principle that is used in a modern circuit breaker. [2]

The circuit breaker is, in contrast to the melting fuse, resettable. This basically means that a circuit breaker can be seen as a switch with high current handling capabilities. Depending on the area of use, there are many different types of circuit breakers but the function in general is the same. When an over current occurs, a thermal or a solenoid sensor detects the fault current and presses the breaker apart with mechanically stored energy, e.g. a spring or compressed air. [8]

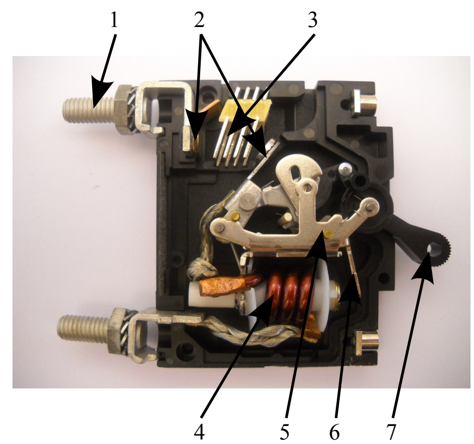
As for a melting fuse, an arc is created in the break. Since the circuit breaker must be able to handle the high current and the high temperature created from the arc without being destroyed, the arc has to be extinguished. Some ways to handle this is to use intensive cooling in a jet chamber, divide the arc in to several smaller arcs or to let the arc grow in length, as in a melting fuse. Depending on the type of the circuit breaker, the arc can pass in different media, e.g. insulating gas, vacuum, air or oil. The lifetime of a breaker often depends on the eroding of the contacts exposed to the arc. The internal resistance of the circuit breaker will be affected from this eroding and depending on the value of the fault current a certain number of over currents will wear out the circuit breaker. When worn out, low power circuit breakers are often replaced but for high voltage circuit breakers wear parts can be exchanged. The biggest advantage in comparison to a melting fuse is of course the feasibility to restore the breaker. [4]

2.2.1 Magnetic hydraulic circuit breaker

As mentioned previously, circuit breakers can detect a fault either thermally or magnetically. The magnetic hydraulic circuit breaker is an all-round device and can operate in many different areas. The magnetic hydraulic circuit breaker can be divided into two different categories; sealed and unsealed breakers. Sealed breakers, made for currents below 20 A, are less dependent of the surrounding environment.

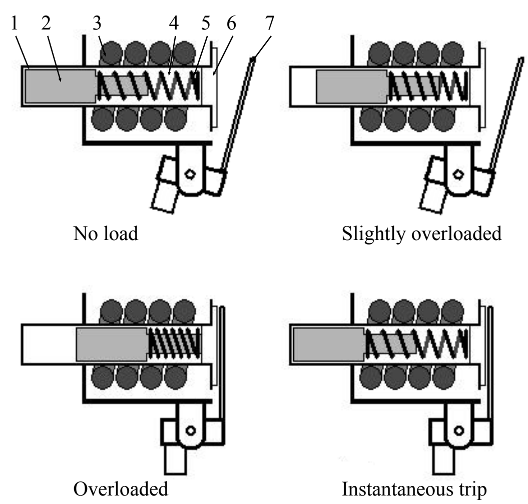
The trip of a magnetic hydraulic circuit breaker is achieved by a solenoid. As the current flows through the breaker, it also passes through a coil which creates a magnetic force. When a fault current occurs, the magnetic force of the solenoid increases until it reaches a certain level where a sear is trigged and opens the breaker. This level is called "the ultimate trip current" and it is the lowest current that still guarantees a break.

The most usual at Ericsson Power Solutions is to use a time delayed magnetic hydraulic circuit breaker that make it susceptible to some current transients. To time-delay a magnetic hydraulic circuit breaker the coil is wound on a sealed, non-ferrous tube which is filled with a silicone fluid. Inside the tube lies a movable core, held under the tension of a spring. At normal current the magnetic field is not strong enough to move the core. During an overload or a transient, the strength of the increased magnetic field attracts the core towards an end piece. If the over current lasts long enough or the transient is big enough, the core has moved all the way to the end piece and thereby magnetizing it. The trigger then is seared by the magnetic force and the circuit breaker trips, see Figure 2.5 and 2.6.



1. Connector
2. Contacts
3. Arc quenching chamber
4. Delay mechanism
5. Armature
6. Sear
7. Lever

Figure 2.5: Cross section of a magnetic hydraulic circuit breaker



1. Tube
2. Core
3. Coil
4. Silicon fluid
5. Spring
6. End piece
7. Sear

Figure 2.6: Delay function of a magnetic hydraulic circuit breaker

If a short circuit occurs the current rushes and the magnetic leak flux from the coil will magnetize the end piece instantaneously (before the core has been pressed against it) making the sear trip the circuit breaker immediately. This current is referred to as the “instantaneous trip current”. The trip current is varied by the number of turns in the coil and not affected by variations in temperature but since the silicon liquid gets more viscid as the temperature decreases, the trip time will vary with varying temperature. Instantaneous tripping is independent of ambient temperature.

To influence the time-delay, liquids with different viscosity and springs with varying stiffness are used. Because of gravity, the mounting of a magnetic hydraulic circuit breaker effects the trip time. If the coil is placed correctly, with the core horizontal, the gravity is of a very small significance. But if a magnetic hydraulic circuit breaker is placed with the core vertical or at any angle, gravity will effect the trip time.

At high over currents, the magnetic hydraulic circuit breaker only depends on the current which often is considered to be an advantage. In complement to a thermal circuit breaker the magnetic hydralic circuit breaker does not have to cool down between two ruptures. Another advantage is that a magnetic hydraulic circuit breaker has a lower voltage drop compared to a thermal circuit breaker. [4]

As for a melting fuse, selecting a magnetic hydraulic circuit breaker also means that important parameters must be considered. Even though it is in general the same parameters, there are differences in how to deal with them; a basic understanding of parameters for magnetic hydraulic circuit breakers follows.

2.2.2 Current rating

The current rating is as mentioned in the part about melting fuses the current carrying capacity of a circuit protector. The difference for circuit breakers is that no derating is necessary. The breaker can be rated to 100% of the operating current. [9] [10]

2.2.3 Ambient temperature derating

The ambient temperature affects magnetic hydraulic circuit breakers as well. In the temperature range between $-40\,^{\circ}\mathrm{C}$ and $+80\,^{\circ}\mathrm{C}$ the temperature only has a negligible affect on the current carrying capacity (rated current). However, the trip time decreases with higher temperature and vice versa. The reason for this is viscosity changes in silicon fluid in the non-ferrous tube inside the coil. As the temperature changes the fluid gets more or less viscous. This also means that it is only for short circuits and over currents below the instantaneous trip current that temperature variations have to be considered. The temperature influence of trip times for a magnetic hydraulic circuit breaker is shown in Figure 2.7. [4] [9] [11]

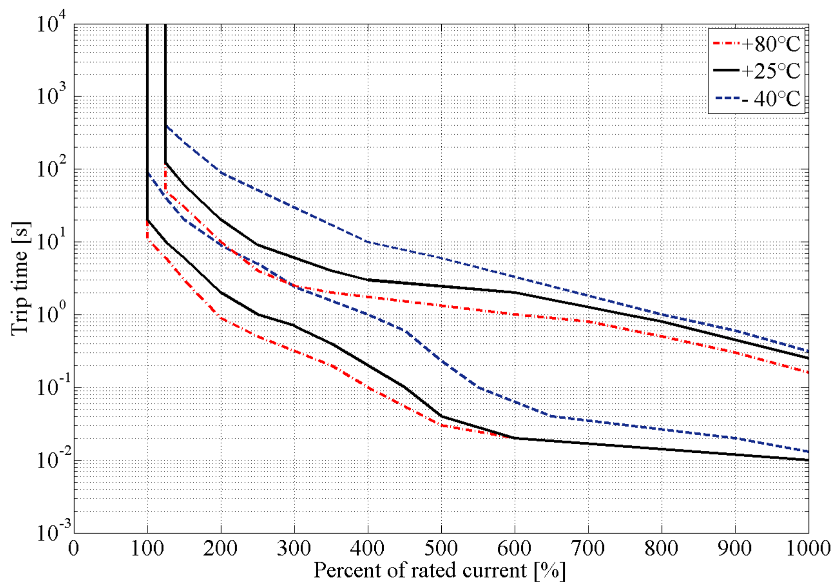


Figure 2.7: An example of the influence of ambient temperature for a magnetic hydraulic circuit breaker.

2.2.4 Environmental aspects

Vibration and shock can be an issue for a magnetic hydraulic circuit breaker because of the mechanical moving parts. The sear may trigger if the circuit breaker is exposed to rough treatment. There are standards concerning environmental conditions to ensure that a circuit breaker withstands a certain magnitude of shock and vibration.

As for melting fuses, the air pressure at high altitude affects the current capacity of a circuit breaker due to the variation of air density. Normally, circuit breakers need altitude derating if operated at more than 2000m above sea level. [4] [9] [11]

2.2.5 Trip time and current pulses

The tripping of a circuit breaker depends on the duration of the over current. Several time-current curves (time delay curves) like the one in Figure 2.8 are provided from the manufacturer. The curve shows how long the circuit breaker withstands a certain level of over current. In this way a constant over current is seen as a long current pulse. The time-current characteristics can be selected for all rated current levels of a circuit breaker and as for a melting fuse; any pulse not supposed to trigger the circuit protector must be considered. [4] [9] [11]

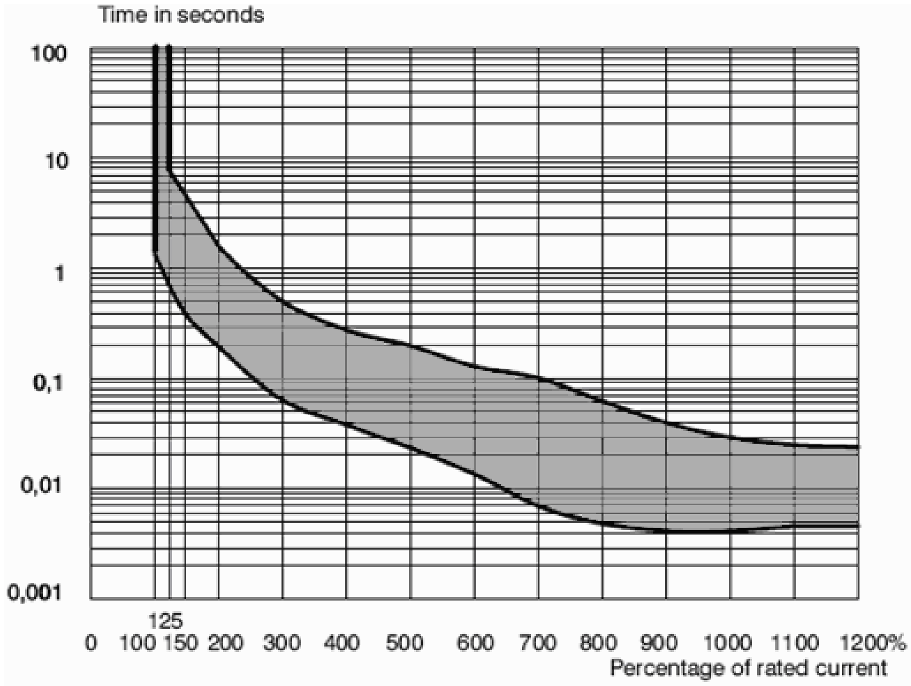


Figure 2.8: An example of a time current curve.

2.2.6 Lifetime

The arc generated from a trip will erode the contacts in a circuit breaker. Since a circuit breaker in contrary to a melting fuse is supposed to be used again after a trip has occurred this is a factor that needs to be accounted for. The eroding of the contacts result in slightly higher resistance and thereby a slightly increased temperature. Because of this, a circuit breaker is often limited to a certain number of switching operations before it has to be replaced depeding on the current level. [4] [9] [11]

2.2.7 Breaking capacity

As for melting fuses the breaking capacity (for circuit breakers some times referred to as *interrupting rating*, *ultimate breaking capacity* or *O-CO cycle*) is the maximum current a circuit breaker is able to safely interrupt. A trip with this amount of current erodes the contacts more than a usual fault current and the circuit breaker is often limited to two or three of these kinds of tripping. The principle of why a circuit breaker shall be rated less than its breaking capacity is the same as for a melting fuse and can be read about in section 2.1.6. [4] [5] [6]

2.2.8 Voltage rating

The voltage rating of a circuit breaker indicates that the circuit can be safely interrupted if a fault occurs up to this voltage level. As with breaking capacity, the principle of voltage rating is the same as for melting fuses. Read more about voltage rating in section 2.1.7. [4] [5] [6]

2.2.9 Resistance and voltage drop

Magnetic hydraulic circuit breakers typically have a very low voltage drop at rated load. If operated at very low voltages, the drop may become significant and shall be taken into consideration. As mentioned above, the resistance and thereby the voltage drop increases slightly as the breaker trips which also may be taken into consideration. [4] [8]

2.3 Electronic fuses

There are many different types of electronic fuses and every manufacturer has their own solution. The principle is the same though; a sensor measures the current and some kind of controller or comparator, often a micro processor, controls a transistor, typically of a MOSFET kind. By master the opening and the closing of the MOSFET, the controller sets if the current should be cut off.

Since a controller is programmable, an electronic fuse has a wide range of applications. Some of those are listed in the section about the Power distribution unit in section 2.5.1. One controller can be in command of many MOSFET's which individually can be put on or off remotely and has an *electronic fuse state memory* to know in which state it is during disconnection. Control equipment can be connected for monitoring voltage and current level.

Sometimes the electronic fuses is constructed with two MOSFET's as seen in Figure 2.9. At start-up, the transistor M1 opens first and once steady state has been reached, M2 will be switched on. Because of the higher resistance R, the current will flow through M2 instead of M1. With this design high start-up currents are limited. M1 is kept on but due to the resistance R only a negligible part of the current will flow through it. If an overload or a current transient occurs the controller turns M2 off and the resistance prevents over currents. If the fault condition lasts longer than the programmed time-current curve allows, M1 will also be turned off and break the circuit.

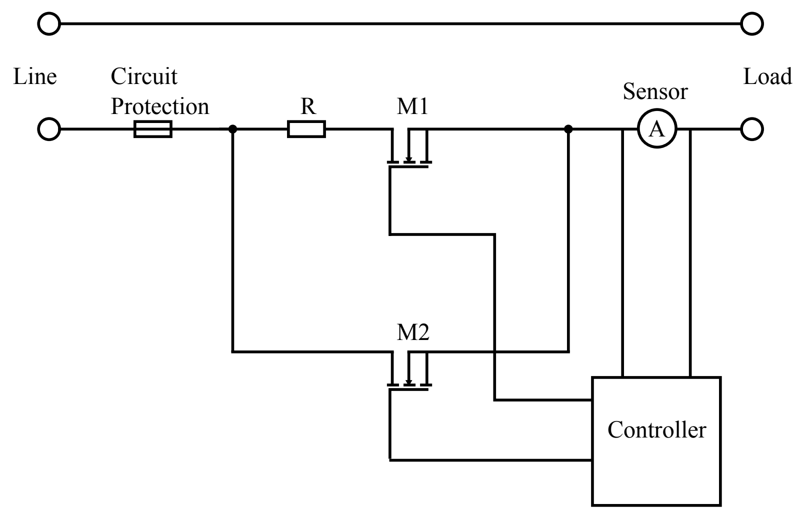


Figure 2.9: A simple circuit diagram of an electronic fuse.

An electronic fuse does not have galvanic insulation and if exposed of too high currents the MOSFET become short circuited. To be able to guarantee circuit protection and to protect the MOSFET from destruction a melting fuse or a circuit breaker often is placed in series. An electronic fuse can limit relatively high currents, as long as the current through the MOSFET stays in the *safe operating area*. See section 2.3.1.

An electronic fuse has a short trip time. Except for the time needed by the electronic control unit to create the control signal, the trip time only depends on the re-combination conditions of the transistor. Since consisting of a MOSFET, an electronic fuse has a leakage current in off mode ($I_{leak} < 10mA$) and a voltage drop at on state. The voltage drop, caused by $R_{DS(on)}$ of the MOSFET, results in heat losses which must be cooled off by a heat sink. The heat sink needed is often relatively expensive which results in increased cost of the electronic fuse. [8] [12] [13]

2.3.1 Safe operating area

The safe operating area is the area of current and voltage over which a semiconductor device is supposed to operate without break down, i.e. the amount of energy allowed in a semiconductor. For a MOSFET there are three variables that determine the safe operating area; drain current $I_{drain,max}$, breakdown voltage BV_{DSS} and the junction temperature T_j. Figure 2.10 shows a typical safe operating area curve for a single pulse.

If the temperature remains until the next pulse, the temperature builds up and the safe operating area can be exceeded. Most manufacturer rate their electronic fuses so that three immediate attempts to restart the fuse can be made without exceeding the safe operating area. [14] [15]

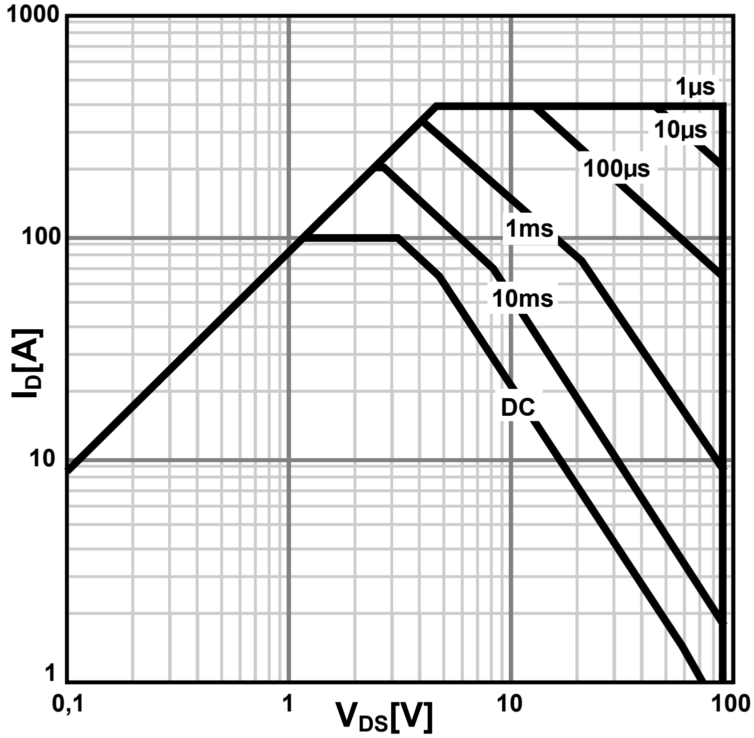


Figure 2.10: A typical safe operating area curve of a MOSFET

2.4 Differences

As mentioned earlier, there are similarities of the three different circuit protectors but there are obvious differences in the functioning. Melting fuses are self destructive in case of a fault but has a very simple function. Magnetic hydraulic circuit breakers are easy to restore and as the melting fuse they provide galvanic insulation at a break. Electronic breakers are flexible and are easy to control but have leakage currents and are not galvanic insulated at off state. A list of advantages and disadvantages is presented in Table 2.2.

2.5 Telecom applications at Ericsson Power Solutions

This part describes the product areas of Ericsson Power Solutions. It gives the reader a basic understanding of the applications developed by Ericsson Power Solutions which the guideline is adapted for.

For each product area and application there is a general description along with information about any circuit protection. Some are more complex and therefore described more than others.

2.5.1 The power system of a radio base station

A Radio Base Station (RBS) is a larger connection point in the communication grid. It can consist of many different units. Some of the units are used during certain conditions while others always are included. The power system with its hardware units can be configured to be used for different types of radio base station needs. The power system provides -48V to internal and external DC Users. The input power supply sources can be AC or DC. When the radio base station is supplied by AC a back-up battery can be included to ensure power is available at all times, when supplied by DC an external back-up power system already exists. Figure 2.11 shows the power system hardware units and interfaces.

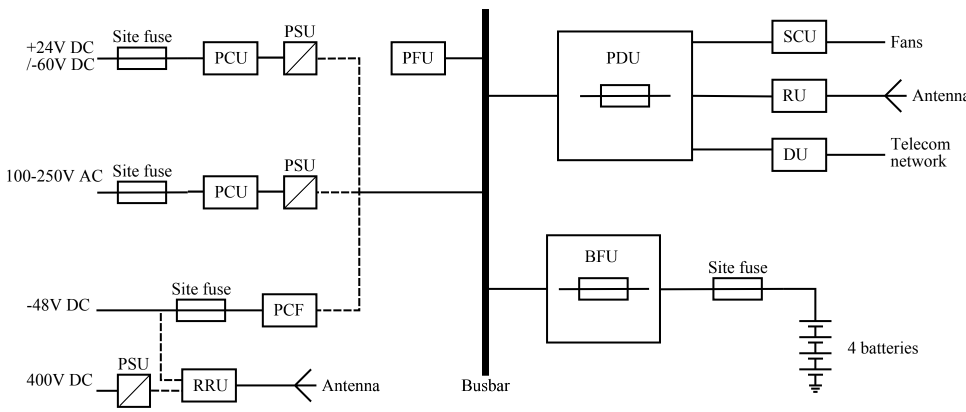


Figure 2.11: Power system hardware units and interfaces of a radio base station.

Power supply unit

The Power Supply Unit (PSU) converts the AC or DC power supply to -48VDC. It has a communication port to communicate with a main processor and also includes remote on/off control. The output power of a power supply unit is settable (1200W/1800W) for minimizing external circuit protection. The power supply unit is designed with an over voltage protection which ensures that the output voltage never exceeds the stated level. It also includes a protective function which limits the current in case of overload or shorted outputs. [16]

Power distribution unit

The Power Distribution Unit (PDU) works as an internal distribution unit within the cabinet. [17] It distributes the system power from the backplane of the Radio base station to separately fused outputs via output connectors. The circuit protection consists of electronic fuses and include the following functions which gives an example of how versatile the functions of an electronic fuse are:

- Two different sizes containing either 7 or 11 outputs.
- Hold up function (10 ms) on two of the outputs
- Settable cold-start function (The device is not started until the ambient temperature reaches a certain value.)
- Shut down of non prio-load (In case of power failure)
- Remote on/off control (can support reduced power consumption possibilities)
- Electric fuse function with adjustable trip values for overload and short circuit protection on each output, see section 2.3.

Battery fuse unit

The Battery Fuse Unit (BFU) is the interconnecting device between the backup battery and the power system. The battery fuse unit will, both during autonomous and controlled operation, control the connection and disconnection of the battery to and from the system voltage. There is also a magnetic hydralic circuit breaker that serve as a switch, with the possibility to physically disconnect and reconnect the battery. The battery fuse unit supervises the battery voltage, system voltage, current and temperature. When the system voltage becomes too low, the battery is connected as power supplier instead, but if any abnormalities appear during battery power, the battery is disconnected as well. [18]

Power Connection Unit

The Power Connection Unit (PCU)) is an interface which connects the external input power, AC or DC, to the Power supply unit. When dealing with outdoor radio base stations the power connection unit also includes voltage surge protection, filtering functions and radio base station options for service outlet. [19]

Power Connection Filter

When the customer provides -48VDC to a radio base station, no power connection unit or power supply unit is needed; instead is the external input power connected to a Power Connection Filter (PCF). The power connection filter consists of an over voltage protection and a filter which the input goes through for further supply to the cabinet. The power connection filter also includes voltage surge protection. [20]

Power Filter Unit

The Power Filter Unit (PFU) filters current ripple caused by radio step loads in the system. The purpose of the power filter unit is to stabilize the -48V power system in the radio base station. The origin of the voltage ripple is the effect of synchronized step loads in combination with the inductance in the supply cables (between the DC source and the radio base station). The power filter unit reduces the slope of the current ripple from the DC source. [21]

Support Control Unit

The Support Control Unit (SCU) works as an interface, providing power to a maximum of 4 individually controlled fans. The support control unit has a connection field for communication between the main processor and the units connected to the support control unit. The speed of each fan is controlled by the main processor and is converted to the relevant pulse width modulation signal by the support control unit. [22]

Radio Unit and Digital Unit

Other telecom devices, such as the Radio Unit (RU) and the Digital Unit (DU) withhold communicative telecom equipment on a printed circuit board. A melting fuse is used to prevent fire in case of a fault on one of the printed circuit boards of the units.

The Remote Radio Unit is separated from the main telecom site and placed near the antenna or on top of a roof. Placing the radio unit close to the antenna port reduces the radio frequency cable losses which improves the radio frequency coverage significant. However, from a power supply point of view this will result in long power supply cables to the remote radio unit. The remote radio unit has to include more protection since the protection of the telecom station is far away. The supplying device at the station also has to include extra circuit protection. [23]

2.5.2 Mini-link

Mini-link is the name of Ericsson's radio link. A radio link offers a wireless connection between two different locations using micro waves. The Mini-link often serves as a transmission between two radio base stations and replaces cable or optical fiber connection. Transmitting data by a radio link is more cost-effective than using a cable. A requirement though is that a radio link need free sight between the sending and the receiving unit and the transmission can be disturbed in bad weather.

A Mini-link consists of a module system of plug in units, i.e. different printed circuit boards, which can be replaced depending on required feature. The Mini-link has a distribution system that distributes the power to the printed circuit boards. Centrally placed in the Mini-link there is a power filter unit with an electromagnetic compatibility (EMC) filter, current surge protection and over current protection. Every printed circuit board has its own power system, with a DC/DC converter and a line protection system consisting of hot-swap function, transient protection and electromagnetic interference protection (EMI-protection). To increase the reliability, the printed circuit boards have redundancy with double input power.

The over current protection of a Mini-link consists of an external circuit breaker. Furthermore every printed circuit board has an electronic fuse in series with a melting fuse to guarantee galvanic insulation. Compared to the electronic fuse in the battery fuse unit, the electronic fuse on the plug in unit is a simple analog breaker just switching the current on or off. The melting fuse is rated to ensure that the electronic fuse triggers first. Correct rating is important to prevent nuisance trips since the whole printed circuit board is replaced if the melting fuse triggers. [24]

2.5.3 Site Solutions

Within telecom power applications a site is a location with telecom equipment, usually a core base station or a radio base station. Within Ericsson, Site Solutions is a department which provides auxiliary equipment to a base station, i.e. everything operators need to establish a core base station or a radio base station except for the actual base station. Among other things it includes power supply, housing, components and tools.

Since Site Solutions handles the power supply, circuit protection is needed. This is often situated between the external power supply and the base station. Sometimes the circuit protection is provided by Site Solutions and sometimes the ratings of a circuit protection are recommended to the customer. Site Solutions primarily uses large circuit breakers compared to other protective devices used within Ericsson. [25]

2.5.4 Central Office

Central office is a department in Ericsson that handles power supply for call-offices. Old switchboard systems in call-offices were space consuming and often placed in buildings with several stories. Since the development of the AXE system in the late seventies the space became redundant. Today that space has been replaced by computer equipment such as broadband and internet telephony. The power supply units in a call-office often consist of one or two "plants" which distribute power to the whole call-office. These power plants are often placed in a basement without temperature changes in a controlled environment. This makes protection from thunder strikes unnecessary. The choice of circuit protection only depends on the length of the cables inside and providing the system.

Since call-offices are built like small grids it is essential to prevent a fault from being spread in the system and there are rules and regulations of how much a fault is allowed to affect other functions in the grid. For telecom industry, a call office is allowed to be down a maximum of one minute/year and power related faults are set to 10% of that.

For central parts of the system there are often back-up systems of capacitors to eliminate the effect of a fault. The fault spread elimination in the grid is done by a "transient limiting distribution system". The transient limiting distribution system is either of a low ohmic distribution (LOD) or as the system Ericsson is using, of a high ohmic distribution kind (HOD). [26]

High and low ohmic distribution

High ohmic distribution was developed by Ericsson along with the developing of the AXE system. As seen in Figure 2.12 the principle of a HOD system is to place a resistor and a circuit breaker in the distribution panel to each subrack. If a fault occurs in one of the units in a subrack, the resistor reduces the fault current that spreads through the grid. In this way the voltage drop in the surrounding subracks is reduced to the maximum allowed 8 Volts until the circuit protection trips. This step is the first in the standard at Ericsson; the *two step high ohmic distribution system* (TS-HOD).

The second step consists of an EMI-filter in the backplane of the subracks. As in the Mini-link, the subracks consists of plug in units with their own redundant power systems containing DC/DC converters and melting fuses to prevent fire.

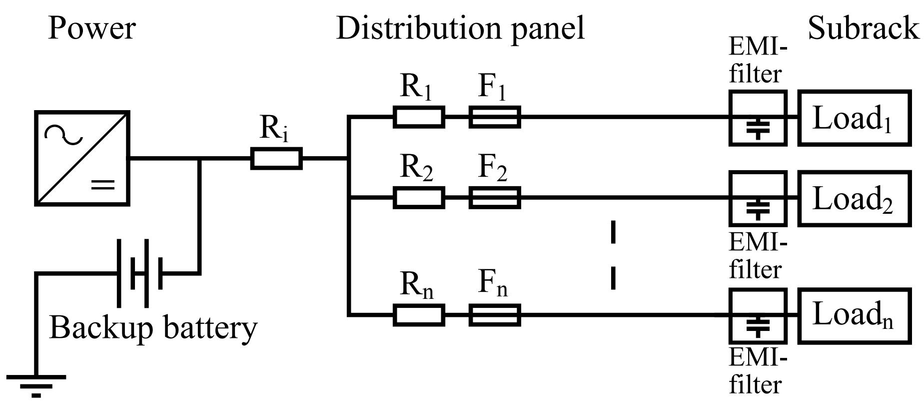


Figure 2.12: Two step high ohmic distribution

The major drawback with HOD is that the system is bound not to exceed 800 W. In a LOD system there are no distribution resistors so the power is not compelled to stay below 800 W. If a printed circuit board is exposed to a short circuit or an overload, the lack of resistance in the system results in a voltage dip for the other circuit boards until the circuit breaker has cut the power to the malfunctioning subrack. To prevent other subracks from being affected by the voltage dip, they need hold-up capacitors to keep the voltage at the required level and diodes to keep the capacitors from being discharged at reverse currents. See Figure 2.13. [27] [28] [29]

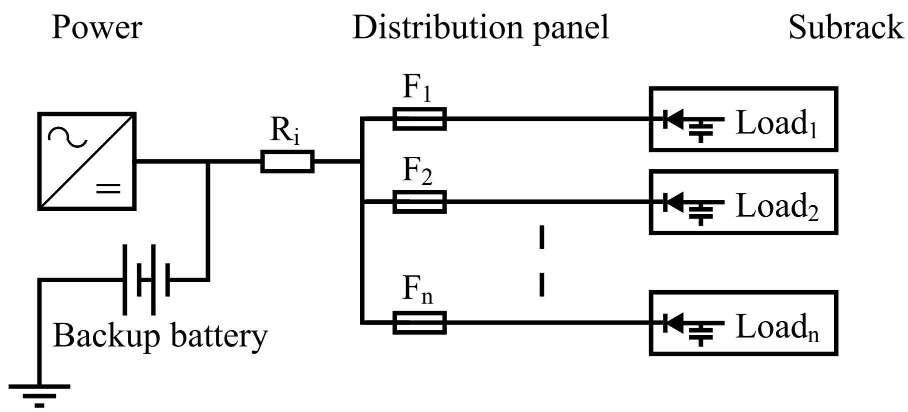


Figure 2.13: Low ohmic distribution

2.6 Standards

There are several national and international standard organizations that state regulations and safety aspects. Different standards regulate different areas. For applications in this thesis there are both standards concerning telecom applications, safety issues and different types of circuit protection. Standards important in telecom business are *European Telecommunications Standards Institute* (ETSI) in Europe, *Alliance for Telecommunications Industry Solutions* (ATIS) in USA and their international counterpart; *International Telecommunication Union*. Safety standards are regulated by *International Organization for Standardization* (ISO). [30]

Standards covering circuit breakers are among others the European organization *International Electrotechnical Commission* (IEC), the USA organization *Underwriters Laboratories* (UL) and the *Canadian Standards Association* (CSA). Listed below are IEC standards covering melting fuses and circuit breakers and their corresponding North American standards. [31] [32] [33]

IEC standards covering melting fuses are:

IEC 60127 covers the general requirements and tests applicable to all types of miniature fuse-links, normally intended to be used indoors.

IEC 60269 covers low voltage fuse-links. Maximum ratings covered are 1000 Vac, 1500 Vdc and breaking capacity of $\geq 6kA$.

Both standards correspond to UL/CSA 248, covering low-voltage fuses rated 1000 V or less, AC and/or DC, with breaking capacity up to 200 kA.

IEC standards covering magnetic hydraulic circuit breakers are:

IEC 60934 covers protection to circuits WITHIN electrical equipment. (With back-up by protection in the fixed installation) Maximum ratings covered are 440 Vac, 250 Vdc and 125 A.

IEC 60947-2 covers molded case circuit breakers. IEC 60947-2 contains no restrictions on design, rating or construction other than to mention that additional requirements may be necessary for specific applications. Maximum ratings covered are 1000 Vac, 1500 Vdc and no limit of current.

IEC 60898 covers over current protection for household and similar installations. (Uninteresting in a telecom application)

Corresponding standards are UL 1077 to IEC 60934, UL 489[1] to IEC 60947-2 and IEC 60898. CSA 22.2 corresponds to all three IEC standards.

Figure 2.14 show a simplified map over where in the world IEC, UL and CSA apply. [34]

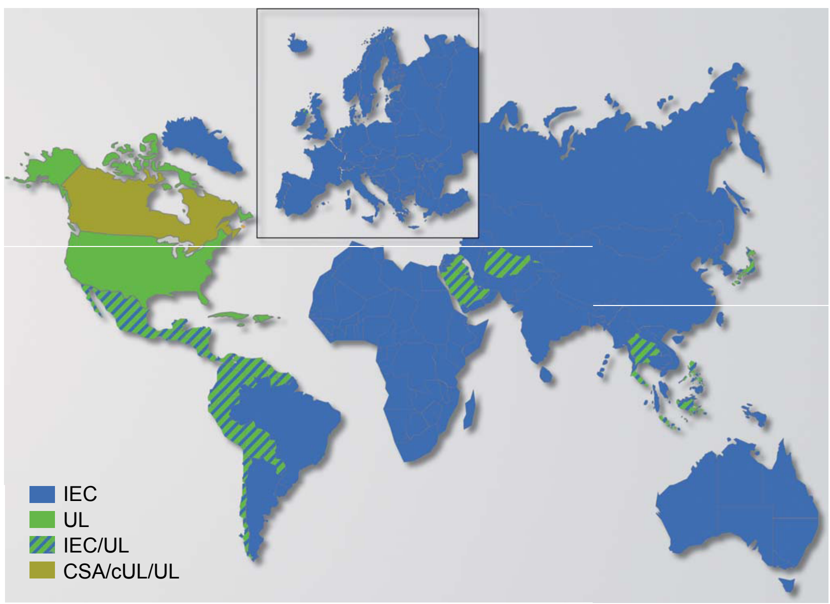


Figure 2.14: Map over where in the world different standard organizations apply. Figure reproduced with the courtesy of SIEMENS AG.

[1] UL489A for DC applications

Table 2.2: Significant differences between melting fuses, magnetic hydraulic circuit breakers and electronic fuses. Note that the pros and cons for the electronic fuse depends on the electronic fuse design. The aspects presented here is valid for the electronic fuses used at Ericsson Power Solutions.

Melting fuse	**Magnetic hydraulic circuit breaker**	**Electronic fuse**
Simple and cheap	Complex means (delay function) necessary to limit short circuit current.	Complex function. Most expensive of the three but contains more functionalities
The necessity to replace often results in troubleshooting but may be dangerous if the current source still is connected	Resettable directly once the fault has been adjusted, the ease to reset may result in no troubleshooting	Can be programmed to reset immediately, good if it is a nuisance trip
Physical isolation at off-state. No leakage current	Physical isolation at off-state. No leakage current	No physical isolation at off-state results in leakage current
Low voltage drop at on-state	Low voltage drop at on-state	Voltage drop at on-state
Small and easy to fit	Compact physical dimensions and less weight than an electronic fuse	Place consuming heat-sink needed
Self-destructible. Has to be replaced after every break	Resettable, need to be replaced after a certain amount of breaks	Resettable, do not need to be replaced
The breaking characterization changes if exposed to non breaking over currents	The breaking characterization does not change if exposed to non breaking over currents	The breaking characterization does not change if exposed to non breaking over currents
The breaking characterization change if exposed to thermal stress	The trip time changes if exposed to thermal stress	No effect of thermal stress
Current derating necessary	More exact current rating than melting fuse	No derating necessary
High surge interrupt capability	High surge interrupt capability	Surge interrupt capability limited due to safe operating area
No additional EMC protection necessary	No additional EMC protection necessary	Additional protective components needed to improve EMC
Break depends on the energy I^2t	Break depends only of I and t	Break depends on programmed characteristics of I and t
Self-destructible. Limited in life to one break	Limited in life to some 10 000 of mechanical cycles (switches) due to mechanical degradation at arcing	Nearly unlimited cycling at rated values. No moving parts and no arcing means less wearing. Operation life is only limited to environmental conditions
——	——	Limitation of current possible
——	——	Programmable (rated current, trip curve, arc fault, wire continuity)
——	——	Voltage and current monitoring possible
——	——	Requires circuit protection itself

3 Case set up

This section gives a description of how the work has been carried out and how the guideline has been developed.

3.1 Approach and information retrieval

A basic understanding of the subject has been obtained by studies of datasheets, guidelines and other documents from manufacturers. This to investigate how circuit protection is best designed from the manufacturer's point of view. To produce a usable guideline for Ericsson Power Solutions the components and the divisions in use of circuit protection has been studied as well. Several interviews have been made with employees at Ericsson Power Solutions. Suggestions of the outlining of the guideline were discussed and information about the components has been obtained. Questions and problems regarding circuit protection obtained from the interviews have been compiled and manufacturers has been consulted.

3.2 Development of the guideline

The primary goal of the guideline has been to compile a brief and easily overviewable guideline on one to two pages. This has been achieved by a table in chapter 2 of the guideline. During the compilation of the guideline, regular meetings with an "expert group" have taken place and it became clear that a more detailed part of the guideline was needed. Therefore the guideline was extended with chapters consisting of deeper information about the considerations that has to be made when designing circuit protection. The result of this thesis is the Circuit protection Guideline in Appendix A.

When reading and trying to understand the guideline it is important to understand the factors that lie behind the writing of the guideline. Considerations have been taken of the fact that information needs to be found quickly and easily understood. Short sentences and corporate language has been used. The guideline is adapted to Ericsson Power Solutions applications and their functions as well as their use of circuit protection with risk analysis and other considerations.

4 Analysis and Results

One of the difficulties with selecting the proper ratings is that the protection should be as cost-effective as possible but still comply with all of the demands. For the customer it could be less expensive to have a smaller current rating because of electric certification. The required size of the conductors will increase as the current rating increases and the fuse itself is often cheaper the smaller it is. But minimizing the margins could be hazardous. The protection shall not trigger during normal operation. As mentioned in chapter 2.5.4; for telecom industry, a call office is allowed to have a down-time of maximum one minute/year and power related faults are set to 10% of the total down-time. It is also of great importance not to disturb other systems when a fault occurs.

4.1 General considerations when developing the guideline

In addition to learning about circuit protection, when developing a guideline it is of great importance to find out how and when circuit protection is used. In telecom power applications there are circuits designed to limit the current and protect from over voltage included in the system. The circuit protection is primarily used to prevent fire and fault spreading. If a circuit protector is triggered, it indicates defect components and the entire part where the fault has occurred needs to be exchanged. Hence, an important issue is to make sure that nuisance tripping does not take place. Just because of this, it is not acceptable to oversize the circuit protection, even if a slightly oversized system results in a small increase of cost, it is obvious that for a multinational company like Ericsson this results in a large total increase of cost. Of course there are also other reasons not to oversize the circuit protection, such as cable size and electric certification mentioned earlier.

In the guideline only magnetic hydraulic circuit breakers and melting fuses have been dealt with. Thermal circuit breakers are not used within Ericsson Power Solutions because of their shortcomings compared to magnetic hydraulic circuit breakers. Electronic fuses are programmable and can be custom rated to fit the needs of the application and the derating rules of the guideline are superfluous when designing an electronic fuse. Though the parameters in the guideline can be applied to other types of protection as well, the derating rules for those are somewhat different.

The original purpose was to develop a brief guideline with rules on how to determine circuit protection ratings. But since circuit protection in general and especially magnetic hydraulic circuit breakers differ amongst manufacturers and applications it is nearly impossible to establish general rules to be followed every time. Like standards are meant to be used in a larger content together with other standards, circuit protection are intended to be used as a part of a circuit and the properties differs depending on where and in what application it is intended to be used. Therefore the guideline has become a larger document than intended, containing parameters of great importance to consider when choosing the proper circuit protection and how to obtain this information.

4.2 When can circuit protection be left out?

No circuit protection at all will of course reduce the anticipated cost of the application considerably. Hence is the first thing to consider if the circuit protection really is required; if it can be replaced by easier and less expensive protection or can the circuit protection be left out? Magnetic hydraulic circuit breakers and especially electronic fuses are expensive and if hundreds of applications are made containing of unnecessary protection the prize shoots off. If they can be replaced by a melting fuse, the cost reduction can be substantial. Another way to reduce cost is to rely on circuit protection upstream. That is for example if printed circuit boards with melting fuses are protected by a higher rated circuit breaker *upstreams* as well. A circuit protection downstream from a larger circuit protection does not have the same safety demands and can thereby be made more cost-effective, although in this thesis this has only been investigated in a small extent.

4.3 Choosing the suitable type of circuit protection

When determining what type of circuit protection to use; cost, mounting and size have to be considered. Which circuit protection that is used often depends on tradition; a similar to the one used earlier are often chosen. In some applications this is the best way to go since there were good reasons for using this kind of protection in the first place. Since the whole printed circuit board is to be replaced if a fault occurs, it would be a waste of both space and money to use anything but a melting fuse in such applications.

In many applications it is not profitable to use the most cost-effective protection. Like for example in a Mini-link, a circuit breaker is placed prior to the printed circuit boards and to exchange it every time would be more expensive than just to switch it back on. And if a circuit protection is placed so that restoration is difficult a more expensive remote-controlled electronic fuse is preferred.

Another obvious variable is that expensive protection is more accurate and the less expensive melting fuse also needs to be derated in a higher extent than the expensive protection.

Also size is an important matter that often correlates with cost. In a small application the weight and size of the circuit protection can be a substantial part.

All three types have benefits and the conclusion is that melting fuses, circuit breakers and electronic fuses fits in different applications. Consequently the selection of circuit protection depends more or less totally on the prerequisites and the safety demands. A comparison between the different types of circuit protection can be found in section 2.4.

4.4 Melting fuses

Melting fuses are most cost-effective and the simplest in function of the circuit protectors. They are small and have a low weight which makes melting fuses the obvious choice on printed circuit boards. At Ericsson Power Solutions, malfunctioning units are replaced; if a melting fuse on a printed circuit board trips, it is irrelevant if the melting fuse is self destructible and has to be replaced.

4.4.1 Current derating

As mentioned, the reason for current derating is to compensate for the optimal conditions in the test applications. In addition to this, it is not guaranteed that the material behaves the same at every over current. It is possible to increase the accuracy of a melting fuse but the cost would increase which is not profitable in most applications. At Ericsson Power Solutions it is more important to keep the costs at a minimum than to be completely accurate since the fuse has to be replaced after tripping.

As mentioned in the introduction, Ericsson Power Solutions has a document consisting of only a derating value [1], regardless of what the recommended value from manufacturers has been. Furthermore it has not been clear what current level is to be derated. These factors have made the derating value inaccurate and since the current value is not constant, it has not been obvious which current level that should be derated.

If for example a radio base station is supplied by a battery fuse unit, the output power will remain constant regardless of any decrease in the battery voltage level. Since the battery voltage is permitted to decrease to a certain level and the output power still will be constant, the current level will increase. This operating state should still be seen as a normal operating mode and it is important that the fuse does not trip. Therefore it has been stated in the guideline that when derating a melting fuse, the stated derating value from the manufacturer is to be used and it is the *maximum operating current* that is to be considered. That is, the highest operating current that are permitted to flow in the specific circuit.

Besides which current is to be derated, the current is usually never smooth as in a theoretical operation mode. As described earlier, in telecom power applications the normal operating current contains current ripple that needs to be considered. This makes it somewhat difficult to know which value that is to be seen as the maximum operating current. After discussions with manufacturers it is concluded that when derating for a DC application it is the average value, and when derating for an AC application it is the RMS value of the maximum operating current that needs to be considered.

4.4.2 Temperature derating

In the existing document at Ericsson Power Solution, temperature derating is only partially included. Again, only a general value covering all different melting fuses is stated. But as mentioned earlier, the temperature coefficient differs depending on the kind of fuse. Therefore it has been stated in the guideline that temperature derating shall be used according to the temperature derating graphs provided from the manufacturer of the fuse.

When derating for temperature variations it is important not to confuse the ambient temperature with the room temperature. In contrast to a melting fuse in fuse boxes like the ones used in regular households, the ambient temperature of a melting fuse at Ericsson Power Solutions is often substantially higher than the room temperature. The melting fuse is normally enclosed or mounted near other heat producing components, such as resistors and transformers. The temperature referred to is therefore the temperature in the immediate surroundings of the fuse.

4.4.3 Environmental stress

The environmental aspects referred to are vibration, shock and altitude considerations. Since a melting fuse does not consist of mechanically moving parts, vibration and shock is not an issue for a melting fuse. High altitude on the other hand can be; standard organizations define normal atmospheric operating conditions. It is generally written that fuse characteristics does not need to be modified up to 2000m above sea level. At Ericsson Power Solutions, electronic equipment is set to be operative up to 3000m. For operation in altitudes above 2000m a melting fuse is to be derated by 0.5% every 100m. Note the difference between derating *by* and derating *of*. A derating *by* 0.5% every 100m gives for example that a melting fuse is to be derated *by* 5% at 3000m. This means an altitude derating *of* 95%.

4.4.4 Current pulses

Considering current pulses, the I^2t value is important as it states the energy required to melt the fuse element. It does not include heating of the fuse element to the melting-point, only the energy required to transform the fuse element from solid to liquid. I^2t depends on the pulse waveform, peak current and duration (independent of voltage and temperature). Any pulse not intended to trip the fuse (transients, start-up currents, inrush currents etc) must be reviewed.

I^2t is the integrated value of the current pulse and can be calculated e.g. by using an oscilloscope. Another way is to approximate the current pulse waveform. A figure similar to Figure 4.1 is often provided in the fuse specification from the manufacturer. I^2t is then obtained by using the equation of the appropriate waveform.

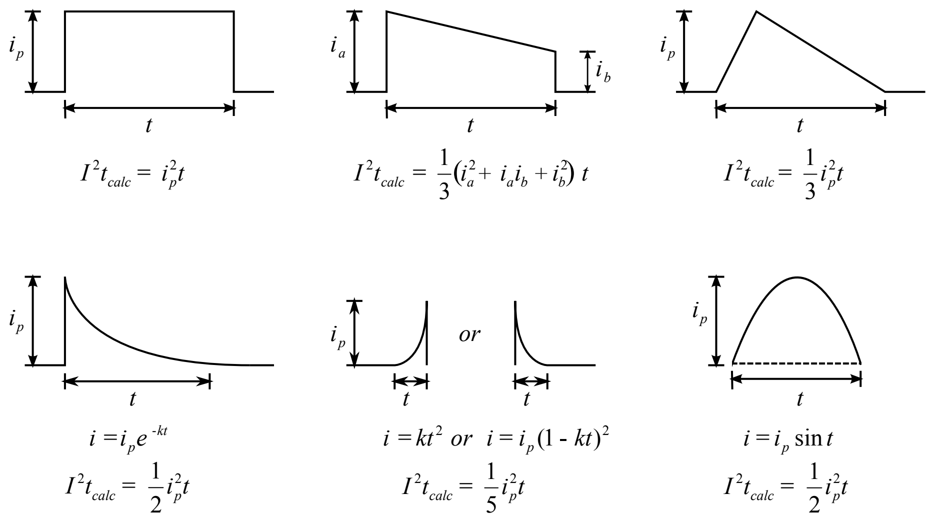


Figure 4.1: Different wave shapes used when approximately calculating the energy of a current pulse.

When calculating the I^2t value, it is important to include the entire current pulse. But as the current often contains current ripple, it is not always easy to determine the beginning and the end of the current pulse. Since the current value that must be derated is the maximum operating current, pulses with peak value below the maximum operating current do not need to be considered. Current pulses are therefore defined as current values exceeding the maximum operating current and the pulse lasts as long as the value of the current exceeds this. When calculating I^2t with assistance of Figure 4.1 it is important to include the DC component. In Figure 4.1 the current is zero before and after the current pulse. If a DC component is present the DC-offset must be included in the approximation. Adequate time (10 sec.) must exist between pulse events to allow heat from the previous event to dissipate.

As seen in Figure 2.3, the number of pulses is a significant parameter that must be considered. In the existing derating document at Ericsson Power Solutions this is not accounted for, but according to Figure 2.3 even for 100 pulses, a derating of just over 50% has to be made. Since a current pulse can occur a few times during the lifetime of a fuse or once every minute depending on the application, the number of current pulses is important to consider.

4.4.5 Trip time

Different components are more or less sensitive to over currents. A cable is for example inductive and has high thermal impedance while a MOSFET is very sensitive to high currents and must be protected instantaneously. Depending on the kind of material in the melting wire and the type of solder joint, the trip time can vary depending on the value of the over current. The recommendation in the guideline is to choose a suitable trip characteristic from the graphs provided by the manufacturer.

4.4.6 Breaking capacity

Breaking capacity does not have any impact on how and when the fuse trips. Since circuit protection at Ericsson Power Solutions mostly is intended to prevent fault spreading in the system, the breaking capacity is very important for safety reasons. If a melting fuse is exposed to a current higher than the stated breaking capacity, the arc will not quench. If so the arc and the heat generated from the current will then most likely cause the melting fuse to rupture, explode or start a fire. This means that a melting fuse must have a breaking capacity equal to or higher than the highest possible output current from the power source. The breaking capacity is stated in the specification of a melting fuse.

4.4.7 Voltage rating

It is stated that the voltage rating should be equal to or higher than the maximum operating voltage. This can seem to be a simple matter with no reason to analyze, but the fact that there are significantly fewer rated values of the voltage compared to the current could cause a problem. Typical fuse voltage ratings are 250V and 500V. If a fuse is set to operate in a system provided by $250V \pm 10\%$ it is an issue that the voltage level is permitted to exceed 250V since a larger fuse is more expensive and also needs larger conductors, causing the cost to increase. It can be claimed that when certifying a fuse, the rated value is a value that the fuse *must* be able to handle for a minimum. The actual value that the fuse is able to handle is allowed to be higher than the rated value but never lower. It is therefore most likely that the fuse rated to 250V can be able to handle the extra 25V that can run in the system. Despite this fact, it is from a safety reason absolutely not permitted to do so.

4.4.8 Resistance and voltage drop

In the applications intended to include melting fuses at Ericsson Power Solutions the voltage drop across a fuse is negligible, hence this has not been included in the guideline.

4.5 Circuit breakers

Since Ericsson Power Solutions does not use thermal circuit breakers, the parameters in the guideline are referred to magnetic hydraulic circuit breakers. Magnetic hydraulic circuit breakers are very adaptable when it comes to rated current value and trip time. Depending on the number of turns in the coil and the viscosity of the oil in the delay tube, the trip time and the rated voltage can be chosen to almost any value, regardless of the current rating. A magnetic hydraulic circuit breaker is also relatively small and easy to fit and can therefore be used in many applications. The ability to reset the circuit breaker is also something that normally is seen as an advantage.

4.5.1 Current rating

It is stated that magnetic hydraulic circuit breakers can be rated to 100% of the operating current. It is important though to realize that even a slight increase of the current may cause the breaker to trip. The breaker *might* trip at 101% of rated current. The standardization organizations Underwriters Laboratories (UL) and International Electrotechnical Commission (IEC) test magnetic hydraulic circuit breakers according to Table 4.1 below.

Table 4.1: Trip calibration in UL and IEC tests

$\mathbf{I_r}$[%]	**UL 489**	**IEC 60 947-2**
105%	No test performed	$<$ 63A, no trip within 1 hr $\geq 63A$, no trip within 2 hr
100%	No trip at stabilized temperature. 40 °C	No test performed

As for melting fuses, the problem is to know which current level that is to be used as the rated current value, and again it is the *maximum operating current* level that is implied. The difference for magnetic hydraulic circuit breakers is that if current ripple is present it is the RMS value that shall be used regardless of whether it is AC or DC current. If the current ripple in a system has high amplitude it reminds more of reoccurring current pulses and it can be difficult to separate the two from each other. After being in contact with distributors and manufacturers, the following rules was determined:

When *one* of the following is satisfied only the RMS value of the current needs to be considered:

- Duty cycle $\geq$ 50% and frequency $\geq 50Hz$
- Current ripple $\leq$ 5% of DC value and frequency $\geq 100Hz$

If neither of these are fulfilled the current ripple is to be seen as reoccurring pulses, see section 4.5.4.

4.5.2 Temperature derating

In contrast to melting fuses the current carrying capacity of magnetic hydraulic circuit breakers is only affected negligibly by ambient temperature changes. In the guideline no additional temperature derating concerning rated current has to be made.

As mentioned earlier, the trip time differs with ambient temperature. The trip time decreases with higher temperature which is often thought of as an advantage, because at high temperatures the surrounding equipment is more sensitive to high currents. If the trip time is important to the application, it is recommended to perform lab tests to determine that the breaker trip sufficiently fast when exposed to very high or low temperatures.

For temperatures between $-40\,^{\circ}\mathrm{C}$ and $+80\,^{\circ}\mathrm{C}$, the following approximative mathematical model used by a manufacturer[2], can be applied to obtain the change in trip time for magnetic hydraulic circuit breakers:

$$t(T) = t(25\,^{\circ}\mathrm{C})d_t(T) \tag{4.1}$$

Where t is the time, T is the temperature and $d_t(T)$ is according to the following equations:

From $-40\,^{\circ}\mathrm{C}$ to $0\,^{\circ}\mathrm{C}$:

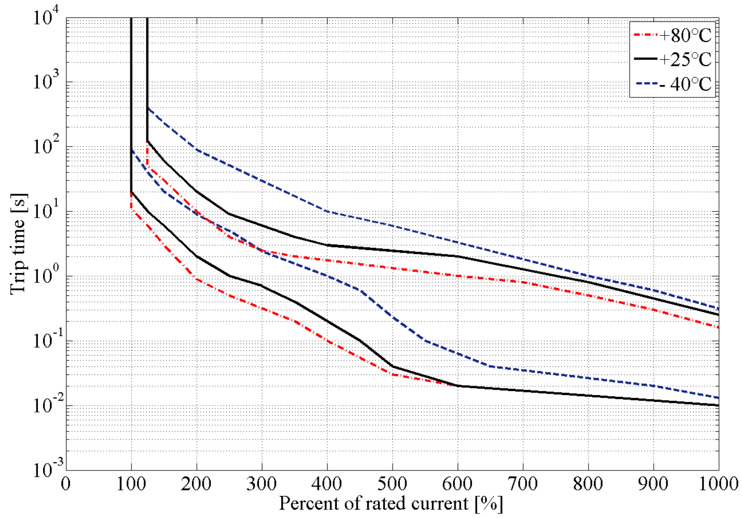
$$d_t(T) = -8T + 166[\%] \tag{4.2}$$

From $0\,^{\circ}\mathrm{C}$ to $+80\,^{\circ}\mathrm{C}$:

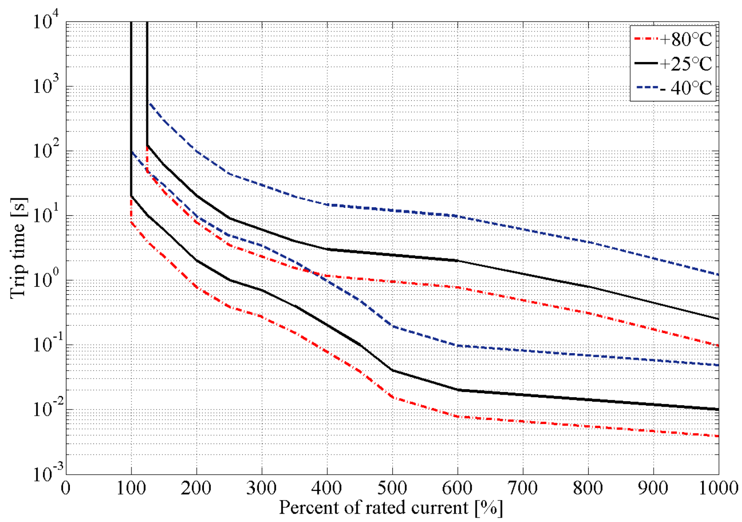
$$d_t(T) = 166e^{-T/55}[\%] \tag{4.3}$$

Using these equations and comparing the result to a measured value from a manufacturer [4] shows that the results agree quite well. The comparison made is shown in Figure 4.2.

[2] Jean-Christophe Barnas, Eaton Corporation



(a) Measured values [4]



(b) Calculated values

Figure 4.2: Comparison of a calculated and measured value of influence of ambient temperature on trip time for a magnetic hydraulic circuit breaker.

It is notable that for values above the instantaneous trip current the equations can not be used, since for instantaneous tripping the temperature only has insignificant influence on the trip time.

4.5.3 Environmental considerations

Environmental aspects can be a problem for a circuit breaker if it is used in an environment where abnormal vibration or chock is present or at high altitude. There are no general way to tell if a breaker can handle vibration and shock since different circuit breakers have varying robustness depending on how they are built and how high current they are rated for. Therefore it is recommended in the guideline to contact the manufacturer to see if the breaker is certified to withstand vibration and shock.

Different circuit breakers use different viscid fluids when detecting over currents, therefore no general approximation can be used, but it is recommended to contact the manufacturer if operation in these kinds of environment are necessary. At Ericsson Power Solutions the requirement of operation up to 3000m are valid for magnetic hydraulic circuit breakers as well. It could be tempting to say that approximately the same altitude derating rules used for melting fuses is valid for magnetic hydraulic circuit breakers as well, but it should be clear that no manufacturer has confirmed this.[35]

Magnetic fields from nearby components and other circuit breakers will not be a problem since the magnetic field decreases significantly by distance. Hence other magnetic fields will not be able to trip the circuit breaker unless very strong.

4.5.4 Current pulses

As stated earlier, any pulse not supposed to trip the breaker must be accounted for and it is important to include the entire pulse.

Reoccurring pulses

After a current pulse has been subjected to a magnetic hydraulic circuit breaker it is important that the core in the coil is given the time to descend to the endpoint in the tube. If not, the trip characteristics will not remain the same and the trip time will be reduced for every pulse. Therefore it is difference between a single current pulse and current pulses that are reoccurring. For reoccurring pulses or current ripple when the duty cycle is less than 50% or has a low frequency ($\leq 50Hz$) two requirements needs to be fulfilled:

1. The RMS value must be lower than the rated current of the breaker.
2. One of the pulses shall not trip the breaker according to the tripping curve of the circuit breaker. use the method described for single pulses below.

If not, the trip characteristics or the current rating of the breaker must be changed to fulfill both demands.

Single pulses

To transfer a current pulse into a time current curve is not as obvious as it can seem. A typical time current curve like the one in Figure 4.3, is divided into three areas. As seen in the figure, the gray area in the middle state where the breaker *may* trip. This means that to make sure that the breaker trips, the pulse must exceed the second curve into the *has tripped* area and to make sure that the breaker will not trip, the pulse can not be allowed into the gray area. This means that for example in the time current curve below, at a current level of 400% the breaker will trip after between 40ms and 300ms.

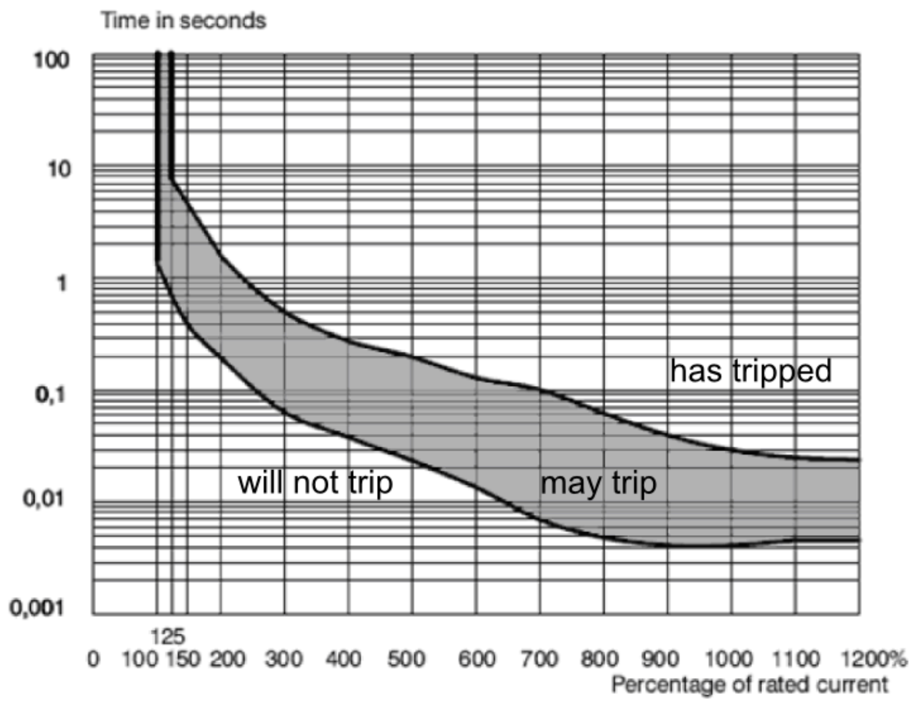


Figure 4.3: A time current curve

The last thing to realize is perhaps the most important; a time current curve is not really a curve, but several dots placed in a figure. Every dot indicates a time for a certain current value. This means that it is not accepted to integrate the pulse since the trip time depends on "constant" current levels. If the current pulse is a square wave, it is easy to see how long the pulse can be allowed at a certain current level before the breaker *may* trip. But in real life current pulses is not always shaped like a square wave. This means that some kind of approximation has to be made.

As described earlier, the trip time of a magnetic hydraulic circuit breaker depends on the time it takes for the core to move from the start point to the end piece, i.e. the breaker trips when the core has moved to the end point (100%), see Figure 4.4.

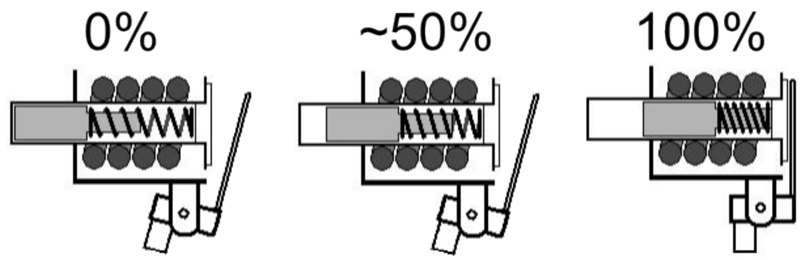


Figure 4.4: Core positions in the coil

As seen in Figure 4.3 at different current levels it takes different time before the breaker trips (may trip). In this time the core has moved 100% for that specific current level.

By approximating a current pulse with one or several square waves, one can approximately calculate how long the core has moved for each square. In Figure 4.5, a breaker rated to 16A is exposed to a start up pulse with a peak current of 76A. The trip characteristic of the breaker is according to curve 3 (Figure 4.3). The start up pulse is approximated with one square pulse and the pulse duration is as long as the current exceeds the rated value of 16A, i.e. 72ms. It is a very rough approximation to say that the pulse is 76A during 72ms, but if the square pulse stay below the may trip area, the breaker will for sure not trip when exposed to the start up pulse.

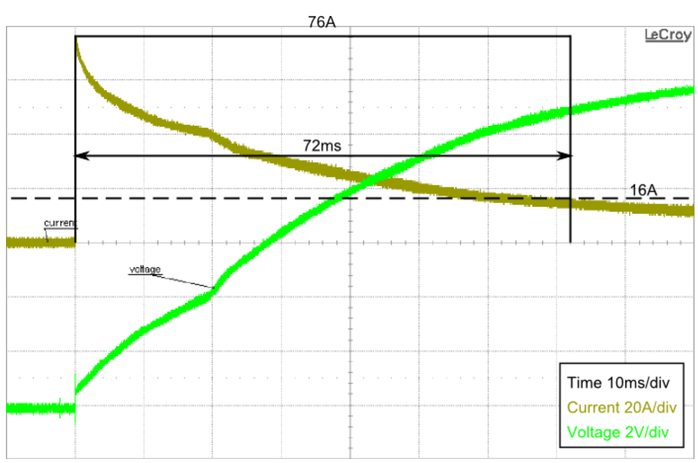


Figure 4.5: Example of a start up pulse approximated with one square.

Peak value divided by the rated value gives:

$$\frac{76A}{16A} = 475\% \tag{4.4}$$

As seen in Figure 4.3, the square wave approximation result in the may trip area which is not okay. Therefore a better approximation has to be made.

If the pulse instead is divided into five square waves according to Figure 4.6 the first square wave is 475% in 2.5ms.

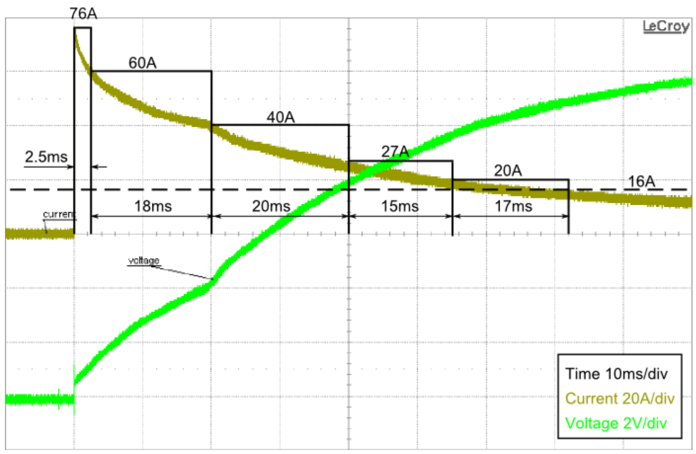


Figure 4.6: Example of a start up pulse approximated with five squares.

In Figure 4.3 it can be seen how long it takes for a pulse with this amplitude to reach the may trip area (100% core movement). Since 100% core movement is 25ms, for a current level of 475%, the core has after 2.5ms moved:

$$\frac{2.5ms}{25ms} = 10\% \tag{4.5}$$

of the total way before the trip.

The second square is 375% for 18ms.

$$\frac{60A}{16A} = 375\% \tag{4.6}$$

According to Figure 4.3 100% core movement for 375% is 40ms so after 18ms the core has moved another:

$$\frac{18ms}{40ms} = 45\% \tag{4.7}$$

of the total distance.

In the same way square waves three (40A), four (27A) and five (20A) gives the final contribution to the total core movement.

The total sum is then given by adding the five contributions to be:

$$10\% + 45\% + 20\% + 5\% + 2.5\% = 82.5\% \tag{4.8}$$

The conclusion is that the core has moved 82.5% of its total way to the end piece and the breaker will be able to handle the start up pulse without tripping. If the total sum still would exceed 100% the number of square waves can be increased again. Eventually the calculated value and the actual value will converge. If the total percentage still exceeds 100%, the breaker will not be able to handle the current pulse and a different time current characteristic or a higher current rating is required.

This way to calculate if a breaker can withstand pulses is only an approximation with many elements of uncertainty. In the approximation it has been simplified that the core movement is linear through the entire tube. Even though the spring constant is linear, a magnetic coil acquires a higher magnetic field when surrounding a core. This implies that the magnetic force on the core increases as the core moves into the coil.

Furthermore the exact time of where the breaker trips (100% core movement) can not be determined from the current curve characteristics. Field tests at Ericsson Power Solutions[3] indicates that the exact breaking curve first follows the top curve and then the lower curve according to Figure 4.7. Exactly where this leap is taken place is not certain but the figure is merely an example to show the element of uncertainties in this approximation.

[3]Patrik Johansson, Ericsson Power Solutions

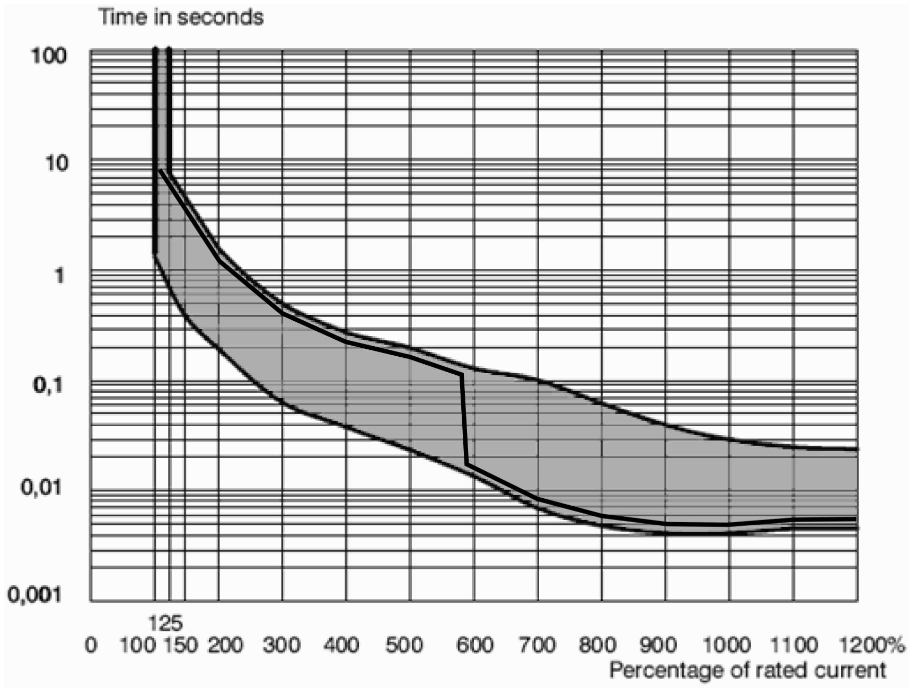


Figure 4.7: Experience on Ericsson Power Solutions indicates that the actual trip time characteristics first follow the top curve and then the lower curve.

These elements of uncertainty and the fact that the square waves includes more than the actual pulse result in a quite rough approximation. But since the uncertainties results in a faster calculated trip time than the actual one, the approximation can be used. There have however not been any practical tests to confirm this.

4.5.5 Life time considerations

Since the contacts in a circuit breaker will erode after a break, the lifetime of a circuit breaker has to be considered. A typical circuit breaker can according to the manufacturers datasheets be exposed to up to 10 000 switching operations depending on the current level. Standard organizations perform so called *open close-open* tests (O-CO tests). This investigates if a circuit breaker is able to trip at the breaking capacity. According to IEC standards, the breaker shall be able to withstand a maximum of two short circuits with a current amplitude equal to the breaking capacity. The test is performed so that the breaker trips (O), than is switched on and tripped immediately once again (CO). According to UL standards a maximum of 3 short circuits at breaking capacity is allowed.

4.5.6 Trip time

The trip time differs depending on the ambient temperature which sometimes can be seen as an advantage. Another influence on the trip time is the mounting of the magnetic hydraulic circuit breaker. It is recommended by manufacturers that when the delay mechanism must be placed vertical or at any angle, additional trip time derating must be done, see Figure 4.8.

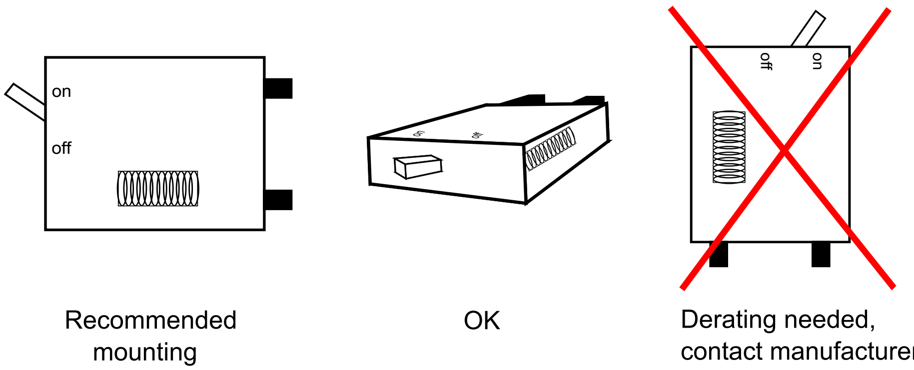


Figure 4.8: Recommended mounting of a magnetic hydraulic circuit breaker.

4.5.7 Breaking capacity, Voltage and Resistance considerations

The same rules are applied as for melting fuses, see section 4.4.6 to 4.4.8.

4.6 Cable and conductor considerations

Another consideration that has to be made concerns the type and size of the conductor to the circuit protection. Not only must the conductors have sufficient current-carrying capacity, I_Z; the conductors also serve as a heat sink to the circuit protection and if the cross-section area is too small the characteristics of the circuit protector might be changed. Also if the conductor has a smaller current-carrying capacity than needed, the internal resistance becomes too high. If a fault occurs the generation of heat and the resistance in the conductors will limit the current and the trip value may not be reached. If so, the circuit continues to operate in spite of that a fault has occurred and heat generated in the conductor might cause a fire.

The current-carrying capacity of a conductor is dependent on type of conductor (cable, busbar, wire, etc), temperature, cross-section area and the length of the conductor. An important detail regarding cables is that if several cables are placed closely together, the heat and thereby also the resistance increase and derating for this is essential. There are standards and regulations of how to calculate I_Z dependent on how and in what application it is to be used.

Since the current-carrying capacity is dependent of in what context it is operated in no general regulation of this can be stated in the guideline but only these formulas that have to be considered:

$$I_{op,max} \leq I_r \leq I_Z \tag{4.9}$$

$$I_{trip} \leq 1.45 I_Z \tag{4.10}$$

$I_{op,max}$	Maximum operating current in the circuit
I_r	Rated current of the protective device
I_Z	Current-carrying capacity of a cable or rated current of busbar trunking systems in continuous service
I_{trip}	Tripping current of the protective device

Which means that the current-carrying capacity of a conductor and the rated current of busbar trunking systems must be calculated in relation to the rated current of the circuit protection and vice versa. [36]

4.7 Circuit protection in series

Circuit protection is among other things used to prevent fault spreading in the systems. To lower the down-time of a system like the one in a telecom station and to prevent just fault spreading, the circuit protection must be rated so the protecting device closest to the fault trip first. If for example a fault occurs on a printed circuit board in a Mini-link, the melting fuse on the printed circuit board shall trip before the circuit breaker in the Mini-link. If not, the power supply will be interrupted for all of the printed circuit boards downstream from the circuit breaker.

Manufacturers only guarantee that the circuit protection nearest the fault triggers first when their circuit protectors are used at every level in the system. Field studies at Ericsson Power Solutions[4] has shown that this can be difficult at high over currents or short circuits.

Figure 4.9 shows the trip characteristics of two circuit breakers rated at different currents. As can be seen, the may-trip areas eventually imbricate, which make it impossible to state which one of the two breakers that will trip first. Nevertheless, the designer must always aim to fulfil this *upstream/downstream selectivity*.

[4]Patrik Johansson, Ericsson Power Solutions

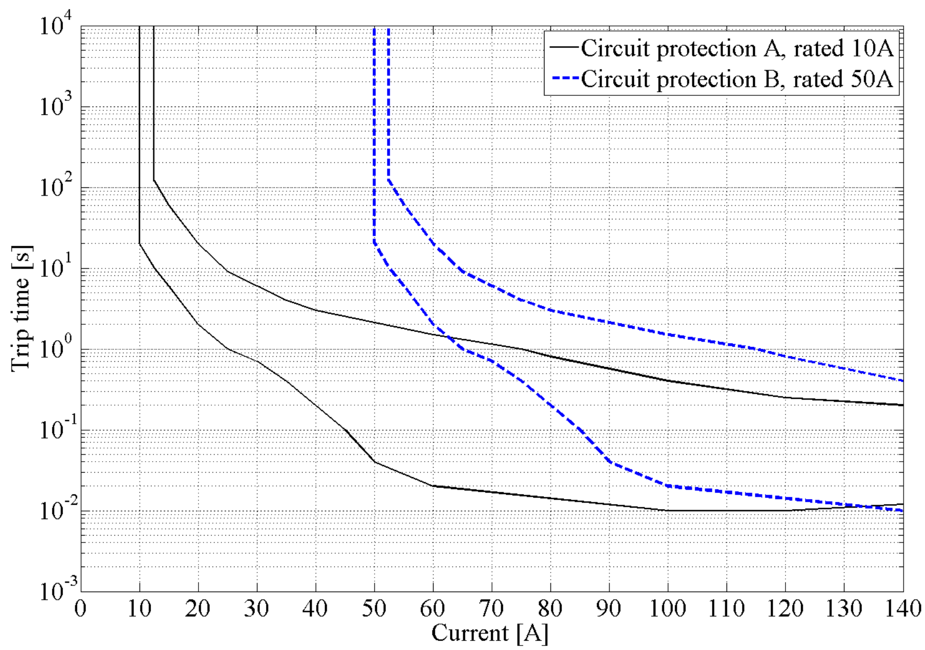


Figure 4.9: Example of trip curves for two different circuit protectors rated at different currents.

4.8 Standards

The subject of standardization is a complex and rather confusing myriad of national and internal standards covering all types of products and safety demands. It is important for a hardware developer in a multinational company to consider different performance and safety demands from all over the world. Most countries have their own regulation offices with their own performance rules and safety regulations.

IEC is a standard writing organization with the purpose of correlating different national standards. Certification of compliance with IEC demands for national standards exists but IEC does not certify anything. Also, there is no demand to follow the standards of IEC, but only a *recommendation* to do so. IEC standards are not feasible worldwide; certification is given by national organizations.

Studies have been done that conclude that since standards are made to fit in different power markets, comparasions of corresponding standards does not provide necessary information on the compability. There are too many aspects that differ. [33] Temperature rise, calibration, short circuit and spacing's are just a few of the differences in test routines that are made according to UL and IEC. Table 4.2 is intended to give an example of the differences that may occur.

Table 4.2: An example of test differences between IEC and UL molded case circuit breaker standards, with respect to circuit-opening time during continuous overload

$\mathbf{I_r}$[%]	**UL 489**	**IEC 60 947-2**
200%	Each pole tested separately. Specified maximum trip time.	Each pole tested separately. Trip time within manufacturers stated value.
135%	Poles connected in series. $\leq$ 50A trip within 1 hr $>$ 50A trip within 2 hr	No test performed
130%	No test performed	Poles connected in series. Conducted immediately following 105% test. $<$ 63A trip within 1 hr $\geq$ 63A trip within 2 hr
105%	No test performed	$<$ 63A, no trip within 1 hr $\geq$ 63A, no trip within 2 hr
100%	No trip at stabilized temperature. 40 °C	No test performed

A standard is furthermore not intended to be used single-handedly. Like a circuit protector is intended to operate in a circuit along with other components, a standard is supposed to co-operate with other standards, depending on the application.

Since the area of standards is a complex subject, no further studies have been made of this topic. The part about standards in the guideline is reduced to a list of the most important standards regarding circuit breakers and melting fuses. Since this is a study of circuit protection, no consideration of telecom standards has been made.

4.9 Electronic fuses

The main reason of leaving out electronic fuses from the guideline is that since all the parameters of an electronic fuse can be programmed, the derating rules of the characteristic parameters in this guideline become superfluous. An electronic fuse is not *one* component but consists of several different components. When derating for example temperature or environmental impacts, all the different components in an electronic fuse must be derated and considered. Since an electronic fuse can be designed in many different ways with varying components, no general guideline of this kind can be made.

4.9.1 Characteristic parameters of electronic fuses

Selecting the characteristic parameters of an electronic fuse is a bit different than for a melting fuse or a circuit breaker. The parameters to be considered are the same but since an electronic fuse is programmable, the characteristics can be set to fit the demand for in where the electronic fuse is to be operated. To determine when the MOSFET shall trip, a simulated breaking curve is programmed. Even if the trip characteristics of an electronic fuse could be very fast (Figure 4.10), it is often programmed to simulate a circuit breaker and tries to replicate the behavior of one. The reason for this is that the surrounding equipment is often designed to match a certain circuit breaker and to change all this equipment is an expensive operation. A benefit compared to a regular magnetic hydraulic circuit breaker is that current pulses that would trip a magnetic hydraulic circuit breaker according to its time current characteristics can be programmed to be passed through in an electronic fuse.

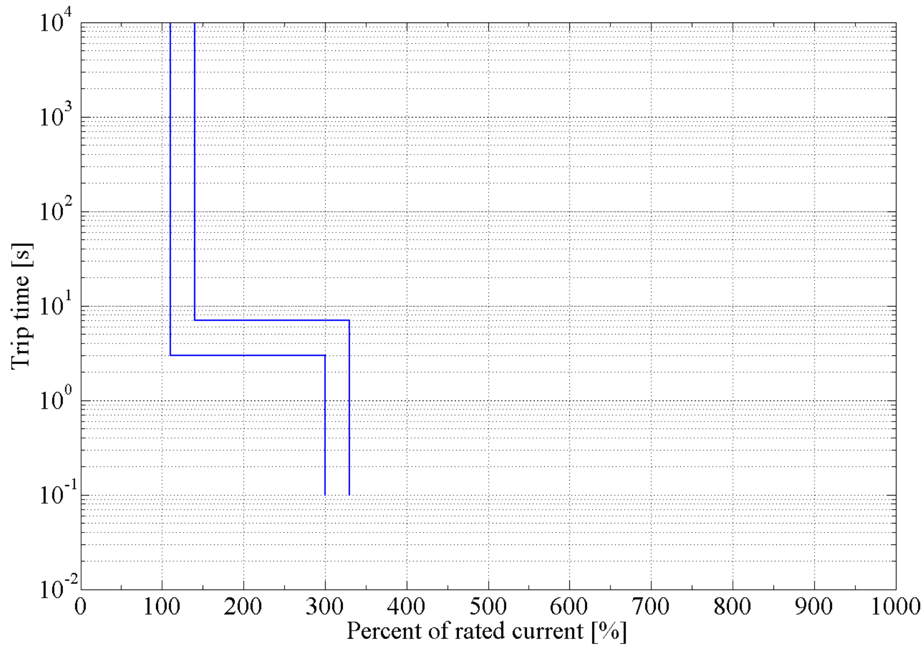


Figure 4.10: Trip characteristics of an electronic fuse.

From a standard point of view, an electronic fuse is not classified as a circuit protection unless it contains a melting fuse or a circuit breaker in series. When short circuit tests are performed on a devices containing electronic fuses, the MOSFET is short circuited and only the standardized circuit protection in series are tested.

4.10 Derating according to the guideline

To easily understand how to use the guideline a section that shows two simple examples of circuit protection design is included in the guideline. The tasks in the examples are to obtain the derating parameters for a melting fuse and a magnetic hydraulic circuit breaker inside a Mini-link.

4.10.1 Derating of a melting fuse according to the guideline

A melting fuse is placed on a printed circuit board inside the Mini-link (see chapter 2.5.2). The Mini-link is fed with -48V but due to losses in the feeding cable, the melting fuse is only exposed to -46 V nominal voltage. Due to supply variations it can vary between -38V and -58V and the load is constant and maximum 60W. Due to a current limiting device in series with the fuse, the maximum pulse current the fuse will be exposed to is 5A over the operating current during 5ms.

Following the flow chart proposed in Figure 4.11 is a good way to find a suitable melting fuse for the application.

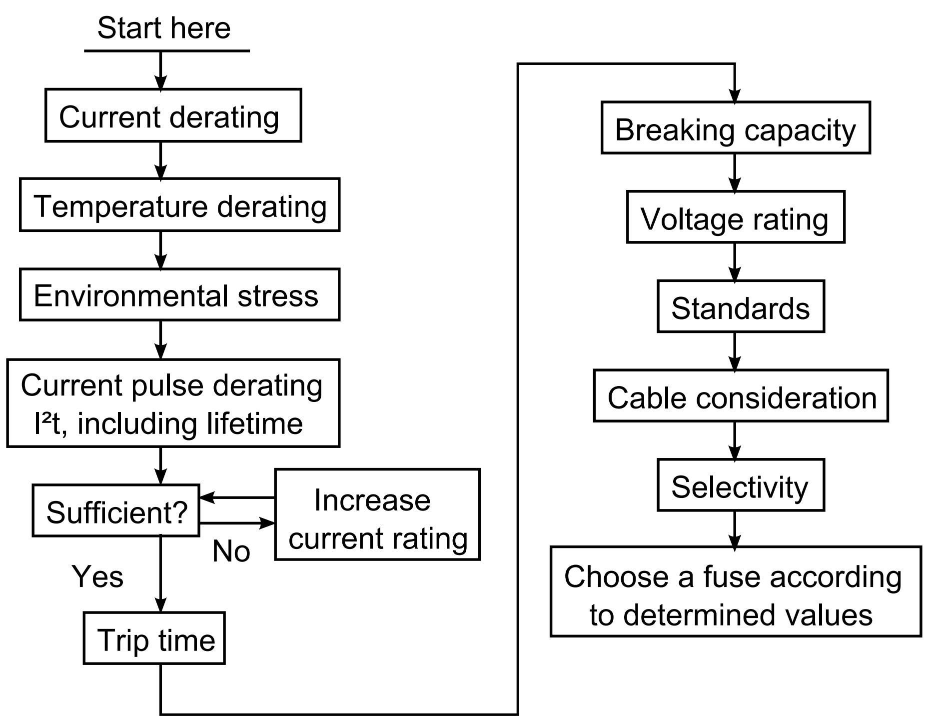


Figure 4.11: Flow chart when choosing a melting fuse.

Step 1. Current rating

The input values Pmax=60W and Vmin=38V and the equation:

$$P_{max} = V_{min} * I_{max} \tag{4.11}$$

result in $I_{max\ average} = I_{max} = 1.58A$
Standard steady state derating is assumed to be 80%.

Step 2. Temperature variations

The ambient temperature will be maximum 55 °C. A fast acting fuse is used, which according to the example in Figure 2.2 gives 97% temperature derating.

Step 3. Environmental stress

The altitude derating is calculated to 95% at 3000m above sea level. The rated current calculated might have to be changed if the current pulse derating later in the flow chart is not sufficient.

$$I_r = \frac{1.58}{0.8 * 0.97 * 0.95} = 2.14A \tag{4.12}$$

Step 4. Current pulses

The maximum current pulse the fuse will be exposed to is a square wave pulse with an amplitude of 6.58A (maximum operating current and pulse amplitude) lasting for 5ms. Using Figure 4.1 and the square wave formula gives:

$$I^2t = 6.58^2 * 0.005 = 0.216A^2s \tag{4.13}$$

Step 5. Lifetime

The fuse is assumed to be exposed to no more than 10 000 current pulses during the system lifetime. According to Table 2.1 an I^2t derating *to* 29% . This gives:

$$I^2t_{fuse} = \frac{0.216}{0.29} = 0.745A^2s \tag{4.14}$$

Melting fuses rated to 2A can cope with an I^2t value of this amplitude. It ought to be no problem to find a fuse rated above 2.14A with this I^2t rating since the I^2t value increases for higher current ratings.

Step 6. Trip time

Since the fuse on the printed circuit board primarily is intended to prevent fire and fault spreading the trip time is less important. According to Figure 2.4 there is a fuse rated to 2.5A with a trip time that will be sufficient for the needs of the application.

Step 7. Breaking capacity

The maximum current that can occur in the system is in the range of kA which is normal for a fuse this size to cope with.

Step 8. Voltage rating

The voltage will be maximum 58V, which the breaker must be rated to.

Step 9. Standards

A normally rated magnetic hydraulic circuit breaker, as in this case is applicable to most standards.

Step 10. Cable consideration

The busbar trunking must, according to equation 4.9 and 4.10 have a current-carrying capacity higher than or equal to 2.14A. In a Mini-link this is normally not a problem.

Step 11. Selectivity

Not enough knowledge of the system is obtained to perform this step yet. When the magnetic hydraulic circuit breaker upstream from the melting fuse is rated, the selectivity can be considered.

4.10.2 Derating of a circuit breaker according to the guideline

A Mini-link is protected by a magnetic hydraulic circuit breaker rated to 30A. Inside the Mini-link there are 20 printed circuit boards, each one protected by a melting fuse according to the one in section 4.10.1.

The Mini-link is provided by -48 V nominal voltages which can range between -40V and -60V. The load is again constant but with a maximum of 1200W. Due to the current limiting device mentioned in section 4.10.1, the maximum pulse current the breaker will be exposed to is 5A over the operating current during 5ms.

Following the flow chart proposed in Figure 4.12 is a good way to find a suitable circuit breaker for the application.

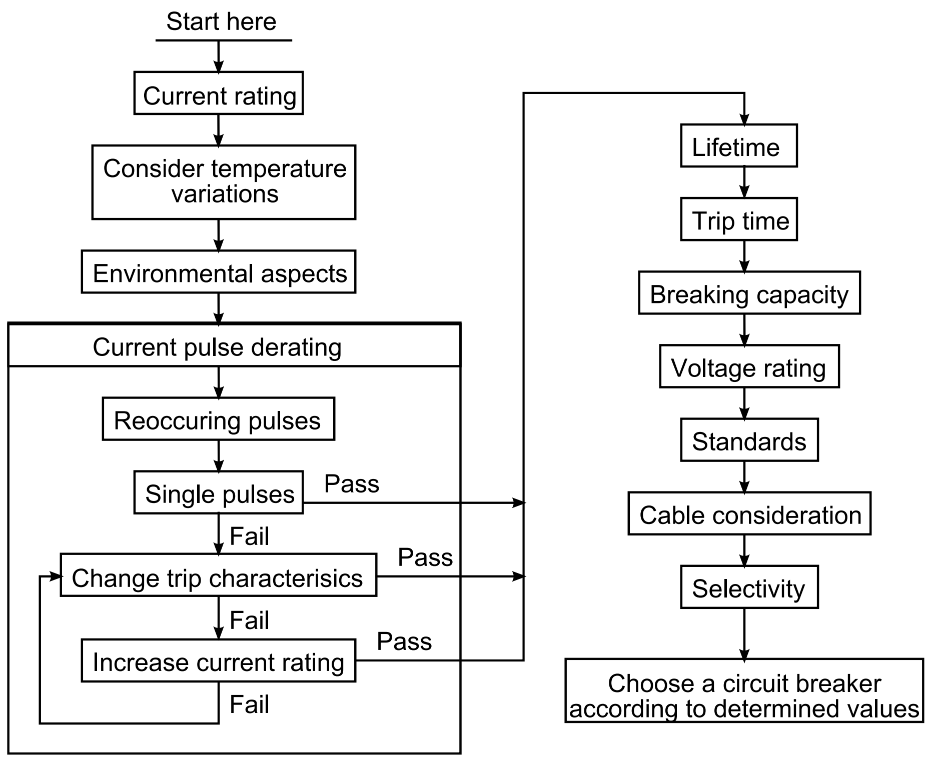


Figure 4.12: Flow chart when choosing a magnetic hydraulic circuit breaker.

Step 1. Current rating

The input values Pmax=1.2kW and Vmin=40V and equation 4.11 result in $I_{max,rms} = I_{max} = 30A$. In this application, only a negligible current ripple is present at the maximum current level.

Step 2. Temperature variations

The temperature will be maximum 55 °C. Equation 4.3 gives:

$$d_t(55\,^\circ\mathrm{C}) = 166e^{-55/55} = 61\% \tag{4.15}$$

This d_t derating is then to be multiplied with the trip time when selecting time-current curve in step 4 and 6 according to equation 4.1.

$$t(55\,^\circ\mathrm{C}) = t(25\,^\circ\mathrm{C}) * 0.61\% \tag{4.16}$$

Step 3. Environmental stress

Recommended by *IEEE Recommended Practice for Applying Low Voltage Circuit Breakers Used in Industrial and Commercial Power Systems* [35], an altitude derating of 99% at 2600m and 96% at 3900m is stated. An altitude derating value of 98% is therefore chosen. The calculated value of the rated current can then be obtained according to:

$$I_r = \frac{30}{0.98} = 30.61A \tag{4.17}$$

A commonly available value is 32A which can be used.

Step 4. Current pulses

The breaker will not be exposed to any reoccurring pulses.

The maximum single current pulse the breaker will be exposed to has the shape of a square wave lasting for 5ms and with an amplitude of 5A above the maximum operating current (total amplitude is 35A). Since the pulse is of a square wave type it is easy to convert it into a time-current curve.

Due to its low amplitude (117%) and the short duration (5ms) of the current pulse, a circuit breaker with instant time delay is chosen in this example. Even if the time-temp derating from step 2 is included a time-current curve of this type will be able to handle a pulse like this. There may however be a problem regarding the selectivity but more of this later on.

Step 5. Lifetime

The circuit breaker will last for 10000 switching operations which is enough for this application.

Step 6. Trip time

Since the circuit breaker is primarily used for protection of connectors the trip time is less important. With an instant time delay circuit breaker the trip time will be more than sufficient.

Step 7. Breaking capacity

The maximum current that can occur in the system is in the range of kA which is normal for a breaker this size to cope with.

Step 8. Voltage rating

The voltage will be maximum 60V, which the breaker must be rated to at least.

Step 9. Standards

A normally rated fuse like in this case is applicable to most standards.

Step 10. Cable consideration

The cables must, according to equation 4.9 and 4.10 have a current-carrying capacity higher or equal to 30.61A. In a Mini-link this is normally not a problem.

Step 11. Selectivity

It is important to choose a circuit breaker with lower trip time than of the melting fuse above. Choosing a circuit breaker with an instant time delay might therefore not be such a good idea depending on the fuse characteristics of the melting fuse since if the melting fuse is to be tripped first, it needs to have a faster trip time than the breaker.

Choosing a breaker according to the values above is not a problem. The rated value of the breaker (32A) differs slightly from the former rated value (30A). The prior designer have probably either not considered altitude derating or taken a chance with a smaller circuit breaker since the voltage value differs between 40-60V and the maximum operating current seldom occurs.

5 Discussion

To compare the guideline with previous work is difficult since the closest to a guideline like this is the "fusology" in the manufacturer's datasheets. These documents are however not comparable since this guideline is aimed to a specific topic in the circuit protection area. There are several guidelines at Ericsson Power Solutions but none of those are as comprehensive as this.

When to design a circuit with proper circuit protection it is a matter of cost versus risk. It is of course possible to use both belt and braces but the expense would be thereafter. The example regarding a magnetic hydraulic circuit breaker rated to 250 volt in a system designed for 250V $\pm 10\%$ described earlier (section 4.4.7) is a typical example. It is of course more cost-effective to use a breaker rated to 250V compared to one rated to 500V but if to do such a change, the designer must be aware of the risks. If a fault with high over current occurs and the voltage is at 275V while the circuit protection is rated to 250V the arc may not be extinguished and if so the current will keep rushing until the voltage or current decreases.(Brand kan uppstå om de fortsätter vara på denna nivå.) However circuit protection is never allowed to perform worse but only better rhan stated and therefore the protector might be able to cope with this.

6 Conclusions

As mentioned in the case set up, the primary object was to compile a simple and brief guideline on maximum two pages and easily overviewed. Since the subject of circuit protection proved to be a rather complex area, difficult to summarize in a short table without any further explanation, the final document became substantially larger than first intended.

The intention was also to in a large extent as possible, lay down rules that can be valid all over Ericsson Power Solutions. This goal also altered during the work. It can not be stated that always when using for example a magnetic hydraulic circuit breaker, some specific rule is valid. The reason of this is as the report and the guideline implies, that circuit protectors do not necessarily behave the same dependent on different parameters and surroundings.

Instead the document made has become a guideline of what parameters that have to be considered and how to obtain substantial facts that are to be considered. This is as told before to save time and money for the designer. But still, despite the guideline this does not mean that the designer can stop thinking. It is always up to the designer to analyze the cost versus risk aspects.

6.1 Future work

The structure of the guideline was altered and thereby the process of developing it expanded during the work, hence more time than planned for development of the guideline elapsed. This resulted that examples and testing of the guideline was almost entirely left out. Further testing of the guideline is therefore something which is recommended. Another suggestion is to investigate the electronic fuse further and also try to develop an electronic fuse to see the functionality and the difficulties that had to be dealt with.

One thing that could be done to save more time for the designer is to compile a database with the different circuit protectors on the market. Even if this is a time consuming and hard work it would make it possible to create a program that compared the different parameters and a suitable circuit protector could be presented depending on application and input values from the designer.

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A Appendix - Circuit protection Guideline

Appendix A includes the Circuit Protection Guideline developed in this master thesis. It is written with the Ericsson document template.