GUIDELINES FOR DESIGNING ORDER BASED ENGINEERED CIRCUITS IN ACS880 MULTIDRIVE

Lappeenranta–Lahti University of Technology LUT

Degree Programme in Electrical Engineering

Master's thesis

2022

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Examiners: Associate Professor Pasi Peltoniemi

Professor Pertti Silventoinen

ABSTRACT

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Guidelines for designing order based engineered circuits in ACS880 multidrive

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Keywords: ABB, ACS880, frequency converter, multidrive, design, IEC, standard

The design of electrical circuits is guided by the international standards, internal corporation guidelines and known best practices. Sometimes for electrical designer, it might be hard to understand the fundamentals behind the selection of wiring and components in certain situations. The objective of this master's thesis is to introduce the key factors related to wiring and component selection in ABB ACS880 -multidrive frequency converter and create a simple design tool to support the electrical design work.

The design tool was made with Microsoft Excel software. The design tool helps electrical designers to select needed components and correct cross section of the conductors based on the load current in different electrical circuits. The usage of the design tool is intended to be simply as possible. The operation of the design tool is based on the IEC standards, ABB internal guidelines, manufacturer manuals and best practices introduced in the thesis.

As a result, workable design tool was presented. The design tool can be used in electrical motor circuit dimensioning in nominal currents below 32 A and in generals circuits up to 250 A. The design tool was tested with variable load currents in both motor- and general circuits. The result given by the design tool were verified by manual calculations and comparison to the information from manufacturer datasheets. The future developments to cover the requirements from UL and CSA standards and to include multiple motor circuits was also discussed in the thesis.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Sähkötekniikan koulutusohjelma

Janne Luodonpää

Tilaussuunnitellun ACS880 multidriven suunnitteluperusteet

Sähkötekniikan diplomityö

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Sähköpiirien suunnittelua ohjaavat kansainväliset standardit, yritysten sisäiset ohjeet ja hyväksi havaitut käytännöt. Sähkösuunnittelijan voi olla välillä hankala ymmärtää, että mihin komponenttien sekä johtimien valinta tietyissä tilanteissa perustuu. Tämän diplomityön tarkoituksena on tuoda esiin johtimien ja komponenttien mitoituksessa määräävät tekijät ABB ACS880 multidrive -taajuusmuuttajassa sekä luoda yksinkertainen suunnittelutyökalu sähkösuunnittelijan työn tueksi.

Suunnittelutyökalu toteutettiin Microsoft Excel -ohjelmalla. Suunnittelutyökalun avulla sähkösuunnittelija voi nopeasti selvittää tarvittavat komponentit ja johdinvahvuudet kuormitusvirran perusteella erilaisissa sähköpiireissä. Suunnittelutyökalu pyrittiin toteuttamaan niin, että sen käyttö on mahdollisimman yksinkertaista. Työkalun toiminta perustuu diplomityössä esitettyihin IEC standardeihin, ABB:n sisäisiin ohjeisiin, laitevalmistajien manuaaleihin sekä aiemmin havaittuihin hyviin käytäntöihin.

Lopputuloksena esitettiin toimiva suunnittelutyökalu. Suunnittelutyökalua voidaan käyttää sähkömoottoripiireissä nimellisvirraltaan alle 32 A moottorilähdöille sekä yleissähköpiireissä alle 250 A sulakelähdöille. Suunnittelutyökalua testattiin eri kuormituksilla sekä moottori- että yleispiireissä. Työkalun antamat tulokset vahvistettiin manuaalisesti laskemalla ja vertailemalla komponenttien valmistajien datalehdistä saatuihin tietoihin. Diplomityössä pohdittiin myös suunnittelutyökalun jatkojalostamista kattamaan UL ja CSA standardien vaatimukset sekä useamman moottorin moottorilähdöt.

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Espoo, November 7, 2022

Janne Luodonpää

ABBREVIATIONS

IEC	International Electrotechnical Commission
UL	Underwriters Laboratories Inc.
CSA	Canadian Standards Association
MD	Multidrive
LV	Low voltage
MV	Medium voltage
OBE	Order based engineering
ACU	Auxiliary control unit
ICU	Incoming unit
DSU	Diode supply unit
IGBT	Insulated-gate bipolar transistor
ISU	IGBT supply unit
RRU	Regenerative rectifier unit
INU	Inverter unit
DDC	DC/DC converter
MOU	Motor options unit
SCU	System control unit
DOL	Direct-on-line
UPS	Uninterruptible power supply
PVC	Polyvinyl Chloride
XLPO	Cross-linked Polyolefin
XLPE (PEX)	Cross-linked Polyethylene

EPR	Ethylene Propylene Rubber
CPE	Chlorinated Polyethylene
HF	Halogen free
MCB	Miniature circuit breaker
MPCB	Motor protection circuit breaker
CLC	Compact liquid cooled

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1 Introduction

Cabinet-built frequency converter manufacturing and design for customer markets must meet the requirements from legislation but also the requirements from standards and classifications and demands from the customer. The purpose of the standards and classifications is to ensure that the drive is adequate and safe to use. By following the standards and classifications it is easier and cost-effective to prove suitability of the drive to be used in the application where it is designed to.

There are various standards worldwide and it is important for designer to recognize the difference between standards and what standard should be used. Customer is responsible to provide information of standard what should be followed (UL /CSA /IEC) but still designer needs to acknowledge what it means in the design point of view. Also, a wide variety of different customer applications sets more specific requirements for the cabinet-built drives.

To ease and clarify the design process it is important that designer has the knowledge where the appropriate standard or specification is derived from. Coherent design guideline also conforms the ACS880MD product and enhances the order-based engineering design process.

This thesis is divided into following sections:

- The first section presents the background, objectives, and limitations of this thesis
- The second section gives a brief look to the environment where this thesis will be used
- The third section clarifies to a reader the different standards used in this work
- The fourth and fifth sections, the principles for the circuit dimensioning are presented
- The sixth section presents the components discussed in this thesis
- The seventh section introduces the circuit design tool and gives examples how this thesis will work in practice
- The eighth section gives conclusions and possible future developments for the thesis

1.1 Background of the thesis

The topic of this thesis is led from System Drives continuous improvement program. The issue is that although the order based engineered projects has been delivered to customers for decades and the fundamentals of electrical design has not been changed, the available documentations and product design principles can be outdated, and accurate information might be hard to find. During the years there have been several different product series (ACS600, ACS800 etc.) and the design principles might differ from the current ACS880 series. For the new designers one issue is also that everyone has their own collection of tables, charts, and dimensioning documents which they are using. New incomers must know where all these materials are derived from, where it can be found and how to use it.

1.2 Objectives of the thesis

The main goal of this paper is to bring together and collect the necessary information needed in electrical design in order-based engineering. This thesis is not a work instruction, but this paper could be used as a support material for electrical designers and guide to a successful design process. This thesis collects requirements and recommendations from several different standards and known best practices related to electrical design of a cabinet-built frequency converter design. This information is used to create a circuit dimensioning tool in Microsoft Excel. Dimensioning tool can be used as a support tool for OBE designers.

Research methods of this thesis are literature research, interviews, and practical research. Literature research includes standards, product design instructions and related component manufacturer materials. The referenced standards are IEC-standards. Discussions and interviews with my co-workers are requisites for the successful outcome. Interviews with more experienced colleagues helps to gain knowledge and self-confidence toward growing as an electrical designer professional. Practical research basically means questioning, evaluating, and rethinking the work practices how I operate in my everyday job as an order-based engineer.

1.3 Limitations of the thesis

The thesis is limited to air cooled ACS880 multidrive product series. The main perspective in this thesis is in OBE point of view and OBE customized circuits and applications. All components and wirings are inside the cabinet and customer supply parts or cablings are not included. This thesis does not include components and wirings inside the modules neither mechanical dimensioning nor mechanical parts (AC/DC-bus for example). Dimensioning and component selection consist of basic components which are commonly used by OBE. Some of the components might be shortly mentioned and explained but precise dimensioning is not concluded. ACS880 special circuits such as charging circuits are also excluded because there are own dimensioning tools available for these.

2 ABB System Drives

ABB is multinational technology company with four leading business areas:

- Electrification
- Process Automation
- Motion
- Robotics & Discrete Automation

As a part of Motion business area, the System Drives division is a global market leader in high-performance drives, drive systems and packages for process industry and high-power infrastructure applications (ABB 2022a). System Drives products can be divided into low-voltage (LV) and medium-voltage (MV) products. In country level, ABB System Drives Finland is distributed in four different product groups:

- System Modules
- LV Cabinet Drives
- LV Multidrives
- Wind

System modules product group produces all-compatible ACS880 drive modules which can be used in your own cabinet design and assembly. ACS880 drive modules are available for single drive and multidrive applications.

Wind product group's main product is ACS880 liquid cooled wind turbine converter for onshore and offshore wind turbines rated from 0.8 MW to 8 MW.

Cabinet drives and multidrives are cabinet-built frequency converters which commonly consist of supply unit(s) and one (single drive) or more (multidrive) inverter units. For single drives, ABB offers both standardized and order-based engineered configurations. For multidrives there are no standard deliveries hence all multidrive project deliveries go through order-based engineering process. This thesis is done for ABB System Drives Finland and more precisely multidrive department.

2.1 Order Based Engineering

Order based engineering department fulfils the customer requests for tailor made cabinet-built drives. Customer related requests can be mechanical or electrical design tasks for various industrial fields. Order based engineering unit gives support to local sales units and co-operates with other stakeholders such as sales support and research & development teams.

OBE design process commonly starts with a kick-off meeting with the customer where all the necessary details are discussed about project delivery schedule and special requirements for the project are pointed out. After all the details are known and the configuration is frozen, design proceeds with dimensional drawing approvals.

OBE engineer prepares the dimensional drawings for the customer. The customer can comment or approve the dimensional drawings and after approval, designer can proceed to the circuit diagram design. When circuit diagrams are ready for the customer review, the same approval process will apply also for circuit diagrams. Approval times are negotiable, and customer can request needed time for drawing reviews considering production schedule and wished delivery dates.

After all documents are prepared and have customer approvals, the project will be released to the production. OBE engineer will collaborate with production responsible during the whole manufacturing phase. Depending on the project size and nature, typical multidrive design phase could last from a few weeks to a several months and manufacturing phase is typically several months.

2.2 ACS880 Multidrive

Multidrive is based on a common DC-bus arrangement which enables single power entry for numerous inverter units. Multidrive solution is space and energy saving, multiple inverter modules can be assembled into one single cabinet. Common DC-bus solution enables shared energy between the drives, example during braking the motor braking energy can be used by another drive unit connected to the same DC-bus instead of wasting the energy in braking resistor. In figure 1 typical multidrive lineup which includes supply unit and multiple drive units.

Figure 1. ABB ACS880 air-cooled multidrive lineup (ABB Oy 2019a)

Supply unit consists of auxiliary control unit (ACU), incoming unit (ICU) and supply module cabinets. Three different supply type available: diode supply unit (DSU), IGBT supply unit (ISU) and regenerative rectifier unit (RRU). Inverter modules (INU) are available from frame size R1i to nxR8i depending on the power needed. Brake units, DC/DC-converters (DDC), motor option unit (MOU) and control cabinets (SCU) are available as standard for multidrives and more tailormade solutions can be engineered on customer request.

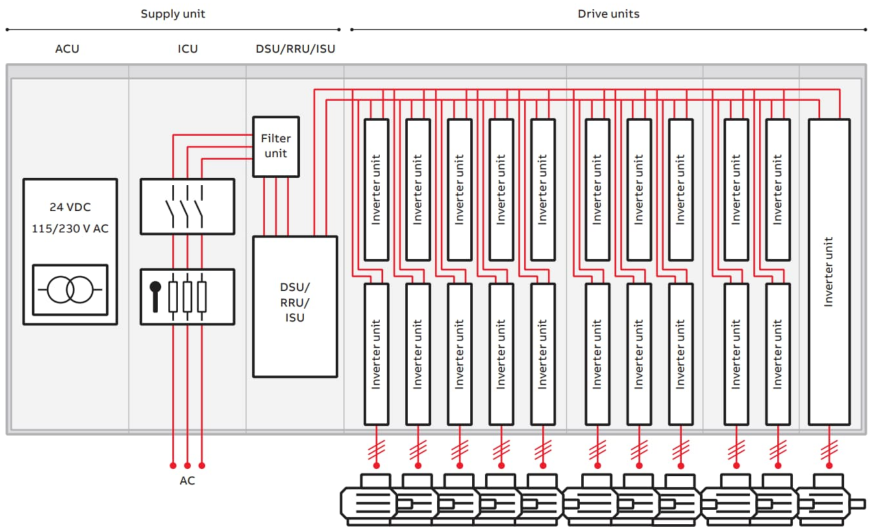

Figure 2. Common DC-bus arrangement enables supply for multiple inverters with a single power line connection (ABB Oy 2019a, p. 20)

The figure 2 shows a typical cabinet arrangement in ACS880 multidrive. ACU cabinet contains the main control parts of the multidrive. Auxiliary voltage distribution parts etc. are also located in ACU cabinet. The main supply entry is in ICU cabinet. ICU cabinet includes terminals for main supply cabling/busbar and main disconnector, contactor or air circuit breaker whichever is selected for the project. Three-phase AC voltage is distributed from ICU cabinet to DSU/ISU/RRU -supply modules where the AC is converted to DC. Common DC-bus supplies the DC voltage to inverter units, DDC-units and braking units.

3 Standards and classifications

In order to meet the customer expectations and requirements globally it is mandatory to familiarize standards and specifications required by local authorities. There are a lot of different standardization organizations worldwide and difficult abbreviations can easily confuse. In this chapter it's briefly explained the difference between international and national standards and how those have connected each other. In figure 3 national and international standardization organizations.

Figure 3. National and international standardization organizations (modified from SESKO 2022)

IEC

The International Electrotechnical Commission is an international standardization organization founded in 1906. The IEC is world leading organization for preparing and publishing international standards for electrical and electronic related technologies. IEC standards are adopted by European countries and globally (IEC 2022).

CENELEC

Comité Européen de Normalisation Électrotechnique is an European Committee For Electrotechnical Standardization. Founded in 1973 CENELEC is responsible for European standardization in electrical engineering field. CENELEC's national members are 34

National Committees in Europe (CENELEC 2022). The most of the CENELEC standards (EN) are identical to or based on IEC standards. EN-standards are identical in every CENELEC member country SFS-EN= Finland, BSI-EN= UK, SS-EN= Sweden etc. (SESKO 2022).

SESKO

SESKO is the National Electrotechnical Standardization Organization in Finland founded in 1965. SESKO represents Finland in the IEC and CENELEC. SESKO is responsible to implement international standards in Finland and verify them as a Finnish national standard.

Totally 95% of the Finnish national standards (SFS) are identical to European standard (EN), (SFS-EN xxx). Finnish standard series *SFS 6000 Low voltage electrical installations* is based on CENELEC and IEC standards but it includes also Finnish national parts so it is published as a four-part SFS-standard (SESKO 2022).

3.1 IEC standards in ACS880 product

ACS880 product is certified according to IEC 61800-5-1 but it follows multiple other standards and ACS880 multidrive can include various components which needs to be approved by IEC in components level. If we zoom out a little and look at the bigger picture the multidrive is also a one component itself in a bigger entity. Basically, when customer is ordering a ACS880 frequency converter it will be a part of larger machine and therefore machine safety standard should be followed.

IEC 61800-5-1 Adjustable speed electrical power drive systems

Standard *IEC 61800-5-1, Adjustable speed electrical power drive systems - Part 5-1* specifies the requirements for adjustable speed power drive systems and their parts focusing on electrical, thermal and energy safety. Standard applies to DC drive systems connected to line voltages up to 1 kV, 50 Hz / 60 Hz and AC drive systems with input voltage up to 35 kV, 50 Hz / 60 Hz and output voltages up to 35 kV (IEC 61800-5-1 2007, p. 7). ACS880 product is certified according to this standard and this is the standard we should always follow.

IEC 60204-1 Safety of machinery – Electrical equipment of machines

IEC Standard *IEC 60204-1 Safety of machinery – Electrical equipment of machines* provides recommendations and requirements for the electrical equipment of machines operating with nominal supply voltages up to 1000 VAC / 1500 VDC and nominal supply frequencies up to 200 Hz. (IEC 60204-1 2016, p. 15). ACS880 drives are not certified according to this but the design tries to fulfil requirements also from this standard.

These two IEC standards mentioned above forms the base for the ACS880 product. These standards specify general requirements for electrical equipment and refers to a several other IEC standards which gives more specific requirements for electrical design. The following standards are the most referenced in this thesis:

- IEC 60364-5-52 Low-voltage electrical installations – Part 5-52: Selection and erection of electrical equipment – Wiring systems
- IEC 60269-5 Low-voltage fuses – Part 5: Guidance for the application of low-voltage fuses.
- IEC 60947-4-1 Low-voltage switchgear and control gear – Part 4-1: Contactors and motor-starters – Electromechanical contactors and motor-starters
- IEC 60228 Conductors of insulated cables

4 Design parameters

When considering cabinet-built drives, it's easy to notice a lot of variables what comes to circumstances inside the cabinet where components and wires are installed. It is not feasible nor cost-efficient to examine every cabinet or project as an individual and use project specific parameters as a base of the design. Standard design is that all the variables are corrected to the same circumstances inside the cabinet with sufficient correction factors. This means that the most adverse conditions are applied even though some cases it might lead to oversizing. Nevertheless, there are also some project specific limitations which are needed to consider for example altitudes above 1000 m and ambient temperature in operation area greater than +40 °C (IEC 60204-1 2016, p. 29)

4.1 Installation method

Wiring installation method is an essential parameter when selecting conductor sizes because it takes into account the heat dissipation from the conductor. When conductor is carrying current, the heat dissipation from the conductor will heat the ambient and without proper escape route it will lead to the ambient temperature increase and reduce the current carrying capacity of the conductor. Current carrying capacities can vary significantly with the same type of conductor installed in free air versus inside thermally insulated wall. By using the adequate installation method in calculations this fact will be considered sufficiently. Also heat sources for example direct sunlight or other direct heat radiation will have an impact to the current carrying capacity.

In cabinet-built drives, standard installation method used is B1 from IEC standard. Lets take a look why this particular method should be used and why not something else. Most of the wirings in cabinet-built drives are inside cable ducts. Standard IEC 60204-1 states that insulated conductor or single core cable in a conduit or cable trunking system is equivalent to the installation method B1 (IEC 60204-1 2016, p. 113). Standard IEC 60204-1 defines cable trunking system and duct as follows:

Cable trunking system:

> “System of closed enclosures comprising a base with removable cover intended for the complete surroundings of insulated conductors or wires” (IEC 60204-1 2016, sec. 3.1.6, p. 18).

Duct:

> “Enclosed channel designed expressly for holding and protecting electrical conductors, cables, and busbars (IEC 60204-1 2016, sec. 3.1.17 p. 19)

Standard IEC 60204-1 section 3.1.17 states that conduits and cable trunking systems are types of duct. Therefore, it would be applicable to use it as a standard installation method.

Although there are wires and cables wired also without cable duct, for simplifying reasons the current carrying capacity inside the cubicles will be commonly calculated using installation method B1. For some cases with special cabinets, it might be justifiable to reconsider if the installation method used in calculations could be something else but as a baseline, method B1 will be applied.

4.2 Temperature factor

IEC 60204-1 specifies the minimum requirement for all electrical equipment to be correct operation in ambient air temperature outside the cabinet between +5 °C – +40 °C (IEC 60204-1 2016, p. 29). ACS880 maximum operational ambient temperature is +40 °C and air cooled multidrive is allowed to exceed this from +40 °C to +50 °C with derating factor of 1% / 1 °C (ABB 2019a, p. 19). Ambient temperature inside the cabinet is derived from maximum operational temperature added with estimation of the heat dissipation from the components inside. In this thesis, the maximum ambient temperature inside the cabinet is estimated to be 60 °C and circuit dimensioning is done accordingly.

4.3 Grouping of circuits

Current carrying capacity of the conductor is highly depended on the ambient temperature as mentioned in section 4.1. Most of the circuits in cabinet-built drives are wired next to each other in ducts and therefore heat dissipation of the adjacent circuits is needed to observe. IEC standard IEC 60204-1:2016 defines that the use of reduction factor for groups of more than one circuit is required, more precise information can be found in IEC60364-5-52 where the derating factors are derived from (IEC60204-1 2016, p. 118).

The conductors which are carrying the load current are the conductors to be considered in a circuit. This means that if operation conditions are known and conductor is carrying a current less than 30% of its current carrying capacity, it can be excluded from the calculations for the reduction factor (IEC60364-5-52 2009, p. 17).

Reduction factor is not needed in cases when horizontal clearance between adjacent cables exceeds two times their overall diameter (IEC60364-5-52 2009 p. 55). It is notable that circuits are the determinant, not the number of conductors. If the group consists of x number of single-core cables it can be considered as x/2 circuits of two loaded conductors or x/3 circuits of three loaded conductors (IEC60364-5-52 2009 p. 55).

The standard design in this thesis assumes the maximum of 8 circuits in one group carrying current: aux. supply, control circuits, UPS-supplies, a couple of fan supplies (IP54-fan, 3-phase DOL-fan) and additional motor fan circuits. Control wires are not expected to affect the calculations due to low continuous load and minor heat losses. There could be also other additional circuits in the group with low continuous currents which effect can be neglected.

Wire dimensioning should be done according to cable arrangement 1 - *Bunched in air, on a surface, embedded or enclosed* shown in figure 4:

Item	Arrangement (cables touching)	Number of circuits or multi-core cables												To be used with current-carrying capacities, reference
		1	2	3	4	5	6	7	8	9	12	16	20	
1	Bunched in air, on a surface, embedded or enclosed	1,00	0,80	0,70	0,65	0,60	0,57	0,54	0,52	0,50	0,45	0,41	0,38	B.52.2 to B.52.13 Methods A to F
2	Single layer on wall, floor or unperforated cable tray systems	1,00	0,85	0,79	0,75	0,73	0,72	0,72	0,71	0,70	No further reduction factor for more than nine circuits or multicore cables			B.52.2 to B.52.7 Method C
3	Single layer fixed directly under a wooden ceiling	0,95	0,81	0,72	0,68	0,66	0,64	0,63	0,62	0,61				
4	Single layer on a perforated horizontal or vertical cable tray systems	1,00	0,88	0,82	0,77	0,75	0,73	0,73	0,72	0,72				B.52.8 to B.52.13 Methods E and F
5	Single layer on cable ladder systems or cleats etc.,	1,00	0,87	0,82	0,80	0,80	0,79	0,79	0,78	0,78				

NOTE 1 These factors are applicable to uniform groups of cables, equally loaded.

NOTE 2 Where horizontal clearances between adjacent cables exceeds twice their overall diameter, no reduction factor need be applied.

NOTE 3 The same factors are applied to:
- groups of two or three single-core cables;
- multi-core cables.

NOTE 4 If a system consists of both two- and three-core cables, the total number of cables is taken as the number of circuits, and the corresponding factor is applied to the tables for two loaded conductors for the two-core cables, and to the tables for three loaded conductors for the three-core cables.

NOTE 5 If a group consists of *n* single-core cables it may either be considered as *n*/2 circuits of two loaded conductors or *n*/3 circuits of three loaded conductors.

NOTE 6 The values given have been averaged over the range of conductor sizes and types of installation included in Tables B.52.2 to B.52.13 the overall accuracy of tabulated values is within 5 %.

NOTE 7 For some installations and for other methods not provided for in the above table, it may be appropriate to use factors calculated for specific cases, see for example Tables B.52.20 and B.52.21.

Figure 4. Reduction factors for one circuit or one multi-core cable, or for a group of more than one circuit, or more than one multi-core cable from IEC 60364-5-52 2009, p. 55)

As stated previously, the standard design assumes 8 circuits but if conditions are known especially wirings inside one single cabinet could be dimensioned according to smaller number of circuits depending on the application. IEC 60364-5-52 states that if installation conditions variates along the route, the most adverse conditions should apply. This requirement can be ignored if the heat dissipation differs only where the wiring is routed through a wall smaller than 0,35 m (IEC60364-5-52 2009, p. 18). It could be concluded that if some point of the route a bunch of 8 circuits + x number of additional circuits goes in the same duct and if the length of the additional circuits in the bunch is less than 0,35m these circuits can be neglected. If the length is more than 0,35m in the same duct, correction factor should be calculated with 8 + x circuits.

5 Protection of the circuits

Protection of the circuit must be done against the currents which are over the current rating of any component in the circuit or over the current carrying capacity of the conductor. Overcurrent in the circuit can reduce the life expectancy of the conductor and the components. Overcurrent occurs every time when the current value exceeds the maximum load current, and it must be switched off. The magnitude of the overcurrent differs depending on is the cause overload or short-circuit situation.

5.1 Protection against overload

Overloads can occur short time during normal operation for example during motor start or transformer power up. Depending on the application, short term overloads can occur also application where the load is not constant for example in conveyor or similar. When selecting overload protection, the time period how long the overload is permitted should be taken into account. When overload remain over the selected time, it must be switched off.

Overcurrent protection device should be located in the point where the current-carrying capacity of the conductor is reduced (e.g., reduction in the cross-section area of the conductor) except when all the following requirements are met (IEC 60204-1 2016, p. 42):

1. the current carrying capacity of the conductors is at least equal to that of the load
2. the part of the conductor between the point reduction of current carrying capacity and the position of the overcurrent protective device is max. 3 m
3. the conductor is installed so that it reduces the possibility of a short-circuit e.g., protected by an enclosure or duct

The figure 5 from the machinery standard IEC 60204-1 represents the relation between the conductor and the protective device for overload protection. Safety of machinery standard IEC 60204-1 states as follows:

> "Correct protection of a cable requires that the operating characteristics of a protective device protecting the cable against overload satisfy the two following conditions:
>
> $$I_b \leq I_n \leq I_z \tag{1}$$
>
> $$I_2 \leq 1{,}45 \times I_z \tag{2}$$
>
> where:
>
> I_b = the current for which the circuit is designed,
>
> I_z = the effective current-carrying capacity of the cable in amperes,
>
> I_n = the nominal current of the protective device
>
> I_2 = the minimum current ensuring the effective operation of the protective device within a specified time" (IEC 60204-1 2016, p. 119)

The current I_2 can be found from the product standard or is provided by the manufacturer. For gG-fuses $I_2 = 1{,}45 \times I_n$ by IEC 60269-5 (2014, p. 23). For ABB S200 K-type miniature circuit breaker $I_2 = 1{,}2 \times I_n$ (ABB 2022b, p. 8)

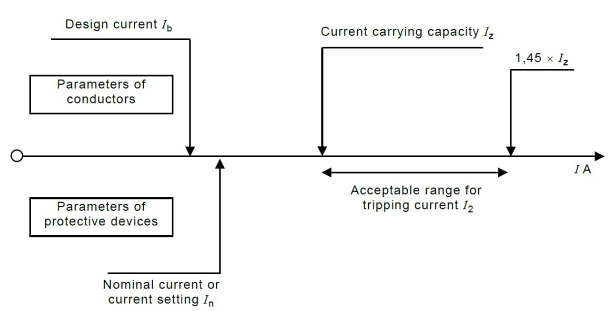

Figure 5. Protective device for overload protection (IEC 60204-1 2016, p. 119)

When overload protection is working effectively it allows certain overcurrents which are not damaging the conductor but cuts-off the overcurrent within a specified time. This avoids the unnecessary disturbances in the operation.

5.2 Protection against short circuit

Short-circuit currents are caused by fault of insulation between live conductor(s) and earth or between live conductors. These currents have greater magnitude compared to the overload currents and short-circuit current needs to cut-off rapidly.

All conductors are required to be protected against short-circuit currents by a short-circuit protection device which interrupts the short-circuit current flowing in all live conductors before the conductor maximum allowable temperature has reached. According to the IEC 60204-1, in practice the overcurrent protection requirements are fulfilled when the protective device at a current *I* cause the interruption of the circuit within a time which in any circumstances does not exceeds the time *t* where $t < 5$ s (IEC 60204-1 2016, p. 120).

Safety of machinery standard IEC 60204-1 (2016, p. 120) states as follows:

> "The value of the time *t* in seconds can be calculated using the following formula:
>
> $$t = (k \times \frac{S}{I})^2 \quad (3)$$
>
> where:
>
> S = the cross-sectional area in square millimetres
>
> I = the effective short-circuit current in amperes expressed for AC as the r.m.s value
>
> k = the factor shown for copper conductors when insulated with the following material: PVC = 115, Rubber = 141, SiR = 132, XLPE = 143, EPR = 143 "

During short time short-circuit faults, all the produced heat is assumed to stay in the conductor which will cause the conductor temperature to rise. The conductor heating process is assumed to be adiabatic which simplifies the calculation and gives a little clearance to the results because in practice some of the heat will transfer from the conductor into the insulation and therefore the occurred conductor temperature is not actually that high (Schneider Electric 2018, sec. 5.2). If protective device is providing only short-circuit protection to the conductors, the protective device should have operating I^2t values lower than which the conductor can withstand. For short-circuit fault ≤ 5 s the I^2t withstand of the conductor can be calculated using the equation 4 (IEC 60269-5 2014, p. 26).

$$I^2t = k^2 \times S^2 \tag{4}$$

where:

S = the cross-sectional area in square millimetres

k = the factor shown for copper conductor when insulated with the following material:
PVC = 115, PVC 90°C = 100, XLPE = 143, EPR =143

5.3 Motor circuit protection

Motor circuits differs from resistive loads with its inrush currents which needs to be considered when selecting appropriate protection device. The figure 6 illustrates the start-up of a direct-on-line IE3/IE4 motor. The motor starting time is dependent on load torque, inertia and motor torque. After starting, the first 10-15 ms motor draws an inrush current peak which can be significantly higher than the motor rated current. After the inrush current there is a locked rotor current which remains constant as long as the rotor starts revolving. This takes typically 0.5 to 10 seconds and is a motor load and design depended. After 0.5 – 10 s the rotor reaches its full speed and current stabilizes to the motor's rated current (ABB 2021, p. 34).

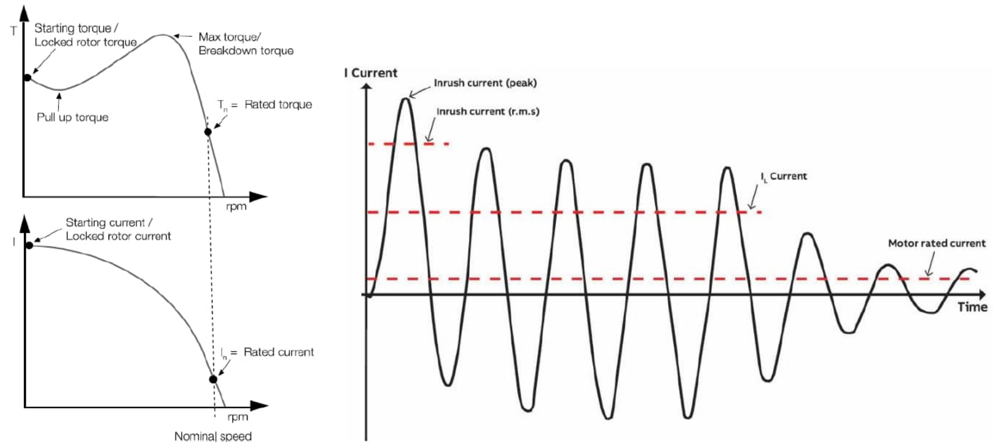

Figure 6. Higher efficiency motor start-up currents (ABB 2021, p. 30)

Common protection solution for motor circuits is combination with manual motor starter as an overload protection and fuse for short-circuit protection for the conductor. Generally, both gG- and aM-fuses can be used but fuse current rating should be selected to withstand the starting current of the motor. Starting current could be from 6x to over 13x (with IE3/IE4 motors) rated current of the motor and start-up could take up to 10 seconds depending on the load and network before the current stabilizes to the rated current level.

The amplitude of the inrush current is depended on several factors (ABB 2021, p. 37):

- The structure of the motor
- Network conditions, voltage stability
- Length and routing of the motor cables
- The switch-on phase position in the respective phase

aM-fuse is designed to withstand high motor starting currents without the need for increasing its current rating, but gG-fuse rating may need to be considerably higher than the rated current of the motor. Time-current characteristics from fuse the manufacturer should be investigated prior to select appropriate fuse for the operation.

5.4 Selectivity

Selectivity is an important part which needs to be considered during protective device design. Selectivity aims to minimize the effects of a failure. The selectivity is achieved if a failure occurs in the circuit and fault is cleared by the nearest upstream protective device while the rest remain in service. Arrow in figure 7 indicates the fault and in selective protection, only the fuse number 4 should be interrupted. Selectivity between different protective devices can be investigated by looking the time -current characteristics and I^2t values (IEC 60269-5 2014, p. 26).

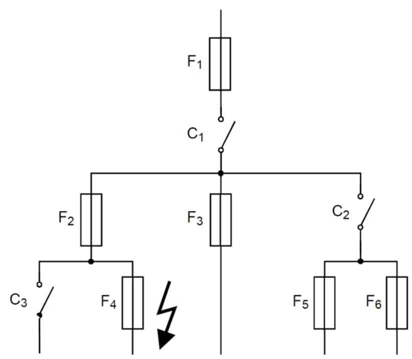

Figure 7. Selectivity between protection devices (modified from IEC 60269-5 2014, p. 27)

Selectivity between fuses is verified from time-current characteristics for operating times 0,1 s or higher. The maximum operating time for fuse 4 should be less than minimum pre-arching of fuse 2. For operating times below 0,1 s, selectivity is verified from pre-arcing and operating I^2t values. The maximum operating I^2t value for fuse 4 should be less than the minimum pre-arcing I^2t of fuse 2 to achieve the total selectivity.

Fuses with rated current ≥16 A of same utilization category manufactured according to IEC 60269-2 meet the total selectivity requirements by default if the rated current ratio of the fuses is 1,6:1 or higher (IEC 60269-5 2014, p. 27).

6 Devices and components

This section gives a brief look to the components and wires inside the cabinets. Air circuit breakers and transformers are not included in this thesis. Special circuits e.g. DC-bus charging circuits are also excluded.

6.1 Internal wiring

IEC 60204-1 defines general requirements for conductors and cables used in cabinet-built drives. Standard states that the conductors should be suitable for the operating conditions and meet the requirements i.a. for voltage and current withstand, conductor material and conductor flexibility (IEC 60204-1 2016, p. 76).

In this thesis, internal wires should be based on IEC standards and meet the requirements from UL and CSA standards where necessary. Default insulation material is PVC but for halogen free applications cross-linked compound (XLPO) insulation must be selected.

Additionally, internal wiring in this thesis must fulfil the following criteria:

- conductor temperature withstand minimum 90 °C (UL 105 °C)
- voltage rating for IEC: 300/500 V for wires ≤ 1,0 mm^2, 450/750 V for wires ≥ 1,5 mm^2
- voltage rating for UL: 600 V
- conductor material tinned copper
- flexible class 5 according to IEC 60228 section 6.1
- maximum resistance of a conductor according to IEC 60228 section 6.2

6.1.1 Wiring types

To simplify the design work, two eligible wire types are used in this thesis as a standard wire. PVC insulated H05/H07V2-K and if halogen free wiring is requested H05/H07Z-K. These two wire types meet the criteria mentioned in chapter 6.1. In case higher voltage ratings are needed NSGAFÖU / NSHXAFÖ single-core cables can be used when applicable.

H05V2-K / H07V2-K

H05V2-K/H07V2-K is special PVC insulated wire for internal wiring. Increased heat-resistance to 90 °C. IEC, UL & CSA approved.

Nominal voltage:

- H05V2-K (300/500 V) (600 V UL)
- H07V2-K (450/750 V) (600 V UL)

Max. wire temperature:

- increased to 90 °C (105 °C UL)
  (Amokabel 2019a)

H05Z-K & H07Z-K

H05Z-K & H07Z-K is halogen free, flame retardant, cross-linked polyolefin insulated wire for internal wiring. IEC & UL approved. CSA approvals with special permission.

Nominal voltage:

- H05Z-K (300/500V) (600V UL)
- H07Z-K (450/750V) (600V UL)

Max. wire temperature:

- 90 °C (105 °C UL)
  (Amokabel 2019b)

NSGAFÖU

NSGAFÖU is double insulated single-core rubber cable used mostly as a tap wire in direct busbar connections when superior protection against short circuit is required. Following info from Prysmian datasheet: Conductor insulation EPR rubber and outer sheath CPE rubber. IEC approved, no UL/CSA approvals. Nominal voltage: 1,8/3 kV. Max. wire temperature: 90 °C (Prysmian Group 2019).

NSHXAFÖ

NSHXAFÖ is halogen free, double insulated single-core rubber cable used in direct busbar connections when great protection against short circuit and HF is required. Following info from Lapp Group datasheet: Conductor insulation EPR rubber and outer sheath halogen-free polymer compound. IEC approved, no UL/CSA approvals. Nominal voltage: 1,8/3 kV. Max. wire temperature: 90 °C (Lapp Group 2022)

6.1.2 Wiring selection principles

Wire dimensioning should be based on the prospective load current in the circuit. The current carrying capacity of the selected wire must be greater than the trip current of the protective device, fuse or MCB.

According to IEC 60204 -1 in power transfer circuits the minimum cross-sectional area of the copper conductor should be at least 0,75 mm^2. Signalling and control circuits can be wired with 0,2 mm^2. This requirement does not include integral wirings of assemblies which are manufactured and tested with their relevant IEC standard. (IEC60204-1 2016, p. 77).

When selecting the sufficient wire, it should be done according to the ambient temperature of the conductor to be 60 °C. Also, other derating factors for current carrying capacity needs to be consider. In this thesis the lifetime of the insulation is assumed to be decades and therefore the maximum loading for wiring should be only 70-75% of the maximum allowed (derated) loading.

Standard design requires 90 °C conductor temperature withstand. Tables 1-3 represents the current carrying capacities for V2-type PVC conductor, halogen free (XLPO) conductor and EPR insulated conductor in open air, ambient temperature 30 °C and 60 °C. It should be noticed that standards IEC 60364-5-52 and IEC 60204-1 does not recognize V2-type PVC with increased heat-resistance to 90 °C and they do not provide values for ambient temperature correction for such insulation. Standards recognizes only V-type PVC which is rated for max. 70 °C conductor temperature in IEC 60204-1. For V-type PVC the ambient air temperature correction factor from 30 °C to 60 °C would be 0,50 but use such value in conductor sizing would lead to unnecessary oversizing. Since standard does not recognize V2 type PVC the temperature correction factor used in calculations of this thesis, is 0,71 which is intended for XLPE & EPR insulation.

Table 1. Current carrying capacity of H07V2-K conductor

Current carrying capacity [A] PVC type V2 conductor			(V2=PVC 90 °C)
Air temp.	30 °C	**60 °C**	Group of 8 circuits in 60 °C
Conversion factor	1	0,71*	0,52**
AWG 16 1015 / H07V2-K **1,5 mm²**	24	**17,04**	8,86
AWG 14 1015 / H07V2-K **2,5 mm²**	32	**22,72**	11,81
AWG 12 1015 / H07V2-K **4 mm²**	42	**29,82**	15,51
AWG 10 1015 / H07V2-K **6 mm²**	54	**38,34**	19,94
AWG 8 1015 / H07V2-K **10 mm²**	73	**51,83**	26,95
AWG 6 1015 / H07V2-K **16 mm²**	98	**69,58**	36,18
AWG 4 1015 / H07V2-K **25 mm²**	129	**91,59**	47,63
AWG 2 1015 / H07V2-K **35 mm²**	158	**112,18**	58,33
AWG 1 1015 / S07V2-K **50 mm²**	198	**140,58**	73,10
AWG 2/0 1015 / S07V2-K **70 mm²**	245	**173,95**	90,45
AWG 3/0 1015 / S07V2-K **95 mm²**	292	**207,32**	107,81
AWG 4/0 1015 / S07V2-K **120 mm²**	344	**244,24**	127,00
Open air, ambient temp. 30 °C values from Amokabel datasheet (2019a)			
* Conversion factor from IEC 60364-5-52 Table B.52.14 XLPE & EPR insulation column			
** Conversion factor from IEC 60364-5-52 Table B.52.17			

Table 2. Current carrying capacity of H07Z-K conductor

Current carrying capacity [A] H07Z-K			
Air temp.	30 °C	**60 °C**	Group of 8 circuits in 60 °C
Conversion factor	1	**0,71***	0,52**
AWG 16 3607 / H07Z-K **1,5 mm²**	24	**17,04**	8,86
AWG 14 3607 / H07VZ-K **2,5 mm²**	32	**22,72**	11,81
AWG 12 3607 / H07Z-K **4 mm²**	42	**29,82**	15,51
AWG 10 3607 / H07Z-K **6 mm²**	54	**38,34**	19,94
AWG 8 3607 / H07Z-K **10 mm²**	73	**51,83**	26,95
AWG 6 3607 / H07Z-K **16 mm²**	98	**69,58**	36,18
AWG 4 3607 / H07Z-K **25 mm²**	129	**91,59**	47,63
AWG 2 3607 / H07Z-K **35 mm²**	158	**112,18**	58,33
AWG 1 3607 / H07Z-K **50 mm²**	198	**140,58**	73,10
AWG 2/0 3607 / H07Z-K **70 mm²**	245	**173,95**	90,45
Open air, ambient temp. 30°C values from Amokabel datasheet (2019b)			
* Conversion factor from IEC 60364-5-52 Table B.52.4 XLPE & EPR insulation column			
** Conversion factor from IEC 60364-5-52 Table B.52.17			

Table 3. Current carrying capacity of NSGAFÖU-cable

Current carrying capacity [A] NSGAFÖU EPR-insulated cable			
Air temp.	30 °C	**60 °C**	Group of 8 circuits in 60 °C
Conversion factor	1	**0,71***	0,52**
NSGAFÖU **1,5 mm²**	30	**21,3**	11,08
NSGAFÖU **2,5 mm2**	41	**29,11**	15,14
NSGAFÖU **4 mm2**	55	**39,05**	20,31
NSGAFÖU **6 mm2**	70	**49,7**	25,84
NSGAFÖU **10 mm2**	98	**69,58**	36,18
NSGAFÖU **16 mm2**	132	**93,72**	48,73
NSGAFÖU **25 mm2**	176	**124,96**	64,98
NSGAFÖU **35 mm2**	218	**154,78**	80,49
NSGAFÖU **50 mm2**	276	**195,96**	101,90
NSGAFÖU **70 mm2**	347	**246,37**	128,11
NSGAFÖU **90 mm2**	416	**295,36**	153,59
NSGAFÖU **120 mm2**	488	**346,48**	180,17
NSGAFÖU **150 mm2**	566	**401,86**	208,97
NSGAFÖU **240 mm2**	775	**550,25**	286,13
NSGAFÖU **300 mm2**	898	**637,58**	331,54
NSGAFÖU **400 mm2**	1050	**745,5**	387,66
Open air, ambient temp. 30 °C values from Prysmian Group datasheet (2019)			
* Conversion factor from IEC 60364-5-52 Table B.52.4 XLPE & EPR insulation column			
** Conversion factor from IEC 60364-5-52 Table B.52.17			

6.2 Protection devices

Different types on protection devices can be used to protect the circuit in different fault occasions. The most common protection devices are fuses, miniature circuit breakers and motor protection circuit breakers.

6.2.1 Fuses

Fuses are used as an overcurrent protection in overload and short-circuit occasions. Several types of fuses are used in different purposes and when selecting the appropriate fuse, the protected circuit and device defines the correct fuse type.

Fuse operation is quite easy and simple. Fuse construction includes the fuse element, surrounding material, fuse body and end connectors. Fuse element is made from high conductive material and when current flows through the element, it produces heat. At rated current the fuse construction is designed to dissipate the generated heat and the heat inside the fuse and in fuse element will not increase over the limit. During overload situation, the current flowing through the fuse element is greater than the rated current of the fuse and therefore the generated heat is also greater than that dissipated which will result the fuse element temperature to rise. When the temperature of the fuse element reaches its melting point the fuse element melts and the circuit is opened. The time from the initiation of the short-circuit to the element melting is the pre-arcing time (Eaton 2016, p. 4).

The arcing time is the time from initiation of the arc to the time when the arc is completely extinguished. When the element material starts to melt it forms a high resistance arc in the fuse element. The high resistance arc vaporizes the element material and combined to the surrounding material it forms a non-conductive substance. In addition to that the melting fuse element will increase the arc length and resistance even more. The outcome is that the arc is extinguished in very short time and the circuit is completely isolated. During a short-circuit, the fuse element will start melting well before the prospective fault current has reached its peak value as seen from figure 8. The total clearance time is the sum of the pre-arcing and arcing time (Eaton 2016, p. 4).

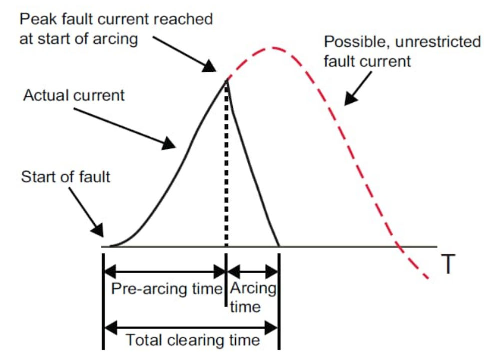

Figure 8. Fuse reduces magnitude and duration of a fault current (Eaton 2016, p. 4)

gG-fuse

gG-fuses have a full-range breaking capacity for general applications. gG-fuses are ideal for general use where the fuse can protect the load and the conductor. It can withstand small short-term overcurrent without melting but higher magnitude currents will melt the fuse rapidly as you can see from the figures 9 and 10. The figure 11 presents the I^2t characteristics of selected 690 V ABB gG-fuse.

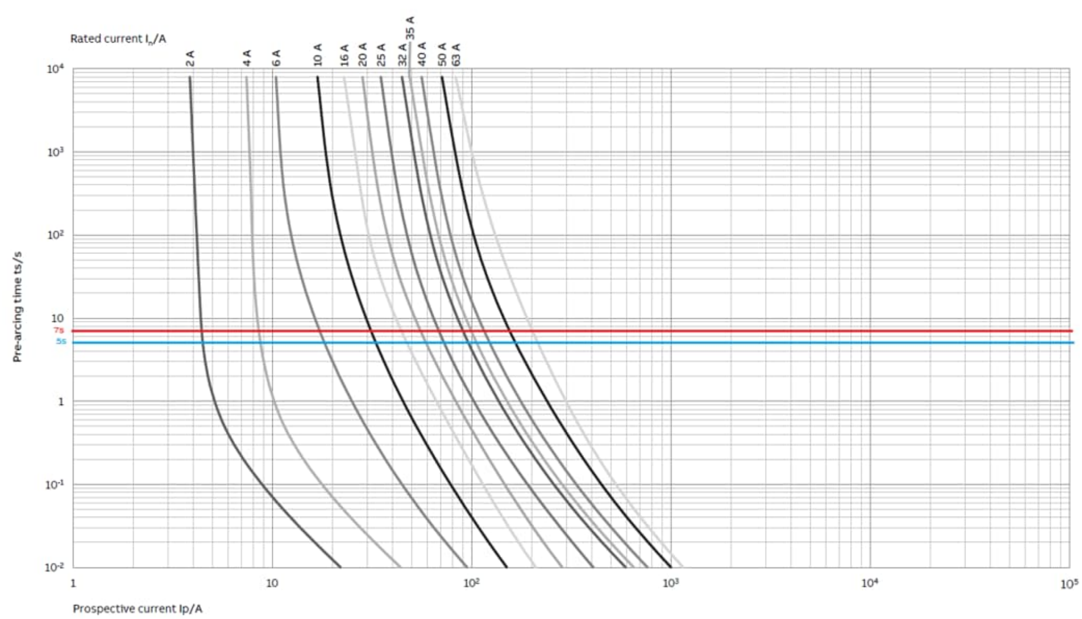

Figure 9. Time-current characteristics of 690 V ABB OFAA000GG fuse (modified from ABB 2019b, p. 18)

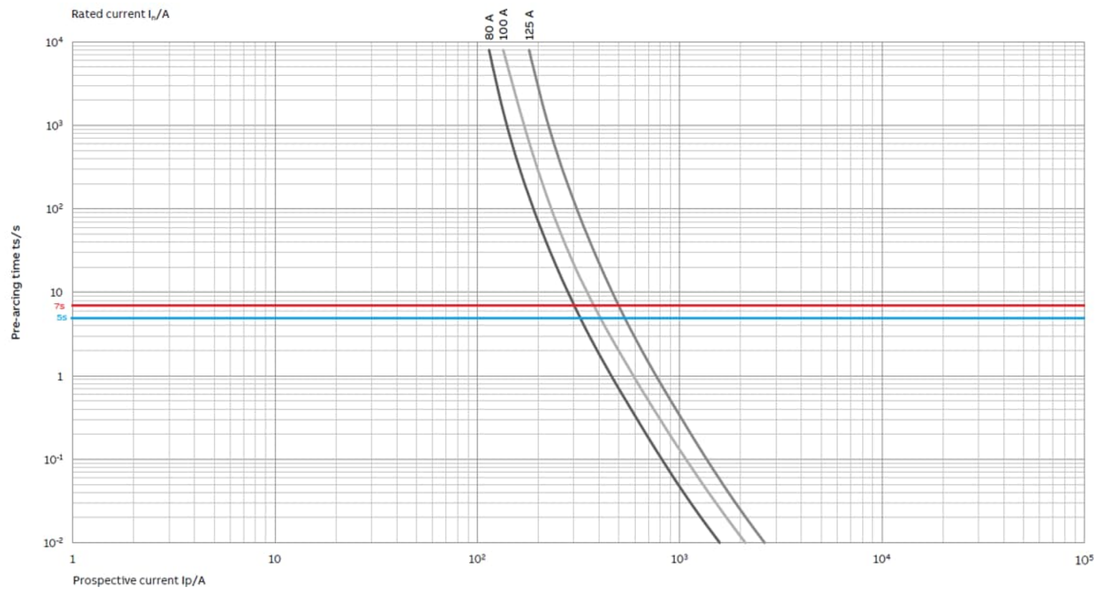

Figure 10. Time-current characteristics of 690 V ABB OFAA00GG fuse (modified from ABB 2019b, p. 18)

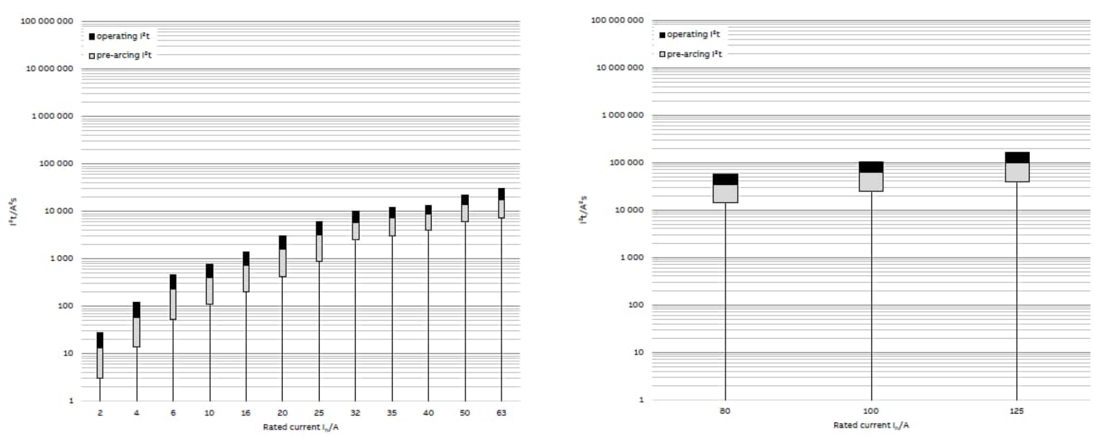

Figure 11. Pre-arcing and operating I^2t characteristics of 690 V ABB OFAA_GG-fuse. (ABB 2019b, p. 46)

aM-fuse

aM-fuses have a partial-range breaking capacity and are generally used for short-circuit protection. By examining the figures 12 and 13 could be noticed that aM-fuse has a better withstand for short-term overcurrent peaks which is why it is ideal for motor circuit protection. aM-fuse is not designed for overload protection and hence they are used in conjunction with suitable overload protection device which can interrupt the small overcurrent. For example, 2 A aM-fuse can withstand over 10 A current without melting and such current can damage the load device. In figure 14, the I^2t characteristics of 690 V ABB aM-fuse.

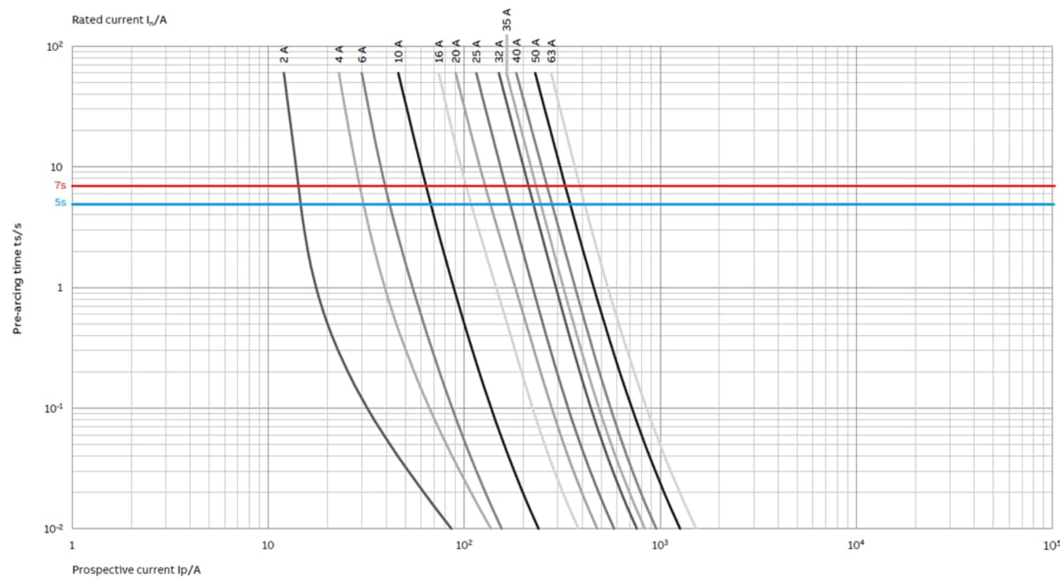

Figure 12. Example of time-current characteristics of 690 V ABB OFAA000AM fuse (modified from ABB 2019b, p. 26)

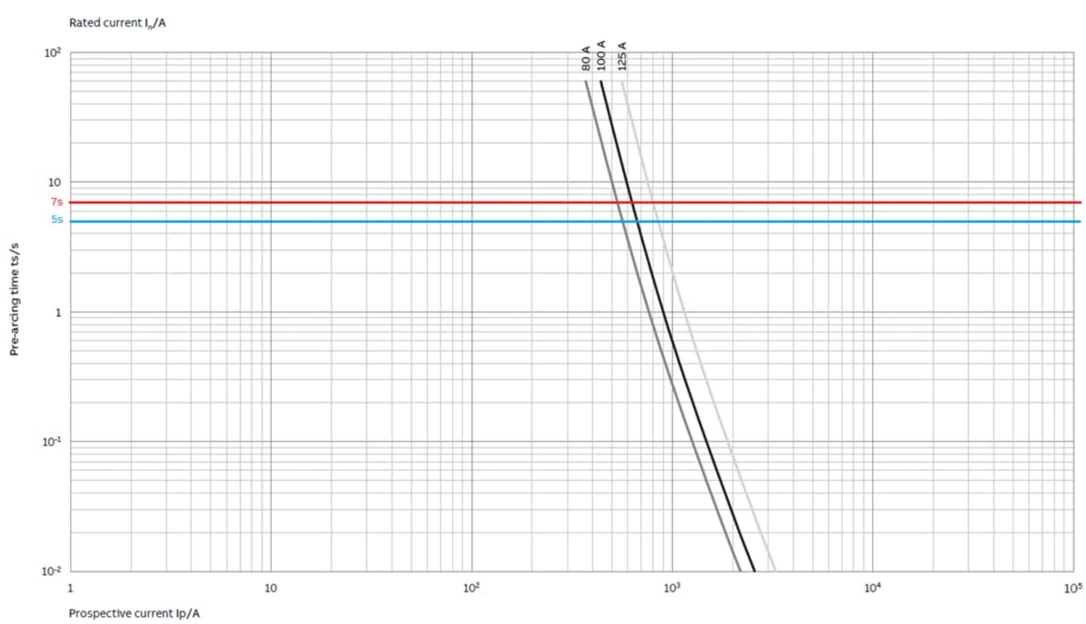

Figure 13. The time-current characteristics of 690 V ABB OFAA00AM fuse (modified from ABB 2019b, p. 26)

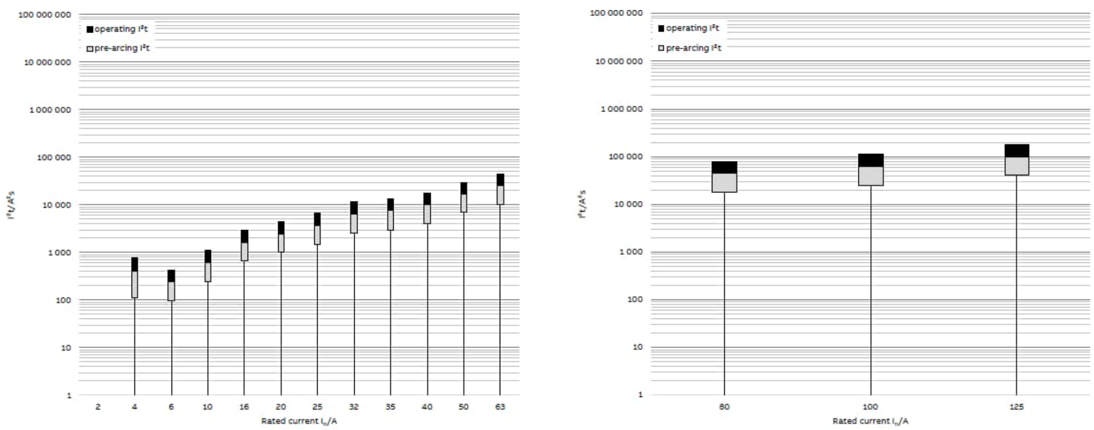

Figure 14. Pre-arcing and operating I^2t characteristics of 690 V ABB OFAA_AM-fuse (ABB 2019b, p. 50)

6.2.2 Miniature Circuit Breaker

Miniature circuit breakers (MCB) are used as protective device for overloads and short-circuits. MCB disconnects the circuit by two different releases. Protection against short-circuit is performed by electro-magnetic release which is only dependent on current. Protection against overloads is achieved with thermal bi-metal release which trips by temperature rise. Depending on the component to be protected, various tripping characteristics are available. In ACS880 usually used MCB is with K tripping curve, it provides fast disconnection in the short-circuits but also allows current peaks in the circuit. Voltage in the circuits may be supplied from the converter AC busbars or from the customer supply and therefore there is no guaranteed good voltage quality and high inrush currents, and voltage peaks may occur in the circuit. In figure 15 Z-type and K-type tripping curves of the S200 MCB are presented. For example, S201-K allows 10 x I_n current peaks without tripping but at 14 x I_n current it will trip less than 0,1 seconds.

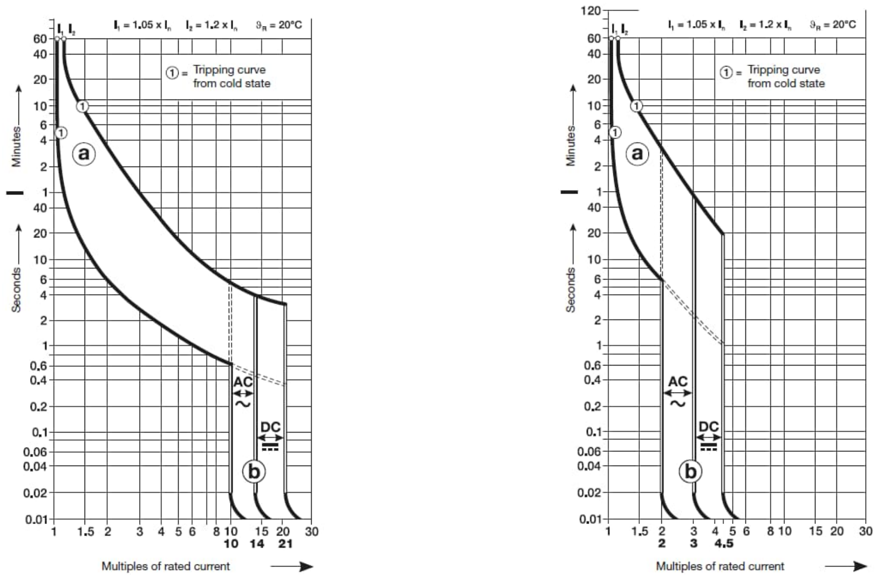

Figure 15. Tripping characteristics of ABB S200 MCB. Left-side is K-type and right-side Z-type MCB (ABB 2022b, p. 8)

Dimensioning of miniature circuit breaker

Nominal current values of MCB are presented in 30 °C temperature. When determining the sufficient value for MCB the temperature deration factor needs to be considered. In table 4 temperature derating values for ABB S200-series K and Z-type MCB are presented. The maximum load current of the miniature circuit breaker inside the cabinet must be determined assuming the ambient temperature to be 60 °C.

Table 4. ABB S200- K and Z-type MCB temperature derating values (ABB 2022b, p. 161)

ABB S200 miniature circuit breaker temperature derating values, characteristics K,Z														
Ambient temp. °C	**MCB size [A]**													
20	**2**	**3**	**4**	**6**	**8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**	**50**	**63**
30	1,9	2,9	3,9	5,8	7,7	9,6	12,5	15,4	19,3	24,1	30,8	38,5	48,2	60,7
40	1,9	2,8	3,7	5,6	7,4	9,3	12,1	14,8	18,5	23,2	29,7	37,1	46,4	58,4
50	1,8	2,7	3,6	5,4	7,1	8,9	11,6	14,3	17,9	22,3	28,6	35,7	44,7	56,3
60	1,7	2,6	3,4	5,2	6,9	8,6	11,2	13,8	17,2	21,5	27,5	34,4	43	54,2

It is important to notice the possibility that the conductor and the protective MCB can be in a different ambient temperature and therefore the MCB dimensioning must be done in the way that conductor will be protected even when the MCB's actual ambient temperature is lower.

Example: Conductor with 17 A current-carrying capacity, the S200-K 16 A MCB is selected for conductor protection. The max. continuous load current for 16 A MCB in 60 °C is 13,8 A.

6.2.3 Motor Protection Circuit Breaker

Motor protection circuit breakers (also known as a manual motor starters) are used as a protection for the load and the installation. The most used MPCB in ACS880 is ABB MS-series (MS116, MS132). They have a thermal tripping for overload- and electromagnetic tripping for short-circuit protection. Thermal tripping current for overload can be set directly in amperes, the setting current (see table 5) is the rated current of the motor. Electromagnetic trip for short-circuit is non-adjustable fixed multiple of the motor protection circuit breaker rated operational current. ABB motor circuit protection breakers are temperature compensated from -25 °C up to +60 °C. Tripping characteristics of ABB MS-series motor starter shown in figure 16. (ABB 2021, pp 14-15, 18).

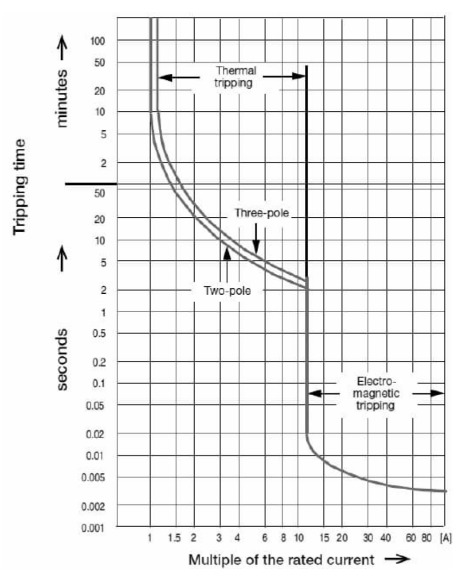

Figure 16. Tripping characteristics of ABB MS-series manual motor starters (ABB 2021, p. 14)

Table 5. Selection of ABB MS132 manual motor starters (ABB 2020a, p. 2/11)

Type	Rated operational power (400 V) AC-3, AC-3e [kW]	Setting range [A]	
		Min	Max
MS132-0.16	0,03	0,1	0,16
MS132-0.25	0,06	0,16	0,25
MS132-0.4	0,09	0,25	0,4
MS132-0.63	0,18	0,4	0,63
MS132-1	0,25	0,63	1
MS132-1.6	0,55	1	1,6
MS132-2.5	0,75	1,6	2,5
MS132-4.0	1,5	2,5	4
MS132-6.3	2,2	4	6,3
MS132-10	4,0	6,3	10
MS132-12	5,5	8	12
MS132-16	7,5	10	16
MS132-20	7,5	16	20
MS132-25	11,0	20	25
MS132-32	15,0	25	32

6.3 Contactors

Contactors should be selected based on the rated operational current of the load I_e and the rated operational voltage U_e. ABB AF-series 3-pole contactors are available up to 1060 A AC-3 or 2850 A AC-1 applications with wide range of AC/DC operational voltage coils.

Contactor dimensioning should also take into account the load type, load current characteristics, duty class and what kind of switching frequency is intended for the device. It should be noticed that contactor rated making and breaking capacity can variate with operational voltage.

Making and breaking are the most stressing operations. In motor applications, the contact making operation is the most wearing due the starting current of the motor which can be remarkably higher than the rated current. During breaking operation, the current is steady and equals to a motor rated current which makes the breaking operation easier. With non-inductive loads making operation is relatively easy because the initial current equals to the rated load current (ABB 2014, pp. 7-8).

6.3.1 Utilization category

When selecting the appropriate contactor device, the correct utilization category is important as it specifies the operation conditions and different electrical load types. The load characteristics determines the requirements for the contactor during switching on and off. The most common utilization categories are AC-3 for motor applications and AC-1 for general non-inductive loads. Utilization categories for contactors are defined in IEC 60947-4-1 standard and can be found in appendix 1.

6.3.2 Electrical durability

Electrical durability is the value of how many operating cycles contactor can withstand during its lifetime. The approximation of required operating cycles should be defined prior to contactor selection. Electrical durability is expressed in millions of operating cycles. The breaking current I_c is the current which needs to be broken by the contactor and I_e is the rated operational current of the load. For utilization categories AC-1 and AC-3 $I_c = I_e$ (ABB 2020b, p. 55). Electrical durability for AF09 – AF2050 contactors in AC1- utilization category is presented in figure 17. Electrical durability for AF09 – AF1650 contactors in utilization category AC-3 in figures 18 and 19.

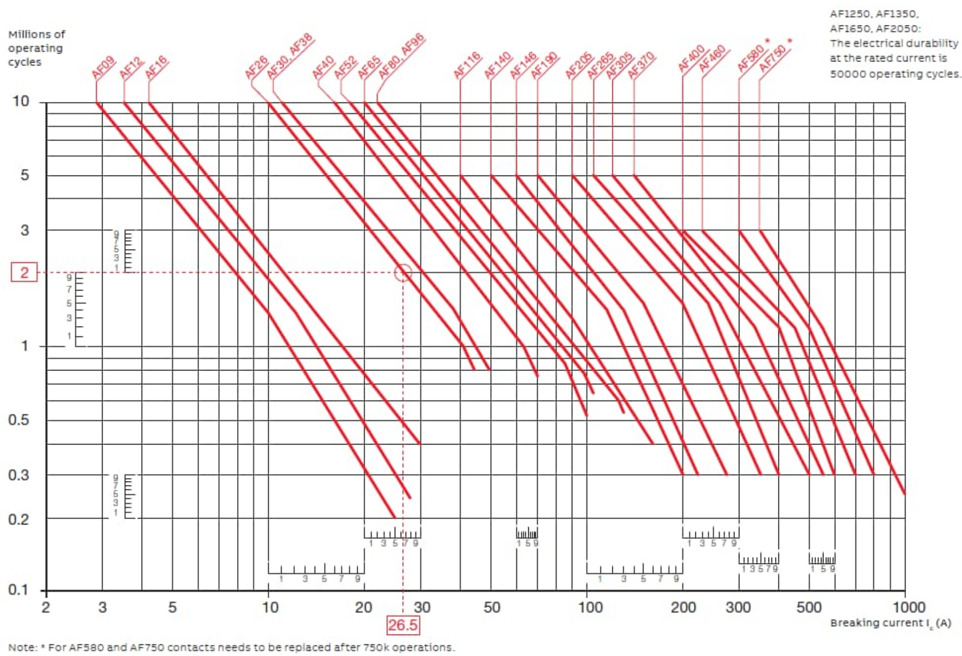

Figure 17. Electrical durability for AC-1 utilization category $U_e \leq 690$ V for ABB AF09-AF2050 contactors (ABB 2020b, p. 55)

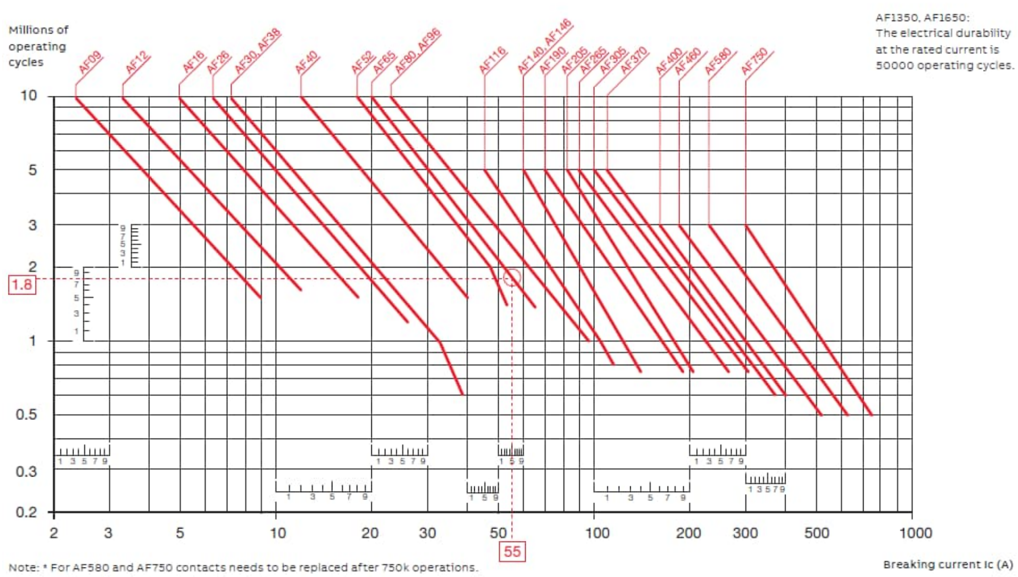

Figure 18. Electrical durability for AC-3 utilization category $U_e \leq 440$ V for ABB AF09-AF1650 contactors (ABB 2020b, p. 56)

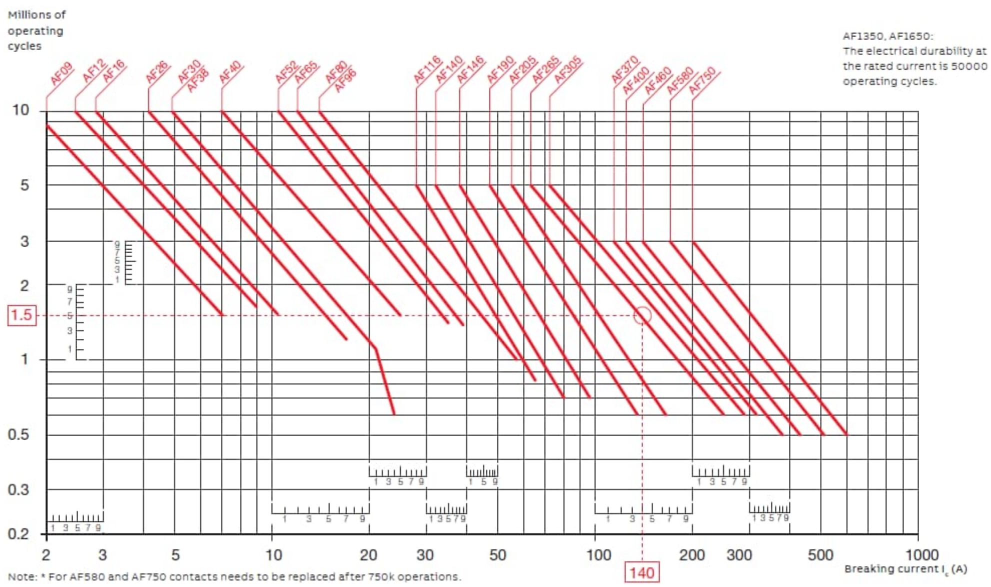

Figure 19. Electrical durability for AC-3 utilization category $U_e \leq 690$ V for ABB AF09-AF1650 contactors (ABB 2020b, p. 56)

For example from the figure 19, if the motor full load current I_e=I_c is 140 A and required electrical durability is 1,5 million operating cycles, the correct contactor for the purpose is AF265. If higher electrical durability is needed (more operating cycles) the bigger contactor should be selected.

7 Circuit Design Tool

One part of this thesis was to design and create a circuit design tool based on the standards and parameters introduced in earlier sections. There was no platform nor other specific technical requirements for the tool and I had an opportunity to start design the tool from my own way and perspective. At start point the easy usability and updateability were the most important requirements.

7.1 Designing the tool

At the beginning of the project, the first thing to decide was the platform for the tool. Microsoft Excel was the first option for the project platform since we have already a several MS Excel -based tools which are daily used by OBE. Along with the straightforward programming, MS Excel based tool is simple to keep updated and it offers a possibility to expand the features quite easily. After a short study of the other alternatives, MS Excel was easy to choose and there were no other realistic options. MS Excel is not too complex but yet a professional platform for this project.

Other relevant question during the early phase of the project was the functionality of the dimensioning tool. Two options were in my mind, the first was to create a table where the selected variables are presented, and user can easily check from the column what components should be used in different situations. This would be a simple and straightforward when user only must know the load current and the table would tell the rest. Downside of this solution would be to keep all the tables updated and expansions for this kind of solution would be troublesome.

The second option was to create a calculator -tool where user sets a known parameters and the tool calculates and suggest the components which are needed for that situation. This kind of a solution would offer more effortless updating, easier modification and expansions to the tool. One major benefit for the second option was the user experience because as I said there are several other MS Excel -based tools in daily use and designers are used to work using MS Excel calculators.

After a short consideration the option number two was selected for the project. This is the mostly due to a updating and expansion benefits which were considerably better than in the first option.

7.2 Implementation

After the platform and functionality decisions, it was time to consider the user interface. The base idea was to create interface where the user does not have to fill too many empty boxes but just select the correct variables. Ideally the best and the most practical solution would be if the user just sets the load current value for the circuit and selects the appropriate parameters from the drop-down menu.

The figure 20 presents the layout of the Input/Output -datasheet where the calculator itself can be found. By centralizing the calculations to one single page it simplifies the user experience when user does not need to go through many sheets but all the things can be done in just on one page. Information and values used in calculator can be found in own sheets, there are datasheets for conductor sizing, protective device and contactor selection.

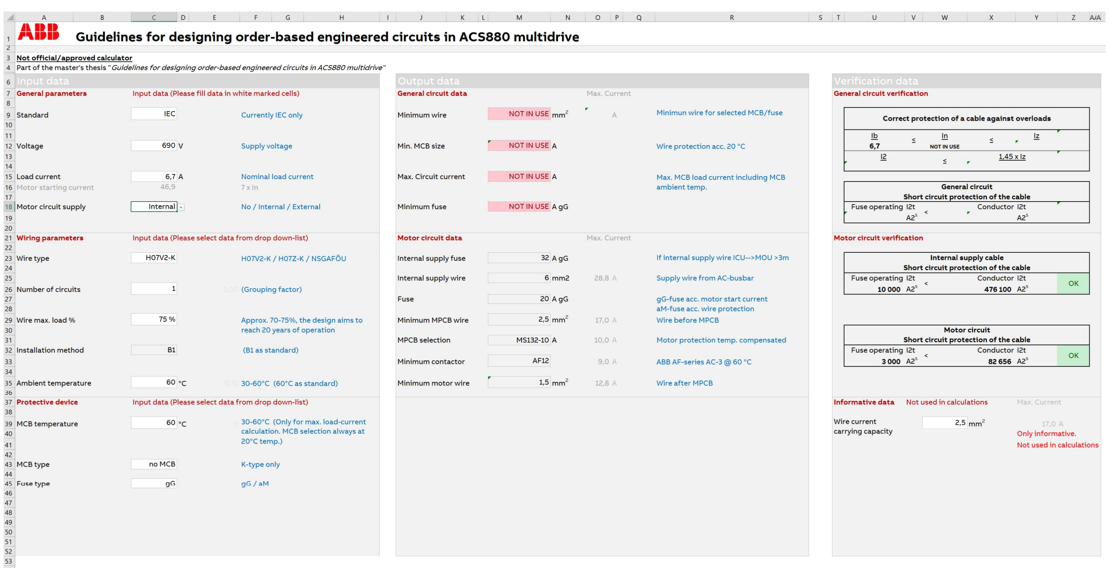

Figure 20. The input/output -sheet of the calculator tool

The calculator consists of three sections, input data, output data and verification data. Input data -section is divided in to three subsections: General parameters, Wiring parameters and Protective device parameters. Output data has two subsections: General circuit data and Motor circuit data. Verification data -section includes protection calculations for General - circuit and Motor circuit verification.

In input -section, general parameters have an overall impact to the result when wiring parameters are mostly for wire selection and protective device parameters are for fuse or MCB selection.

General parameters include:

- Standard
- Voltage
- Load current
- Motor circuit supply selection

Currently only IEC standard is implemented to the calculator, in future UL/CSA standard could be included. Voltage is the AC supply voltage in the circuit. At this point voltage is needed only when selecting the contactor since its current rating variates depending of the supply voltage. Voltage selection is mainly for the future use when e.g., short-circuit calculations could be included. Load current is the nominal load current in the circuit. In most of the OBE applications, load current value is specified by the customer. Motor circuit selection defines if there is a need for motor protection device and contactor. The tool is designed to be instructional to the user e.g., when motor circuit is selected, the general circuit output data section is not in use and the calculator shows the results in motor circuit data -section as can be seen in figure 21. In programming point of view, it is easier to separate these circuits from each other since general circuit does not need motor protection switch or contactor and it would confuse the user.

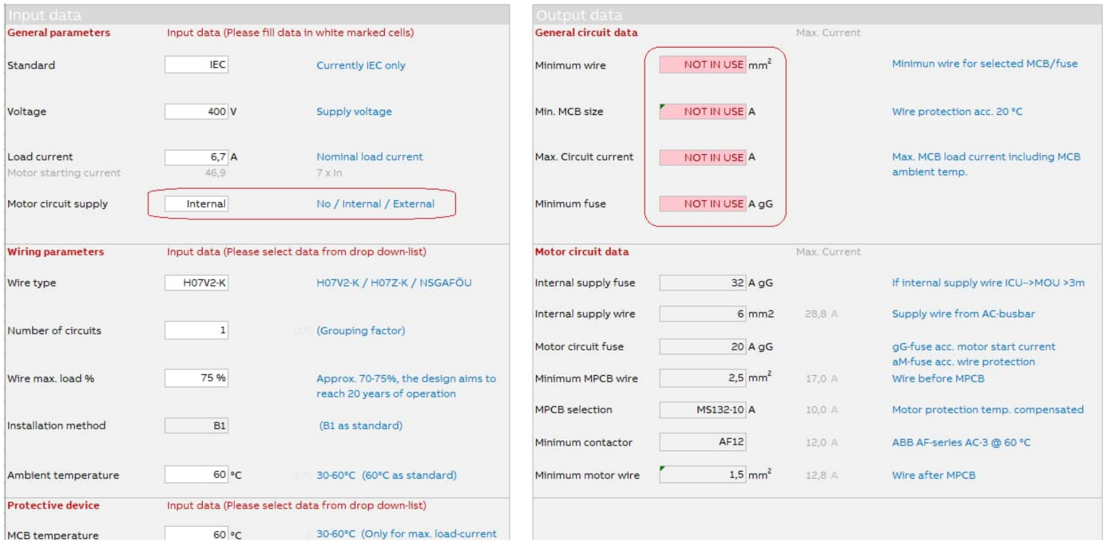

Figure 21. The user interface aims to be instructional

Wiring parameters include:

- Wire type
- Number of circuits
- Wire max. load %
- Installation method
- Ambient temperature

Wire types are the three basic wires introduced in section 6.1.1 of this paper. In the calculator, the wire type selection affects to the current carrying capacity of the conductor. Number of circuits and ambient temperature are the derating factors for wiring according to IEC 60204-1. Number of circuits is selectable from 1 to 8 circuits. Ambient temperature range is from 30 °C to 60 °C. Wire max. load percentage is selectable from 50% to 100%. Preferred load percentage should be approximately 70-75% to improve the lifetime of the insulation. Installation method is not used in calculations and it is for an information purpose only. Installation method can be used when using the wire current carrying capacities from the IEC standard but in this tool, the wire current carrying capacities are provided by manufacturer.

Protective device parameters include:

- MCB temperature
- MCB type
- Fuse type

MCB temperature is the ambient temperature of the miniature circuit breaker and it defines the derating factor for MCB maximum load. MCB-type is currently IEC version S200 K-type but for future UL approved 2-pole and 3-pole SU200M K-type could be also implemented. Fuse type can be selected between gG- or aM-fuse depending on the application. For a general circuit fuse, only gG-type is available but for motor circuits both gG- and aM-type can be selected.

Output data is divided into two subsections for general circuit data and motor circuit data.

General circuit data parameters include:

- Minimum wire
- Minimum MCB size
- Maximum circuit current
- Minimum fuse

Minimum wire is the smallest wire considering the derating factors defined in the input-menu which can carry the load current. Minimum MCB size is derived from the maximum circuit current which is the temperature dependent derated current of MCB. Minimum fuse is the smallest gG-type fuse that can carry the load current continuously without tripping.

Motor circuit data includes:

- Motor circuit fuse
- Minimum MPCB wire
- MPCB selection
- Minimum contactor
- Minimum motor wire

Motor circuit fuse is selectable between gG- or aM-type. In motor circuits, the fuse is dimensioned for short-circuit protection. Fuse is selected to withstand motor starting current without melting. In gG-type fuse this requirement leads to a considerably higher rated current of the fuse compared to the rated current of the motor. If aM-fuse is selected the time-current characteristics shows that the motors starting peak is already taken into account and the rated current of the fuse is much closer to the motor rated current. In both cases the fuse operating I^2t should be lower than the I^2t withstand of the conductor. Minimum MPCB wire is the wire between motor circuit fuse and motor protection circuit breaker. It includes the derating factors selected in input data section. MPCB – motor protection circuit breaker is the correct motor overload protection device for installation. Currently only ABB MS132 protection devices from 0,1 A to 32 A are available in the tool but other types could be introduced in later phase e.g. ABB MS165 which has setting range up to 80 A. Minimum contactor is selected as to utilization category AC-3 in contactor ambient temperature of 60 °C. Minimum motor wire is the wire between the contactor and customer connection terminals with derating factors.

In case of internal supply for the motor circuit is selected, the calculator suggests internal supply components:

- Internal supply fuse
- Internal supply wire

If the motor circuit is supplied from multidrive internal AC-busbar, usually the AC coupling is in incoming cabling cubicle (ICU). Internal supply wire is between AC-busbar and motor circuit fuse. Since the supply is from busbar and high short-circuit currents can occur, the smallest internal supply wire is 6 mm^2 and double insulated wire or insulation sleeve should be used. In cases where the internal supply wire is over 3 m e.g. from ICU cabinet to MOU cabinet, it needs a short-circuit protection fuse (internal supply fuse).

From the verification data section in figure 22, it is easy to ensure that the protection of the cables and devices operates as intended. Verification data has own section for general circuits and motor circuits. General circuit verification calculates the fuse or MCB operation against overloads and short-circuits when motor circuit verification verifies the correct operation against short-circuits. In motor circuit applications the MPCB device protects circuit from overload currents. Verification data has also an informative section where current carrying capacities of the wires can be examined. This is purely for informative purposes only and this is not used in calculations. The point for this feature is when user wants to examine different solutions for wiring and wants to know the load capacity of different wiring than the tool proposes.

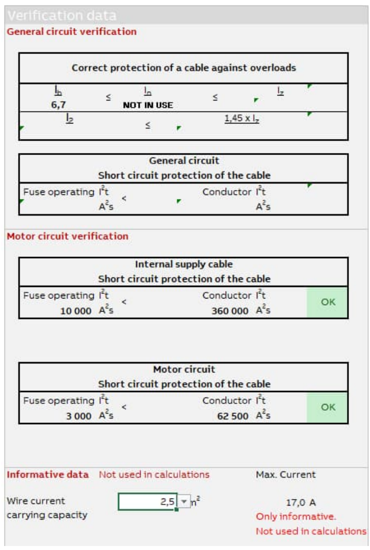

Figure 22. Verification data section

7.3 Usage and examples

This section gives a brief introduction to the usage of the design tool. There will be instructions how to operate the tool and three examples where this tool is used. The examples include both general circuits and motor circuits. The figure 23 shows the block diagram where the functionality of the design tool is presented.

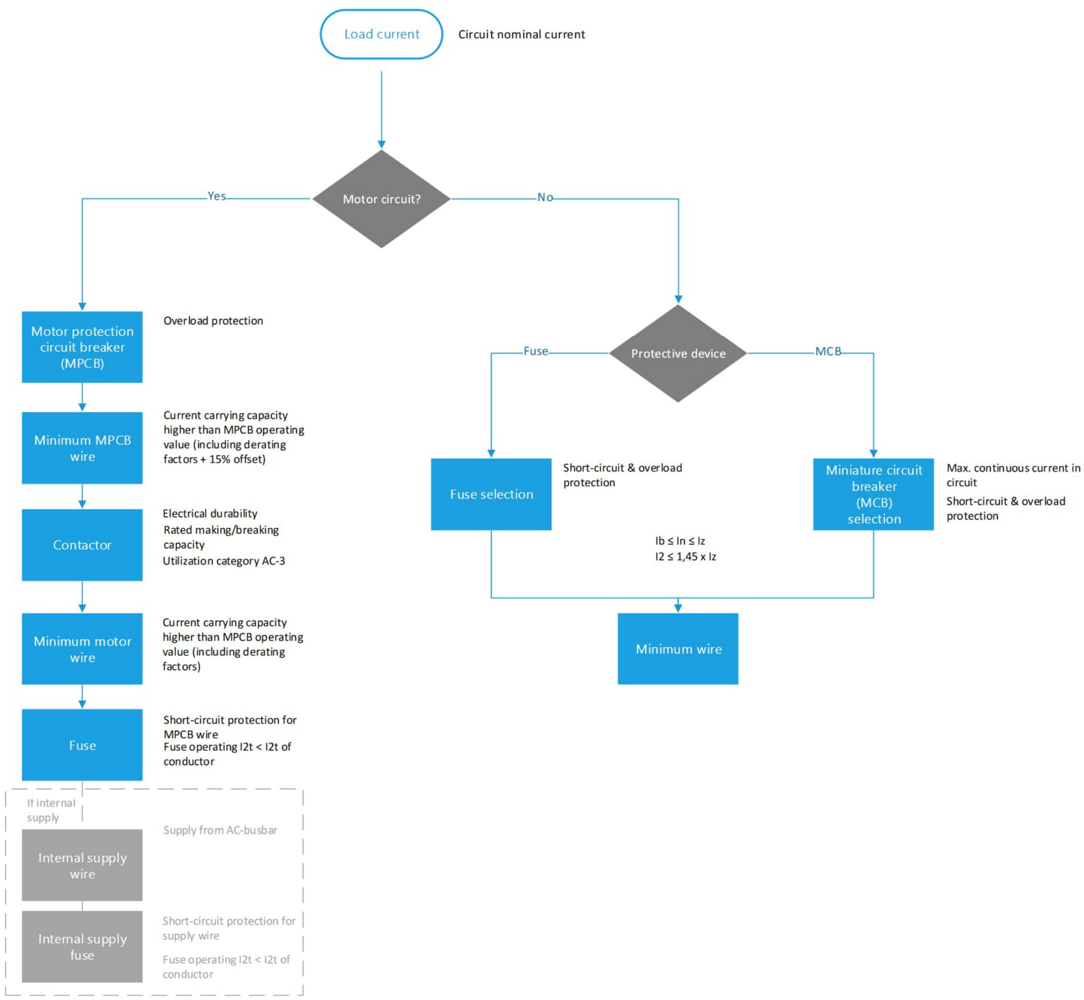

Figure 23. Block diagram of circuit design tool

Operation for general circuit data:

1. If MCB is selected for protection device, the tool defines a suitable miniature circuit breaker based on the temperature derated max. circuit current

   If fuse is selected for protective device, the tool chooses gG-fuse with higher rated current than the load current + margin.

2. Minimum wiring to have a higher current carrying capacity than rated current of the protective device.

Operation for motor circuit data:

1. Defines suitable motor protection circuit breaker (MS132) based on the set load current.
2. Minimum supply wire for MPCB to have a higher current carrying capacity than max. continuous current of the MPCB + 15% reserve. Minimum wire 2,5 mm^2.
3. Minimum contactor selected to have a higher rated operational current (AC-3) than MPCB max. continuous current.
4. Minimum motor wire selected to have a higher current carrying capacity than MPCB max. continuous current
5. If motor circuit fuse is gG-type, it is selected to withstand motor starting current 7x nominal current for 5 seconds.
   If motor circuit fuse is aM-type, it is selected to have a higher rated current than MPCB.
6. Internal supply wire at least 6 mm^2 if MPCB rated current < 20 A otherwise minimum 10 mm^2.
7. Internal supply fuse rated current is approximately 1,6x higher than the motor circuit fuse to meet the criteria of selectivity.

Motor case #1

This is an example case where the ACS880-107-1760A-3 inverter unit is supplying the main hoist machine. Customer has requested auxiliary motor supply inside of ACS880 multidrive lineup (in figure 24) to supply the fan motor of the main machine. Fan motor will be supplied from ICU cabinet internal AC-busbar and motor components will be located in Motor Options Unit cabinet. Fan motor specifications in table 6.

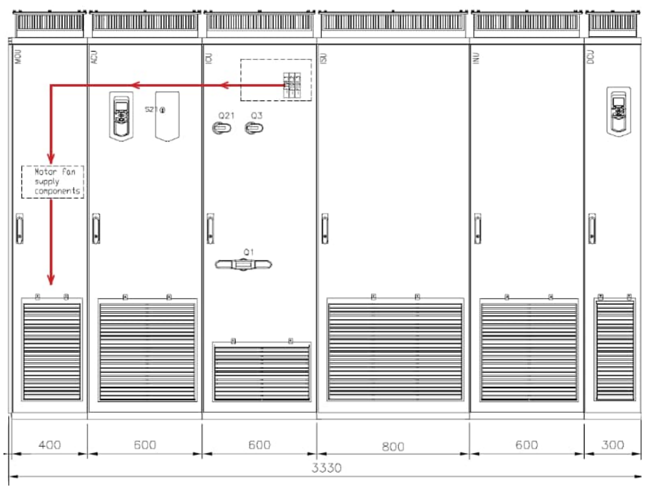

Figure 24. Motor case #1 lineup drawing

Table 6. Motor case #1 fan motor specifications

Nominal power P_n	Nominal current I_n	Supply voltage U_n
3 kW	6,5 A	400 V

Calculation

All cells which need input data are highlighted in white color and informing text are next to every input data cell. Most of the input data cells have a drop-down menu for quicker and easier use.

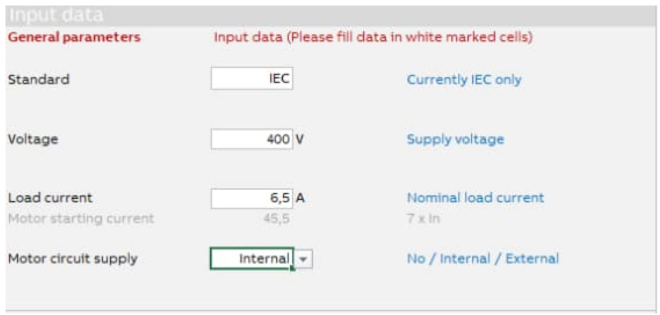

Figure 25. Input data, general parameters

The dimensioning starts from general parameters (figure 25) by defining the necessary load current. In this case motor nominal current 6,5 A will be used. Motor supply voltage is 400 V and internal supply-type selected. When motor circuit is selected, calculator shows an approximation of motor starting current.

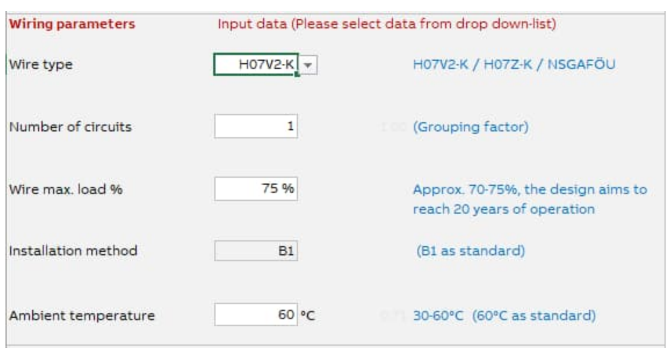

Figure 26. Input data, wiring parameters

Wiring parameters are in figure 26 where the PVC-wire H07V2-K is selected. Number of circuits in this case is 1 because motors supply wires will be wired inside own duct and no notable thermal impact from other wires. Wire maximum loading percent is selected to be 75% which gives enough reserve for conductor loading. Ambient temperature inside the cabinet is assumed to be 60 °C.

Protective device	Input data (Please select data from drop down-list)	
MCB temperature	60 °C	30-60°C (Only for max. load-current calculation. MCB selection always at 20°C temp.)
MCB type	no MCB	K-type only
Fuse type	gG	gG / aM

Figure 27. Input data, protective device parameters

The last input section, the protective device data is shown in figure 27. Now when we have motor circuit, MCB is not selected and thus the MCB temperature does not affect in calculations. In this case fuse-type is gG-fuse. When all input-parameters are set, output data gives the needed wires and components for the installation.

Output data				
General circuit data			Max. Current	
Minimum wire	NOT IN USE	mm^2		Minimun wire for selected MCB/fuse
Min. MCB size	NOT IN USE	A		Wire protection acc. 20 °C
Max. Circuit current	NOT IN USE	A		Max. MCB load current including MCB ambient temp.
Minimum fuse	NOT IN USE	A gG		
Motor circuit data			Max. Current	
Internal supply fuse	32	A gG		If internal supply wire ICU->MOU >3m
Internal supply wire	6	mm2	28,8 A	Supply wire from AC-busbar
Motor circuit fuse	20	A gG		gG-fuse acc. motor start current aM-fuse acc. wire protection
Minimum MPCB wire	2,5	mm^2	17,0 A	Wire before MPCB
MPCB selection	MS132-10	A	10,0 A	Motor protection temp. compensated
Minimum contactor	AF12		12,0 A	ABB AF-series AC-3 @ 60 °C
Minimum motor wire	1,5	mm^2	12,8 A	Wire after MPCB

Figure 28. Output data for motor circuit in motor case #1

In figure 28, the output data for motor circuit and in figure 29 the circuit diagram for the motor circuit. Calculator suggests a minimum internal supply wire between AC-busbar and fuse link to be 6 mm^2, motor circuit fuse 20 A gG, motor protection circuit breaker MS132-10 with AF12 contactor. Minimum wire before MPCB 2,5 mm^2 and 1,5 mm^2 after the MPCB. The minimum internal supply fuse size should be 32 A gG.

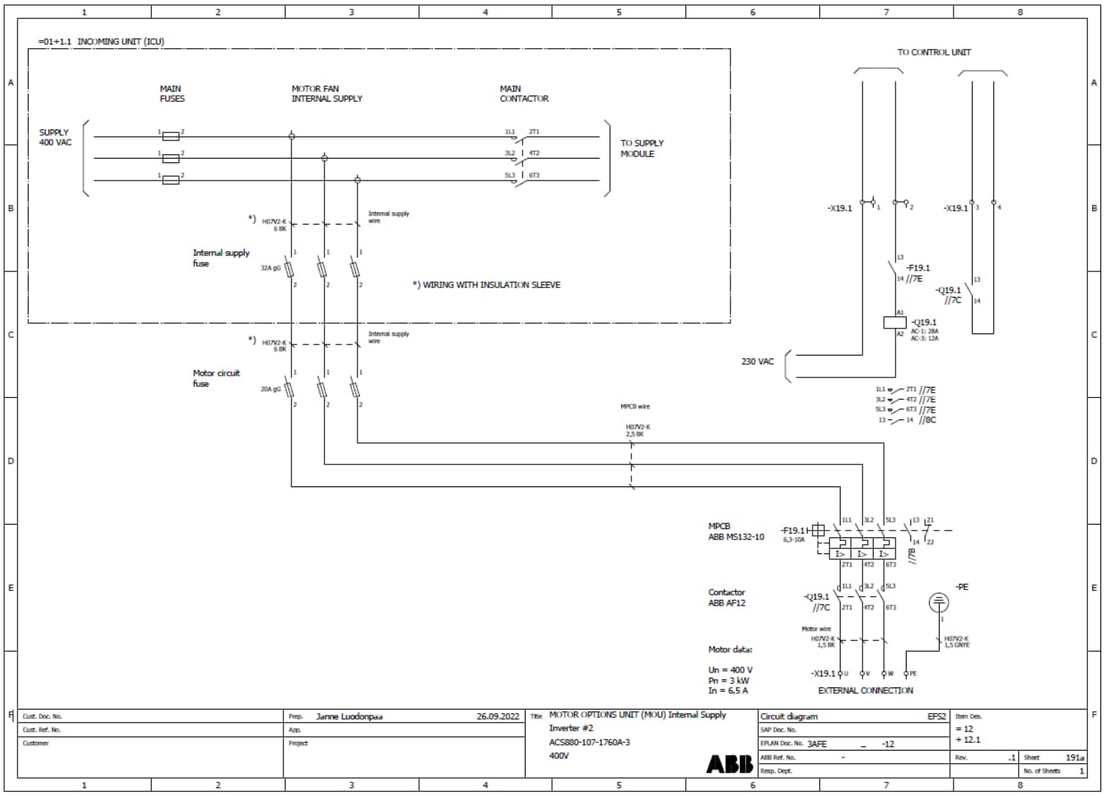

Figure 29. Circuit diagram for motor case #1

Verification

We can take a closer look on the results to verify is the design tool working correctly and is the outcome usable.

Motor protection circuit breaker (MPCB)

Suggested motor protection circuit breaker MS132-10 has a current setting range from 6,3 A to 10 A. The load current 6,5 A is setting in between the limits and is therefore suitable to use.

Supply wire for MPCB

Supply wire H07V2-K 2,5 mm^2 for MS132-10 protection device has a current carrying capacity 32 A in ambient temperature 30 °C. Derated current carrying capacity can be calculated by applying the ambient temperature correction factor from table 1 and formula below.

$$32\text{ A } \times 0{,}71 \times 0{,}75 = 17{,}04\text{ A}$$

In 60 °C ambient temperature and with 75% loading the calculated current carrying capacity for the wiring will be 17,04 amperes which is significantly higher than required. Maximum allowable thermal stress for 2,5 mm^2 PVC wire can be calculated using equation 4 from section 5.2 of this paper.

$$I^2t = 100^2 \times 2{,}5^2 \approx 62{,}5 \times 10^3\text{ A}^2\text{t}$$

Motor circuit fuse

Motor circuit fuse 20 A gG should withstand the assumed motor starting current 45,5 A. By examining the figure 9 could be verified that OFAA000GG20 fuse can withstand that current over 10 seconds which is more than enough for motor start peak.

Additionally, as the figure 11 illustrates the OFAA000GG20 fuse has an operating I^2t value ~3000 A^2s which is considerably lower than maximum value allowed for 2,5 mm^2 PVC-wire and the fuse is then protecting the cable adequately.

Contactor

Suggested contactor ABB AF12 has a nominal operational AC-3 current 12 amperes in 400 V supply. With load current of 6,5 A AF12-contactor has an electrical durability more than 3,5 million operating cycles according to the figure 18 in section 6.3.2.

Minimum motor wire

Minimum motor wire 1,5 mm^2 with derated current carrying capacity 12,8 A can carry the maximum continuous current of motor protection device.

Internal supply wire

Internal supply wire H07V2-K 6 mm^2 has a derated current carrying capacity 28,8 A which is sufficient for the set load current. Maximum allowable thermal stress for 6 mm^2 PVC wire can be calculated using equation 4 from section 5.2 of this paper.

$$I^2t = 100^2 \times 6^2 \approx 360 \times 10^3 \text{ A}^2\text{t}$$

Internal supply fuse

The figure 11 provides the operating I^2t values for OFAA000GG fuses. According to that, 32 A gG-fuse has an operating I^2t ~10 000 A^2s which is considerably lower than maximum value allowed for 6 mm^2 PVC-wire. The fuse is then protecting the cable adequately. The ratio between internal supply fuse and motor circuit fuse is 1,6:1 which fills the requirement for selectivity.

Motor case #2

Second example is from ACS880-07CLC which was designed and delivered earlier to a certain shipyard. In this example the circuit is redesigned using the calculator tool with the same parameters as were in the original project. The purpose of this example is to investigate how the design differs when the tool is used compared to the old way when everything had to do manually.

In figure 30 the ACS880-07CLC lineup, CLC refer to a compact liquid cooled DSU-supply unit where the control section, connection cabinet and rectifier are integrated in the same cabinet. Due to a limited space an empty cabinet is added to lineup for the motor circuit components and circuit is externally supplied from customer 380 V switchboard. The motor specifications can be found from table 7.

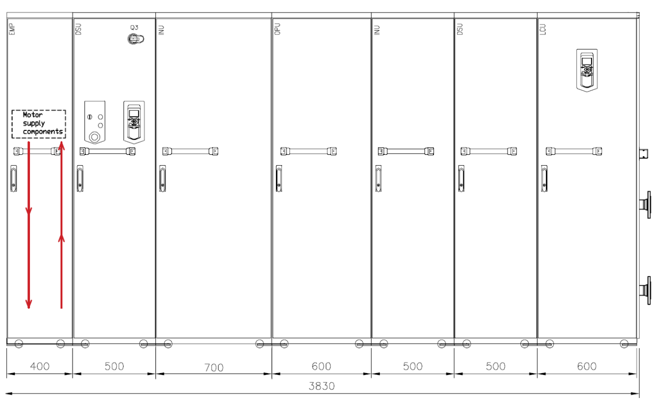

Figure 30. The dimensional drawing of the drive. Motor circuit is externally supplied, red arrows indicate the incoming and outgoing cables

Table 7. Motor case #2, motor specifications

Nominal power P_n	Nominal current I_n	Supply voltage U_n
11 kW	23 A	380 V

The input/output data section is shown in figure 31. In this case external motor circuit supply is selected, wire type is halogen free H07Z-K which is commonly used in marine applications. Motor circuit components are placed in empty cabinet with a charging transformer. Both circuits are supplied from external and wirings installed inside the same duct, then the grouping factor of two circuits need to be applied. Wire loading percentage and ambient temperatures are as standard and aM-fuse is selected for use.

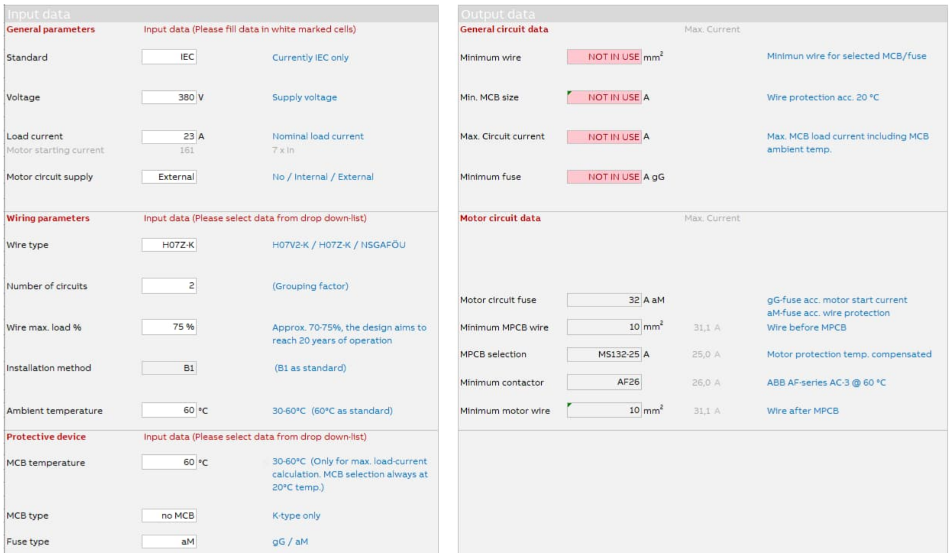

Figure 31. Input and output data for motor case #2

Calculator suggests a motor circuit fuse 32 A aM, motor protection circuit breaker MS132-25 with AF26 contactor. Minimum MPCB wire 10 mm^2 and 10 mm^2 minimum motor wire.

Verification

<u>Motor protection circuit breaker (MPCB)</u>

The suggested motor protection circuit breaker MS132-25 with current setting range up to 25 A is sufficient for the 23 A load current.

<u>Supply wire for MPCB and motor wire</u>

Supply wire H07Z-K 10 mm^2 for MS132-25 protection device has a derated current carrying capacity 31,1 A in ambient temperature 60 °C with grouping factor 0,8 and 75% max wire loading. Maximum allowable thermal stress for 10 mm^2 XLPE-wire is $2{,}04 \times 10^6$ A^{2}s by using the equation 4.

Motor circuit fuse

Motor circuit fuse 32 A aM can withstand the assumed motor starting current 161 A as we can verify that from the figure 12. The fuse has an operating I^2t value ~11 000 A^{2}s (see figure 14) which is substantially lower than maximum value allowed for 10 mm^2 XLPE-wire and the wiring is then protected adequately.

Contactor

Suggested ABB AF26 contactor has a nominal operational AC-3 current 26 A in 380 V supply voltage. With load current of 23 A AF26-contactor has an electrical durability more than 1,4 million operating cycles according to the figure 18.

When comparing the calculator result to the circuit diagram for motor case #2 in figure 32, it's easy to perceive that the results are quite similar. The results given by calculator tool comply with the original design which has been proven to work. The only difference between the calculator-based dimensioning and the manual dimensioning is the contactor size. In new calculator-based design the contactor is a two size smaller compared to the original design.

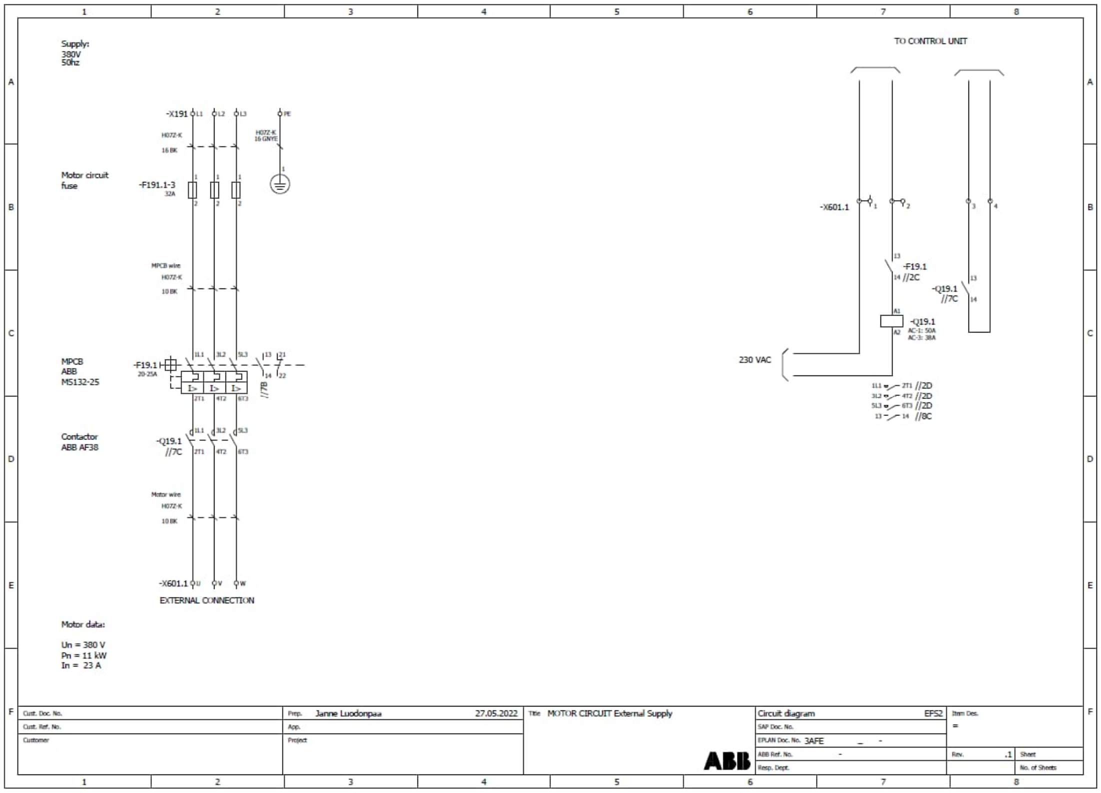

Figure 32. Circuit diagram for motor case #2

The reason for bigger contactor in original design might be the fact that some of the contactors (and other devices), are listed with lacking information into SAP system. When the designer chooses the suitable device there might be characteristics available e.g. only for 690 V supply. AF38 has nominal current 24 A in 690 V and if the contactor is listed in SAP showing only that information, it is easy to misunderstand the current ratings. For example, the AF26 contactor is sufficient to use for 23 A load current but only for supply voltages ≤ 500 V. For higher supply voltage, the AF38 contactor is required.

In this case it is of course good that originally selected contactor has a greater nominal current than requested but it is obvious that in a long term, continuous unnecessary oversizing will have a negative cost impact.

General circuit

In this example 250 A external auxiliary output has designed upon a customer request. Due to a lack of space in electrical room, customer wanted to supply an external switchboard directly from the ACS880 multidrive. The space limitations in electrical room complicated the design work since the output needed to be placed inside the existing multidrive lineup and no extra cabinet allowed for auxiliary output. Customer cabling is routed from 200 mm wide cabinet next to ICU. Fuses and customer terminals are locating in ICU cabinet as shown in figure 33.

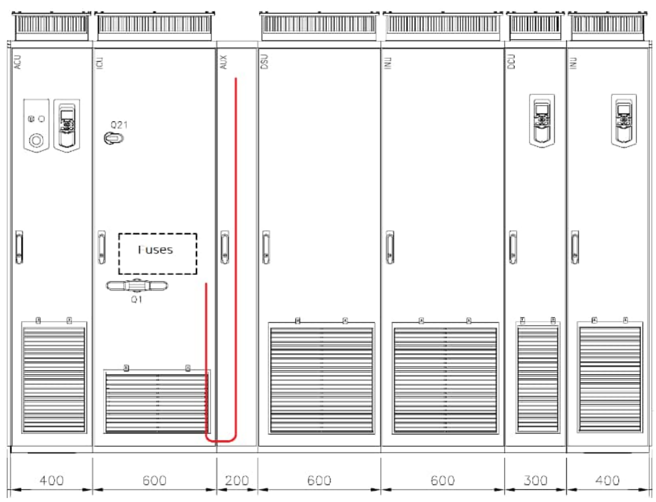

Figure 33. The dimensional drawing of the multidrive lineup. Top exit in 200 mm cabinet for 250 A output customer cables

In figure 34 the parameter selections are shown. Motor circuit is not selected, wire type is double insulated NSGAFÖU. Wire loading percentage is set to be 85%. The calculator suggests 250 A gG-fuse and 95 mm^2 wiring. The reason why the wire loading percentage in this time is 85% is that with recommended 75% value the wire size would increase significantly and that would lead to a lack of space issue because bigger wires would need more bending space etc. in already tight ICU cubicle. Next wire size after 95 mm^2 is 120 mm^2 which is over 26% bigger. It is noted that 15% margin in these types of cases is enough. Circuit diagram for general circuit in figure 35.

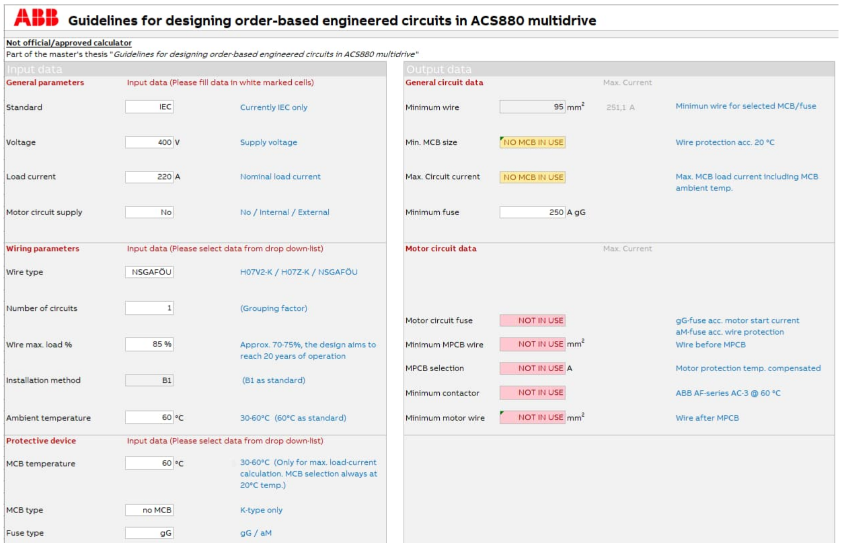

Figure 34. Input and output data for general circuit

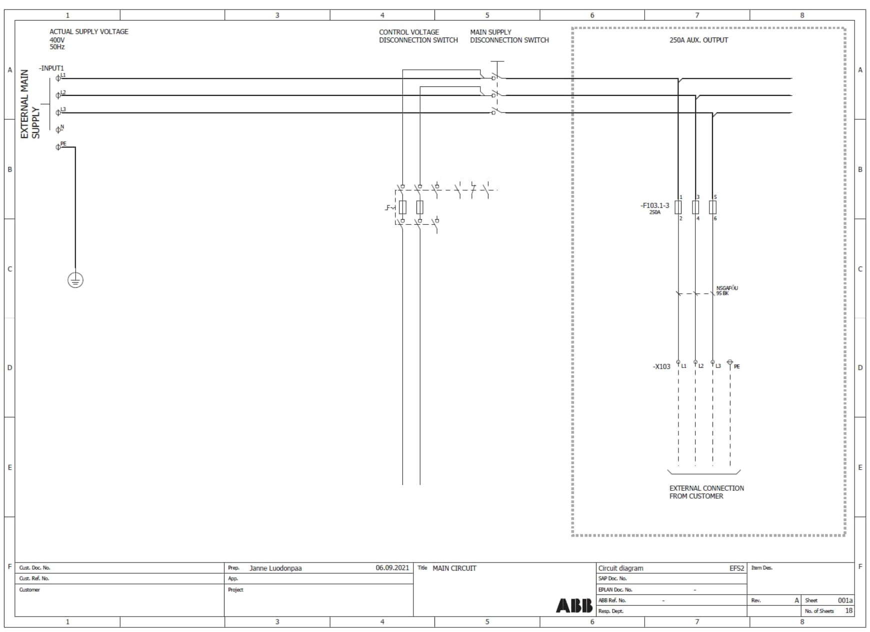

Figure 35. Circuit diagram. 250 A auxiliary output inside the dashed line

Verification

Correct protection of the cable can be verified by using the equations 1 and 2 from section 5.1 of this thesis. The design tool verifies the correct protection as can be seen from the figure 36.

Verification data

General circuit verification

Correct protection of a cable against overloads					
I_b 220	≤	I_n 250	≤	I_z 251,1	OK
I_2 362,5		≤		$1{,}45 \times I_z$ 364,0	OK

Figure 36. Protection of the wire is ensured if both conditions are fulfilled

8 Conclusions

The main objectives of this thesis were to study what standards and instructions are needed and how to bring together all the information, recommendations and known best practices related to electrical design in order-based engineering. The aim of this work was also to create a design tool which would simplify and speed up the design work and reduce the possibilities for human error.

Considering these objectives, this thesis was successful. The design tool was successfully created and it can be used to support designers in their everyday job. The design tool was developed to be easily expanded and new features can be added when necessary. At testing phase the design tool was successfully tested with variable load currents in both motor- and general circuits. The results given by the design tool corresponds to those from manual selection. The design tool was also tested by using it to redesign older projects which are already delivered and comparing the results to original. Based on these tests, it could be verified that design tool is working as planned. The results between the original design and that done by design tool were mostly similar, the major difference what came up was the fact that when calculating and selecting devices manually there is a higher probability for unnecessary oversizing.

Some requirements were partly achieved. Due to a time and resource limitations at this point the tool can be used only in IEC projects and the requirements from UL and CSA standards for North American markets were left out. Currently the design tool works with single motor circuits up to 32 amperes and general circuits up to 250 amperes.

The design tool makes the selection purely by the electrical characteristics. It does not take into account mechanical dimensions of the components, neither it does not take into account the cost or purchasing volume of the components. The user must ensure that the device which the design tool is suggesting can mechanically fit inside the cabinet. Also, when producing products on high volume sometimes it might be more cost efficient to use same components (e.g. contactor) in all product variants even though in some situations it may be oversized.

Future improvement could be expanding the design tool for multiple motor circuits. That upgrade would be quite meaningful but relatively easy to execute. Also, the requirements from UL and CSA standards are necessary to introduce at some point in the future. This would also lead to expand the component selection to UL and CSA approved components, including fuses, miniature circuit breakers etc. Other topics to investigate could be increasing the motor circuits over 32 A by MS165 motor protection circuit breakers.

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Appendix 1. Utilization categories for contactors and starters according to IEC 60947-4-1 2018, p. 38.

Kind of current	Utilization categories	Additional category designation	Typical load
AC	AC-1	General use	Non-inductive or slightly inductive loads
	AC-2		Slip-ring motors or mixed resistive and inductive loads, including moderate overloads
	AC-3		Squirrel-cage motors [d]: starting, switching off motors during running, reversing [a]
	AC-3e[e]		Squirrel-cage motors with higher locked rotor current [e]: starting, switching off motors during running, reversing [a]
	AC-4		Squirrel-cage motors [d]: starting, plugging, inching
	AC-5a	Ballast	Discharge lamps
	AC-5b	Incandescent	AC incandescent lamps
	AC-6a		Transformers
	AC-6b		Capacitor banks
	AC-7a[c]		Slightly inductive loads for household appliances and similar applications
	AC-7b[c]		Motor-loads for household applications
	AC-8a		Hermetic refrigerant compressor motor [b] control with manual resetting of overload releases
	AC-8b		Hermetic refrigerant compressor motor [b] control with automatic resetting of overload releases
DC	DC-1		Non-inductive or slightly inductive loads
	DC-3		Shunt-motors: starting, plugging, inching, dynamic breaking of DC motors
	DC-5		Series-motors: starting, plugging, inching, dynamic breaking of DC motors
	DC-6	Incandescent	DC incandescent lamps