

# **Current Carrying Capacity Calculations for High- and Medium Voltage Cables**

William Sundqvist

Degree Thesis

Thesis for Bachelor of Engineering (UAS) - degree

Electrical Engineering and Automation

Vaasa 2022

## **DEGREE THESIS**

Author: William Sundqvist

Degree Programme and place of study: Electrical Engineering and Automation, Vaasa

Specialisation: Electrical Power Engineering

Supervisor(s): Juha-Matti Huhtanen, Ronnie Sundsten

Title: Current Carrying Capacity for High- and Medium Voltage Cables

---

Date: 20.4.2022    Number of pages: 71    Appendices: 3

---

### **Abstract**

When sizing cables for a particular installation it is essential to find the current rating of those cables in their thermal environment. Cables will heat up as a result of the imposed current in the system. The cables can only withstand a certain temperature without sustaining damage. Their current rating will depend on the amount of current that will cause the maximum allowable temperature rise.

The calculation of the current carrying capacity of power cables is a critical part of the design of an electrical power system. Optimally sized cables grant high reliability at minimum cost. These calculations are quite excessive and include a lot of steps. Having a software tool to quickly calculate this saves a lot of time and minimizes the chances of a calculation error.

The purpose of this thesis was to develop such a tool using Microsoft Excel and formulae from IEC60287 for Hitachi Energy. There are a handful of common methods presented in this thesis that will increase the current rating. Engineers can use the tool developed in this thesis to determine which methods to apply. There was also research conducted in the area, in particular the current distribution between adjacent cables and a comparison of calculation methods. The result of this thesis was a working calculation tool.

---

Language: English

Key Words: Power Cables, Ampacity, Heat Dissipation

## EXAMENSARBETE

Författare: William Sundqvist

Utbildning och ort: El- och automationsteknik, Vasa

Inriktning: Elkraftteknik

Handledare: Juha-Matti Huhtanen, Ronnie Sundsten

Titel: Belastningsbarhetsberäkningar för hög- och mellanspänningskablar

---

Datum: 20.4.2022    Sidantal: 71

Bilagor: 3

---

### Abstrakt

Vid dimensionering av kablar för en viss applikation är det centralt att finna märkströmmen hos kablarna under de gällande termiska omständigheterna. Kablar hettas upp till följd av den ström som passerar genom dem. Kablar kan endast utstå en viss strömstyrka utan att ta skada. Deras märkstöm kommer att bero av den strömstyrka som orsakar den maximala godtagbara temperaturökningen.

Beräkningen av belastningskapaciteten för elkraftskablar är en känslig del i planeringen av ett elkraftssystem. Optimalt dimensionerade kablar garanterar en hög driftsäkerhet till lägsta möjliga kostnad. Beräkningarna är omfattande och inkluderar många steg. Ett beräkningsverktyg som snabbt beräknar belastningsbarheten sparar mycket tid och minimerar risken för beräkningsfel.

Syftet med detta examensarbete var att utveckla ett sådant verktyg åt Hitachi Energy Finland Oy med hjälp av Microsoft Excel och formler hämtade från IEC60287. Det finns ett antal välkända metoder för att förbättra märkspänningen hos elkraftskablar. Detta verktyg ska kunna användas av ingenjörer för att avgöra vilka metoder som behöver tillämpas. Efterforskningar inom området utfördes också som en del i arbetet, i synnerhet vad gäller strömfördelningen mellan parallella kablar och jämförelser av beräkningsmetoder. Resultatet av examensarbetet blev ett fungerande beräkningsverktyg.

---

Språk: engelska

Nyckelord: elkraftskablar, belastningsbarhet, värmeavledning

## OPINNÄYTETYÖ

Tekijä: William Sundqvist

Koulutus ja paikkakunta: Sähkö- ja automaatiotekniikka, Vaasa

Suuntautumisvaihtoehto: Sähkövoimatekniikka

Ohjaajat: Juha-Matti Huhtanen, Ronnie Sundsten

Nimike: Keski- ja suurjännitekaapeleiden kuormitettavuuslaskelmat

---

Päivämäärä: 20.4.2022 Sivumäärä: 71

Liitteet: 3

---

### Tiivistelmä

Kun mitoitetaan kaapeleita tiettyä sovellusta varten, on keskeistä löytää kyseisten kaapeleiden nimellisvirta soveltuviin lämpöolosuhteisiin. Kaapelit lämpenevät niiden läpi kulkevan virran seurauksena. Kaapelit kestävät vain tietyn määrän virtaa vahingoittumatta. Niiden nimellisvirta riippuu virrasta, joka aiheuttaa suurimman hyväksyttävän lämpötilan nousun.

Sähkökaapeleiden kantavuuden laskeminen on herkkä osa sähköjärjestelmän suunnittelussa. Optimaalisesti mitoitettujen kaapelien takaaminen korkean käyttövarmuuden mahdollisimman alhaisin kustannuksin. Laskelmat ovat laajoja ja sisältävät monia vaiheita. Nopeasti kantavuuden laskeva laskentatyökalu säästää paljon aikaa ja minimoi laskentavirheen riskin.

Tämän opinnäytetyön tarkoituksena oli kehittää tällainen työkalu Hitachi Energy Finland Oy:lle, Microsoft Excelin avulla ja IEC60287:n kaavoilla. Sähkökaapeleiden kantokyvyn parantamiseksi on olemassa useita tunnettuja menetelmiä. Tässä opinnäytetyössä kehitetyn työkalun avulla insinöörit voivat määrittää, mitä menetelmiä on sovellettava. Kaapeleiden kuormitettavuudesta tehtiin myös tutkimusta osana opinnäytetyötä erityisesti koskien rinnakkaisten kaapeleiden sähkönjakelua ja vertailuja eri laskentamenetelmien välillä. Opinnäytetyön tuloksena on toimiva laskentatyökalu.

---

Kieli: englanti

Avainsanat: sähkövoimakaapeli, kuormitettavuus, lämmönjohtavuus

## Symbols

$D_e^*$  = external diameter of cable (mm)

$D_i$  = diameter over insulation (mm)

$D_s$  = external diameter of metal sheath(mm)

$I$  = electrical current in one conductor (RMS value) (A)

$R$  = AC resistance of conductor at maximum operating temperature

$R_A$  = AC resistance of armour at maximum operating temperature

$R_{A0}$  = AC resistance of armour at 20 °C

$R_S$  = AC resistance of the sheath or screen at maximum operating temperature

$R_{S0}$  = AC resistance of sheath or screen at 20 °C

$R'$  = DC Resistance of conductor at maximum temperature

$R_0$  = DC resistance of conductor at 20 °C

$T_1$  = thermal resistance between conductor and sheath

$T_2$  = thermal resistance between sheath and armour

$T_3$  = thermal resistance of external serving

$T_4$  = thermal resistance of surrounding medium

$U_0$  = voltage between conductor and screen or sheath

$W_d$  = dielectric losses of cable (W/m)

$X$  = reactance of sheath (three-core cables and single-core cables in trefoil)

$X_1$  = reactance of sheath (single-core cables in flat formation)

$X_m$  = mutual reactance of the sheath of a cable and the conductors of the other two in flat formation.

$c$  = the distance between the axes of the conductors and the axis of the cable for three-core cables.

$d$  = the mean diameter of sheath or screen

$d_A$  = mean diameter of armour

$d_c$  = External diameter of conductor

$f$  = system frequency

$g_s$  = Coefficient used for calculating eddy current losses

$k_p$  = factor used for calculation of proximity effect,  $X_p$

$k_s$  = factor used for calculation of skin effect,  $X_s$

$\ln$  = natural logarithm

$m = \frac{\omega}{R_s} * 10^{-7}$  factor used for calculating metallic sheath losses

$n$  = number of conductors in a cable

$s$  = the axial separation of conductors (three-core cables)

$s_1$  = the axial separation of two adjacent cables in a horizontal group of three cables, not touching

$s_2$  = the axial separation of cables

$t$  = insulation thickness between conductors

$t_3$  = thickness of serving

$t_s$  = thickness of sheath

$x_p$  = argument of a Bessel function used to calculate proximity effect

$x_s$  = argument of a Bessel function used to calculate skin effect

$y_p$  = proximity effect factor

$\gamma_s$  = skin effect factor

$\alpha_{20}$  = temperature coefficient of electrical resistivity at 20 °C, per Kelvin

$\beta_1$  = coefficient used for calculation of eddy current losses

$\Delta_1, \Delta_2$  = coefficients used for calculation of eddy current loss

$\tan\delta$  = loss factor of insulation

$\varepsilon$  = relative permittivity of insulation

$\theta$  = maximum operating temperature of conductor

$\theta_{ar}$  = maximum operating temperature of armour

$\theta_{sc}$  = maximum operating temperature of screen or sheath

$\Delta\theta$  = Maximum allowable temperature rise of conductor above ambient temperature

$\lambda_0$  = Coefficient used for calculating eddy current losses

$\lambda_1, \lambda_2$  = ratio of total losses in metallic sheaths and armour respectively to the total conductor losses.

$\lambda'_1$  = ratio of the circulating current losses in one sheath to the conductor losses of one conductor (Three-core cables)

$\lambda''_1$  = ratio of eddy current losses in one sheath to the losses in one conductor

$\lambda'_{1m}$  = loss factor of the middle cable (cables in flat formation without transposition, sheaths bonded at both ends)

$\lambda'_{11}$  = loss factor of outer cable with greater losses

$\lambda'_{12}$  = loss factor of outer cable with least losses

$\rho$  = electrical resistivity of conductor at 20 °C

$\rho_s$  = electrical resistivity of sheath at 20 °C

$\omega$  = angular frequency of the system

# Table of contents

1	Introduction.....	1
1.1	Goal and scope.....	2
1.2	Presentation of employer .....	3
2	Power transmission and cables .....	3
2.1	Power cables .....	4
2.1.1	Voltage ratings for cables.....	5
2.1.2	Cable calculation constants.....	5
2.1.3	Substation cabling.....	5
3	Power Cables: Electrical Design Concepts.....	5
3.1	General design criteria for cables .....	6
3.2	Conductors.....	6
3.2.1	Air insulated conductors.....	7
3.2.2	Rising voltage.....	8
3.2.3	Conductor sizes .....	9
3.2.4	Material considerations.....	9
3.2.5	Direct current resistance .....	9
3.2.6	Weight.....	10
3.2.7	Voltage regulation.....	10
3.2.8	Short circuit operation.....	10
3.2.9	Other factors.....	10
3.3	Insulation.....	10
3.3.1	Dielectric strength .....	11
3.3.1	Insulation materials .....	11
3.3.2	Insulating layer requirements .....	14
3.4	Insulation screen or sheath/shield.....	14
3.4.1	Conductor shield is needed.....	15
3.4.1	Sheaths.....	15
3.4.2	Insulation levels and screening.....	16
3.4.3	Shielding layer requirements.....	16
3.5	Armouring.....	16
3.6	Jackets / Servings.....	17
3.7	Finish .....	17
3.8	Terminology .....	17

4	Cable installation practices .....	18
4.1	Cable Sizing .....	18
4.2	Trefoil and flat formation .....	18
4.3	Cables laid in air .....	19
4.4	Cables laid in direct ground .....	20
4.5	Cables installed in ducts .....	21
4.6	Joints and Terminations .....	21
4.7	Earthing and bonding .....	22
4.7.1	Three-core cables .....	22
4.7.2	Single-core cables .....	23
5	Heat losses in electrical power cables .....	24
5.1	Heat development in conductors .....	24
5.2	Insulated conductors .....	25
6	Ampacity .....	26
6.1	Soil thermal resistivity .....	27
6.2	Ampacity calculations .....	27
6.3	Heat transfer model .....	28
6.4	Load Factor .....	29
6.5	Loss Factor .....	29
6.6	Conductor losses .....	30
6.6.1	Direct current conductor resistance .....	30
6.6.2	Alternating current resistance of a conductor .....	31
6.7	Proximity effect .....	33
6.7.1	Proximity effect factor $Yp$ for three-core cables and for three single-core cables	33
6.8	Hysteresis and eddy current effects .....	34
6.8.1	Effect of Milliken conductors .....	34
6.8.2	Single-core cables, with bonded sheaths at a single point or cross-bonded	35
6.9	Dielectric losses and calculations .....	37
6.10	Metallic shield losses .....	38
6.10.1	Screen or sheath losses .....	40
6.10.2	Loss factor calculation for sheath and screen .....	40
6.11	Armour losses .....	42
6.11.1	Three-core cables – steel wire armour (round conductor) .....	42
6.12	Typical Thermal Circuits .....	43

6.13	Single layer of insulation, continuous load .....	44
6.13.1	Cable thermal circuit for primary cable with metallic shield and jacket, continuous load.....	44
6.13.2	Same cables as above, cyclic load .....	45
6.13.3	External thermal circuit, cable in duct, continuous load .....	45
6.13.4	External thermal circuit, cable in duct, time varying load, External heat source	46
6.14	Full thermal circuit of a single conductor shielded power cable in a multiphase system laid in duct.....	46
6.15	Calculation of thermal resistances.....	47
6.15.1	Thermal resistance between one conductor and sheath $T_1$ .....	47
6.15.2	Thermal resistance between sheath and armour $T_2$ .....	47
6.15.3	Thermal resistance of outer covering (serving) $T_3$ .....	48
6.15.4	External thermal resistance $T_4$ .....	48
6.16	Ampacity tables and computer programs .....	50
6.16.1	Tables.....	50
6.16.2	Computer programs .....	50
6.17	Ampacities under short circuit conditions.....	50
6.18	Relationship between Ampacity and voltage drop calculations.....	51
7	Comparison of Calculation methods .....	51
7.1	Ampacity calculations methods .....	52
7.1.1	The black books .....	52
7.1.2	IEEE 835 Cable Ampacity Tables.....	53
7.1.3	Computer modeling.....	53
7.1.4	Nehrer-McGrath Adaption.....	53
7.2	Conclusions .....	54
8	The Balance of current distribution in parallel cables.....	54
8.1	Electrical Characteristics associated with current distribution .....	55
8.2	Calculation of current distribution .....	57
8.3	Processing techniques.....	59
8.4	Results.....	61
9	Calculation tool development .....	63
9.1	Useful Excel Features and Functions .....	63
9.1.1	Dropdown list – data validation.....	63
9.1.2	XLOOKUP .....	64
9.1.3	IF and IFS .....	66

9.2	Application of IEC60287 Formulae .....	66
10	Breakdown of Results.....	67
10.1	Excel workbook for calculations.....	67
10.2	Comparison of methods .....	67
10.3	Balance of current distribution between adjacent cables .....	68
11	Discussion .....	69
12	References.....	69

### **List of Appendices**

Appendix 1	Selection of installation properties
Appendix 2	Cable Selection
Appendix 3	Calculation results

# 1 Introduction

As the global demand for electrical energy rises, so does the energy output, required from power generation facilities. The current global energy trend is to implement more renewable energy. In Finland this is particularly apparent in the rapid growth of wind power plants. The power generated needs to be collected, transformed, and transmitted through the electrical power grid. This is done using electrical substations that collect the power generated at the generation site.

When more power is to be transmitted at a fixed standardized voltage level it will result in larger load currents that need to be passed through the substation. Substations often use cables at the medium voltage side to transfer electrical power from the medium voltage switchgear housed in the substation building. These cables are sensitive to high currents as these along with the electrical resistance in the conductors will cause the cables to heat up.

Cables are insulated conductors that aren't cooled as effectively as non-insulated conductors. The problem grows when the cables are submerged underground where the heat conductivity is lower. Too much heat will not only result in a great loss of power but may also cause damage to the cable insulation, eventually leading to a failure of the entire electrical power system.

Cables are sometimes also used on the high voltage side of the transformer particularly, in applications where high voltage gas insulated switchgear are used. These high voltage switchgear require a separate building to which power is usually transmitted from the power transformer(s) using cables. The current here is somewhat lower than on the medium voltage side due to the higher voltage level.

Substation engineers use different techniques to counteract the issue of cables heating up. A common countermeasure is the use of multiple cables per phase. This will in theory divide the current equally between the cables given that the impedance of each cable is the same. This decreases the load on each cable which means less stress on one cable.

Substation engineers may choose to use cement around cables installed in pipes or ducts as concrete has better heat conductivity than earth. This method is often used in locations where the heat conductivity of the earth is poor.

Substation engineers need to determine which cables to use, and the extent of installation works that will be required in their projects. This is a time-consuming process as one needs to find the most cost-effective and functional solution. Having a tool to quickly determine this will greatly benefit the substation engineers and save resources for the whole company.

## **1.1 Goal and scope**

The purpose of the thesis is to develop a software tool for the calculation of load capacity for electrical power cables used in substations for Hitachi Energy Oy. The tool is developed using IEC60287 formulae in Microsoft Excel.

When given a few input parameters such as voltage level, cable type, and apparent power in the system, the user will be able to quickly determine the current specifications of the cables required. This tool will assist the user will in determining the extent of installation works, that will be required at the site. The user will need to know what kind of cables that are going to be used in order to get a result. The cable size may have to be changed depending on the result of the current carrying capacity calculation performed by the program.

The input parameters are easily changeable so that the user can get an idea of what kind of cables and conditions will be required. This tool will be used by substation engineers and planners. It will allow them to quickly get an idea of the extent of work required to handle the power load at hand. The tool will also be useful for checking if the use of cables is even possible or if air-insulated conductors are a better option.

Hitachi Energy has also requested research in the area, in particular the effect of adjacent cables, when several cables are used to help carry the current of the same phase. Hitachi Energy also requested a comparison between different methods used for the calculation of current carrying capacity.

The power cables included in this thesis are to be used in substations. This thesis will only include alternating current power cables, excluding power cables made for voltage levels below 20 kV as medium voltage levels in substations rarely fall short of 20 kV. This thesis only focuses on XLPE insulated cables. For the voltage levels in question, only XLPE and ERP are nowadays used as insulation for power cables. ERP insulation is more expensive than XLPE and does not hold any significant benefits over XLPE in terms of load capacity.

## **1.2 Presentation of employer**

Hitachi Energy Finland Oy is the Finnish fraction of Hitachi Energy which is an international company that focuses on electrical power solutions. Hitachi Energy promotes sustainable development. Hitachi energy serves the markets for utilities, data centres, industries, transportation, and smart life. The selling, construction, and operation of electrical substations are a large part of the business conducted by Hitachi Energy. [1]

## **2 Power transmission and cables**

Electrical power is not an energy form, only the result of an energy transfer process. Electricity can be used for a wide variety of tasks and is an excellent way to transmit energy from one place to another. Electrical energy is mostly produced using different sources of energy to drive an electrical generator. Electrical energy cannot be stored and needs to be consumed at the same time it is produced. Therefore, countries and energy companies build up electrical power grids that become like large circuits that transfer energy throughout the countries. The grids mostly use alternating current in a three-phase configuration. Voltage levels vary depending on the distance of transfer. High voltage is used for long-distance transmission and medium voltage for regional distribution and low voltage for local consumption. The electrical power is transported in metal conductors that are insulated from ground using post insulators. [2]

The air-insulated conductor can be considered the simplest form of insulated conductor. These are metallic conductors suspended from insulating supports, surrounded by air. Air

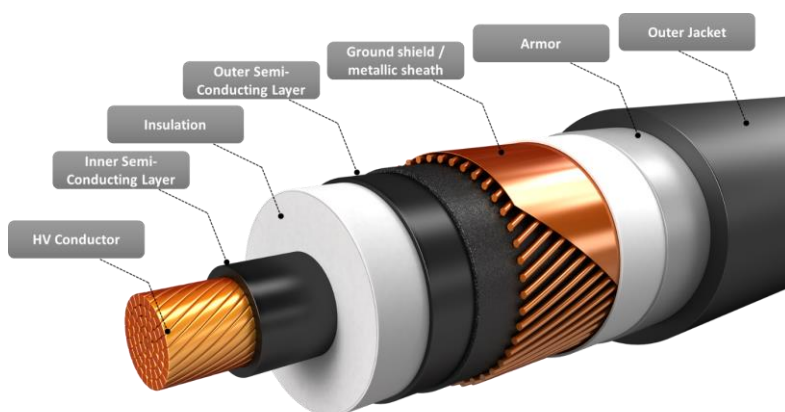
is not a particularly good insulation material since it has a low breakdown voltage compared to most of the other insulating materials used. It is, however, a very cost-effective option if space is not a constraint.

Lack of space is a common constraint that excludes the use of air as insulation. The conductor is then surrounded by a dielectric material that grants better insulation than air. This kind of conductor is called a cable and can be placed under ground and in water. [3]

## 2.1 Power cables

An electrical cable can be defined as just a conductor fitted with overlying insulation or an exterior shield or jacket. This simplistic concept may be part of the reason that power cable engineering is often neglected in the current electrical engineering education. Power cable engineering is technically complex and plays an important role in connecting electrical power systems.

The purpose of an electric cable is to convey electric current to the intended location. To accomplish this a conductor that is adequate to convey the imposed electric current is used. It is just as important to keep the current from flowing in unintended paths. Therefore, electrical insulation is used to isolate the conductor from external paths or surfaces. [3]



**Figure 1: High voltage power cable layout showing layers [4]**

A power cable is designed to be able to withstand the imposed voltage and current as well as environmental aspects. The measures taken to better handle voltages reduce the amount of current that can be carried by the cable. Note that a bare air insulated conductor can carry much more current than any cable. This has to do with heat dissipation and the

maximum temperature the insulation can withstand under continuous operation. There are several sources of heat in a high voltage power cable, such as the conductor, the sheath, and even the insulation. [5]

### **2.1.1 Voltage ratings for cables**

The voltage class rating of a cable is based on the phase-to-phase voltage of the system regardless of if it is used in a single- or three-phase configuration. The phase-to-phase voltage is  $\sqrt{3}$  times higher than the phase to ground voltage of a cable. Therefore, a system that operates at 14,4 kV to ground must use cables rated at 25 kV or higher since:  $\sqrt{3} * 14,4 \text{ kV} = 24,94 \text{ kV}$  [3]

### **2.1.2 Cable calculation constants**

There are 4 main electric constants that affect the functioning of a cable system. These are Resistance, inductance, capacitance, and conductivity. [3]

### **2.1.3 Substation cabling**

A substation building is used at the medium voltage side to house medium voltage switchgear cabinets as well as control and protection equipment. A common way to connect the switchgear cabinets to the power transformer(s) is the use of cables. These insulated conductors are dug into the ground allowing for more space for service vehicles to navigate in the substation. Cables are not as common on the high voltage side but can be used to connect power transformer(s) to a high voltage GIS (gas-insulated switchgear). [2]

## **3 Power Cables: Electrical Design Concepts**

The selection of cable for a specific application is best done in reference to the latest manufacturers' cable datasheets and application guides. This chapter focuses on the properties of different MV and HV power cables, useful installation practises, their merits for different applications, cable sizing, and loss calculations. [6]

### **3.1 General design criteria for cables**

The following design criteria apply to the manufacturing of power cables:

- 1) The cross-sectional area of the chosen conductors should be of the optimum size to carry the specified load current and withstand the specified short-term short circuit current without overheating and needs to be within the required limits for the voltage drop across the cable.
- 2) The applied insulation must be adequate for continuous operation at a specified voltage level with a high degree of thermal reliability, stability, and safety.
- 3) All materials used in the construction must be carefully selected to ensure a high level of physical and chemical stability throughout the life of the cable in its selected environment. The cable must be able to withstand the conditions of its environment throughout its lifetime.
- 4) The cable must be mechanically strong and flexible enough to withstand the handling during transportation and installation.
- 5) Adequate external protection must be applied to the insulation and or outer sheathing to enable it to withstand the required environmental service conditions.

After the selection of voltage level, cables are specified by describing the materials and their properties. For instance, conductor, insulation, shields, and jackets. A drawing of the cross-section through the cable, relevant technical parameters, and guarantees associated with the design will be provided by the manufacturer. [6]

### **3.2 Conductors**

The most fundamental concern of power cable engineering is to transmit power economically and efficiently. When choosing the conductor material, size, and design one must take into account the following:

- Ampacity / Current carrying capacity

- Voltage stress at the conductor
- Voltage regulation
- Conductor losses
- Bending radius and flexibility
- Overall economics
- Mechanical properties [7]

If we consider a conductor carrying current to a load and the return conductor as two separate cylinders of charge and neglect the diameter (line of charge), there will be electric field lines emitted from the conductor. There are equipotential lines perpendicular to the field lines due to each charge. The voltage at any point is the sum of the voltages at that point caused by each charge.

Current flow is a charge in motion, these moving charges cause electric field lines to form around a conductor in which current flows. Voltage is the difference in electric potential between one point and another. [3]

### **3.2.1 Air insulated conductors**

The simplest form of an insulated conductor is a metallic conductor surrounded by air, suspended from insulating supports carrying electric power. These are commonly used for high voltage applications.

The charge separation between the conductor and ground results in a phenomenon equivalent to a capacitor, and because there is some conduction a large resistance also exists.

Electric field lines leave the conductor surface in reasonably straight lines emanation from the centre of the conductor if the distance to ground is large enough. Electric field lines bend to ultimately terminate at ground.

Air is not a particularly good insulating material since its breakdown strength is lower than most insulating materials. It is however cost-effective and if space is not a constraint it is widely used.

If the voltage between the conductor and ground is increased, a point is reached where the electric stress at the conductor exceeds the voltage breakdown strength of air. The air around the conductor then breaks down forming ionized conducting air. This phenomenon is called corona and it represents power loss. It can also cause interference to other electromagnetic signals such as radio. It is not uncommon for this to appear at insulated spots and a rough burr appears on the conductor or at a connector. This happens because the electric stress is locally increased by the sharpness of the irregularity or protrusion from the conductor. The ionized air around the conductor increases the diameter of the conductor to the point where the air beyond the ionized boundary is no longer stressed to break down at the prevailing temperature, pressure, and humidity.

It is possible for the stress level to become so high that an ionized channel can breach the entire gap between conductor and ground. However, this generally requires a very high voltage source such as a lightning strike.

The ability of a dielectric to not break down under voltage stress is thickness dependent. However, the breakdown strength does not increase proportionally to the thickness of the insulation. [3]

### **3.2.2 Rising voltage**

When a metallic conductor is brought close to or touches the covering, the electric field lines must bend more sharply to terminate at the right angles to the ground plane. Recognizing that equipotential lines are perpendicular to the field lines, the bending results in potential differences on the covering surface. As voltage increases a point where the potential gradients are sufficient to make current flow across the surface of the covering is reached. This phenomenon is known as tracking. Even though the currents are small, the high surface resistance causes heating, which ultimately damages the covering. If this is allowed to continue the erosion may progress to significant covering damage and if the cable is in contact with ground, this results in failure. [3]

### 3.2.3 Conductor sizes

Conductor sizes vary between a cross-sectional area of  $35 \text{ mm}^2$  being the smallest conductor used at 20 kV to  $2000 \text{ mm}^2$  being the largest standardized conductor size in use at any voltage level. Depending on the type of conductor different ranges are specified. The larger the conductor the lower the resistance, which means it can carry more current. [8] In discussions with engineers at Hitachi Energy, it was stated that conductor sizes required for a regular substation project are growing. The sizes in question are so large that three-core cables are rarely used because the cables would be too bulky.

### 3.2.4 Material considerations

There are several low resistivity materials that may be considered as conductors for power cables. Considering the resistivity values and the cost of each material, copper, and aluminium become the logical choices. These are the dominating materials used in power cables today.

Copper is the predominant material for segmental sectorial formats, stranded conductors, shaped conductors, and Milliken formats. Aluminium is also specified based on the cost in the country of manufacturing at the time of tender. Aluminium also has the benefit that its density is lower than copper which makes it lighter which assists with the ease of handling large cables. Additional care needs to be taken when jointing aluminium cables to ensure that the contact surfaces are free from oxide and to ensure that no corrosion is formed when connecting the aluminium conductor to copper or brass terminals. [6]

When choosing between copper and aluminium one should carefully compare the properties of each material as both have advantages that may outweigh the use of the other under certain conditions. The most important properties are described under the following headlines:

### 3.2.5 Direct current resistance

The conductivity of aluminium is only 61,2 - 62% of that of copper. Because of this, the cross-sectional area of an aluminium conductor needs to be 1,6 times larger than that of

copper conductors to carry the same amount of electrical power. This same concept also applies to ampacity.

### **3.2.6 Weight**

Aluminium's perhaps most significant advantage other than economics is low density. A unit length of aluminium wire only weighs 48% as much as a copper wire of the same length with an equivalent DC resistance. However, some of the weight advantage is lost when the conductor is insulated, because more insulation is required to cover the greater circumference of the aluminium conductor. [7]

### **3.2.7 Voltage regulation**

The lower the resistance the lower the voltage drop. The effect of resistance is particularly important in AC circuits.

### **3.2.8 Short circuit operation**

Copper conductors have better capabilities in short circuit operation. However, when making this comparison the materials in contact with the conductor must be considered. (sheaths, insulations, coverings, jackets, etc.).

### **3.2.9 Other factors**

Aluminium is not used extensively in substation cables because the lower bending life of small strands of aluminium does not always meet the mechanical requirements of those cables. The 8000 series aluminium alloys have found good acceptance in several applications. [7]

## **3.3 Insulation**

A voltage divider is created from the impedance from the conductor to the outside covering surface and from the impedance between the covering surface and ground. The

distribution of voltage from the conductor to the covering surface and from the covering surface to the ground will be in proportion to these impedances. Note that when the conductor is far from ground most of the voltage exists from the covering surface to the ground.

The amount of current that can flow from an intact covering in the event of contact with a grounded object is limited by the thickness, permittivity, the surface impedance of the covering, and the area of contact. If the covering is made of excellent insulation, then most of the current will be due to capacitive charging current, which can be released from the covering surface by the contacting object.

When the current available at the covering surface is so low that it's imperceptible the covering is considered insulation and is suitable for continuous contact with a grounded surface. (As long as the surface does not result in chemical or thermal degradation).

### **3.3.1 Dielectric strength**

Dielectric strength is usually specified as the average stress at dielectric breakdown. The dielectric strength of a material depends upon the testing conditions and the dimensions of the material. [9]

### **3.3.1 Insulation materials**

#### **3.3.1.1 XLPE Insulation / PEX insulation**

Crosslinked polyethylene is a thermosetting material that is achieved by a process that relates to the vulcanisation of rubber. The material has many advantages such as high dielectric strength, a non-hydroscopic nature, good mechanical strength, and thermal stability over a wide temperature range. XLPE allows for high current carrying capacity, short circuit, and overload performance.

Partial discharge values are extremely important for XLPE cables to be reliable and have a long service life. Improvements in the manufacturing process have made it possible to reduce XLPE insulation thickness so that the stress levels could be increased. Despite this

improvement, XLPE cables have greater insulation thickness than their equivalent paper insulated cables which make for a larger overall diameter.

XLPE cables for voltages up to 36 kV are generally manufactured with tree retardant material and do not require a shield. It is recommended that cables with stress levels above 6,5 MV/m are protected by a metal sheath. [6]

XLPE cables have a low power factor,  $\tan\delta$  of 0,001 at the nominal system voltage to earth. The permittivity,  $\epsilon$  of PEX is 2,5 and its thermal resistivity is 3,5 Km/W. [10]. The capacitance in the cable affects the protection settings and the voltage regulation. The “star-capacitance” can usually be found on the manufacturer’s datasheets for three-core screened cables operating at 6,6 kV and above. That is the capacitance between the conductor and screen. Unscreened cables are only commonly used at voltages below 6,6 kV. [6]

PEX is used as an insulation material in power cables ranging from 1kV to 420 kV. By cross-linking polyethylene the temperature sensitivity is reduced and the temperature for continuous operation is increased from 70°C to 90°C. After the crosslinking, polyethylene does not melt and remains elastic at high temperatures up to 300 °C where the polymer chain will begin breaking down and the material char. PEX is also highly resistant to chemicals. [11]

### 3.3.1.2 Insulation thickness

The thickness of the PEX/XLPE – insulation varies depending on voltage level and conductor sizes.

Thickness of insulation (mm) at different voltage levels ( $U_0/U (U_m)$ )

<b>Conductor Size, mm<sup>2</sup></b>	<b>12/20 (24) kV</b>	<b>18/30 (36) kV</b>	<b>36/60 (72,5) kV</b>	<b>64/110 (123 kV)</b>	<b>127/220 (245) kV</b>	<b>220/400 (420) kV</b>
<b>35</b>	5,5	-	-	-	-	-
<b>50 – 150</b>	5,5	8,0	-	-	-	-
<b>150 – 185</b>	5,5	8,0	12	-	-	-
<b>300</b>	5,5	8,0	12	15	-	-
<b>400</b>	5,5	8,0	12	15	-	-
<b>500</b>	5,5	8,0	12	15	23	-
<b>800</b>	5,5	8,0	12	15	22	35
<b>1200</b>	5,5	8,0	12	15	22	32
<b>1600</b>	5,5	8,0	12	15	22	29
<b>2000</b>	-	-	12	15	22	29
<b>2500</b>	-	-	12	15	22	29

Table 1: Insulation thickness for different conductor sizes and voltage levels

Where,

$U_0$ = Rated voltage of cables an accessories (phase to ground)

$U$  = nominal system voltage (phase to phase)

$U_m$ = Highest voltage for equipment [12] [13] [14]

### 3.3.2 Insulating layer requirements

- 1) It is important that both the insulation and the insulation shield interfaces are contamination free at medium voltages. Contamination at the interfaces causes stress enhancement that increases the probability of breakdown.
- 2) Voids are to be avoided as they can do the same as contamination with the additional possibility of capacitive resistive (CR) discharges in the gas-filled void as voltage gradients appear across the void. These discharges can damage the surrounding insulating material and lead to progressive deterioration and breakdown.

### 3.4 Insulation screen or sheath/shield

Imagine that the ground plane was wrapped around the conductor with the same thickness of air separating the two barring irregularities at the conductor or ground. The electric field lines would be straight lines taking the shortest path from conductor to ground and the equipotential lines would be concentric cylinders around the conductor. This would form a cylindrical capacitor and make the most effective use of the dielectric.

To make ground contact possible a semiconductive or resistive layer is placed over the insulation surface. This material forces the electrical field lines to bend in the semiconducting layer. However, this doesn't come without complications.

Shields are used to bend the electrical field lines in order to make the most use of the dielectric.

A great deal of charge can be contained in the capacitor involving ground because the other layer is semiconducting allowing for greater charge mobility in this layer. This charging current must be controlled so that a path to ground is not established along the surface of the semiconducting layer. A path like that can lead to burning and ultimately failure of the layer.

Accidental human contact would be a serious event, therefore is it necessary to provide continuous contact with earth. This provides an adequate conducting path to drain the

capacitive charging current without damaging the cable. This is done by adding a metallic path in contact with the semiconducting shield and making a relatively low resistance connection with the ground. However, the metallic members have a significant impact in cases of underground fault conditions. Therefore, adequate conductive capacity or other means to handle fault currents must be added to the shield. This is a critical factor in cable design.

### **3.4.1 Conductor shield is needed**

The presence of an insulation shield creates another problem. The grounded insulation shield results in the entire voltage stress being placed across the insulation. There is concern about exceeding the maximum stress that the insulating layer can withstand. The problem is magnified by stranded conductors or burrs and scratches that may be present in both stranded and solid conductors.

A semiconducting layer can also be added over the conductor to smooth out irregularities. This reduces the probability of protrusions into the insulating layer. Protrusions into the insulating or semiconducting layer increase the localized stress. This stress may exceed the long-term breakdown strength of the insulation. This is particularly critical in extruded dielectric insulations. Any damage will be progressive and may lead to a total breakdown of the insulating layer. [3]

### **3.4.1 Sheaths**

Nowadays very little lead sheeting is specified except for special high voltage cables. The lead and lead alloy sheaths were traditionally used to prevent the ingress of moisture. Lead corrosion and fatigue resistance are important, and improvements were made by the addition of other elements creating lead alloys. Aluminium alloy sheaths are nowadays used as a cheaper and more popular alternative to lead-based sheaths. The composition of elements is important in reducing the possibility of corrosion during service. Corrugated aluminium sheath constructions help improve the overall cable flexibility.

Foil laminate sheaths are becoming increasingly popular for XLPE cables above 60 kV, as they offer a cheaper alternative to the expensive metal extrusion processes required for aluminium- and lead alloy sheaths. The disadvantage of foil is a decrease in robustness. [6]

### **3.4.2 Insulation levels and screening**

The selection of correct cable voltage designation is dependent upon the system and the type of network earthing arrangements. Generally, if the network is solidly grounded the voltage will not rise above the maximum phase to neutral voltage of the system during fault conditions. However, if the network earthing is such that it allows the voltage to rise above the level of the line voltage, then the cable insulation must be specified accordingly.

A grading shield is used to minimize the possibilities of discharges at the inner surfaces of the cable core dielectric. This screen is comprised of one or two layers of semiconducting tapes of compounds over the core insulation. These measures are applied at 3300/6000 V for XLPE insulated cables. [6]

### **3.4.3 Shielding layer requirements**

Requirements are placed on the shield layer in order to reduce stress enhancement.

- 1) Protrusions must be minimized as they defeat the very purpose of a shield by enhancing electrical stress.
- 2) Shields should be easily removable to facilitate splicing and terminating. This is important at medium voltage (5-35 kV) but at high voltages, the inconveniences of a bonded insulation shield can be tolerated to achieve smooth, void-free insulation.

## **3.5 Armouring**

Armouring is applied to protect cables from external mechanical damage such as pick blows or vibrations. For three-core cables galvanised steel wire armouring is preferred since it gives a more flexible construction, gives better stress performance, and is easy to gland. However, for single-core cables, aluminium armouring is used in order to avoid losses.

### **3.6 Jackets / Servings**

Jackets are commonly used to protect the underlying layers from physical abuse, sunlight, flame, or chemical attack, including corrosion of underlying metallic layers for shielding and armouring. Special emphasis is put on the last statement for high and medium voltage cables. The ability of jackets to protect the underlying layers from ingress of moisture makes them an important part of cable design. [3]

### **3.7 Finish**

One of the most important factors that affect cable life is the degree of protection against chemical corrosion, electrolytic action, insect or rodent attacks, and mechanical damage. MDPE and LSF outer sheaths that may be impregnated with chemicals to deter insects are used for this purpose. The integrity of the outer sheath can be tested after installation. A graphite outer coating may be specified to allow for an electrical connection to the outside of the sheath. [6]

### **3.8 Terminology**

Non-shielded cable: A cable cannot be considered fully shielded unless both conductor and insulating layers have shields present. Non shielded cables are not used at high and medium voltage levels. [3]

## 4 Cable installation practices

This chapter covers the common practices that are applied when high- and medium voltage cables are installed.

### 4.1 Cable Sizing

After correct voltage classification of the cable the following considerations apply:

- Current carrying capacity (ampacity)
- Short circuit rating
- Earth loop impedance
- Voltage drop
- Loss evaluation

Important research around cable ampacity has been done by the Electrical Research Association (ERA) in the United Kingdom. For voltage levels, 36 kV and above calculations are undertaken in accordance with IEC60287. This standard provides detailed calculations and algorithms for the calculation of current ratings. The calculations take into account details such as cable design, ambient temperature, installation conditions, type of sheathing bonding, phase spacing and arrangement, and proximity to other cables. [6]

### 4.2 Trefoil and flat formation

In three-phase circuits, the cables can be placed in different formations. Typical formations are trefoil and flat formations. The choice between these two depends upon several factors, such as conductor area, space for installation, and the screen bonding method. [15]



Figure 2 Illustration of formations [15]

The trefoil formation is electrically the superior choice as it places the phases at the same distance apart. This means that the magnetic fields and circulating currents are equivalent for each cable in the three-phase configuration. This formation is easily installed and does not require much space. However, the touching cables in trefoil formation will result in worse heat dissipation lowering the current carrying capacity compared to flat formation. A flat formation requires a lot more space and puts a lot of stress on the centre cable being affected by the magnetic fields of the two other cables. Phase transposition can be used to counteract this problem. [16]

### 4.3 Cables laid in air

Current ratings for cables laid in air are usually based upon the ambient temperature of air, which is 25 °C in Europe and 40°C in Japan. Separate manufacturers' tables state the parameters that need to be applied in order to obtain the current ratings for particular site conditions.

Derating factors are used to adjust the current rating to higher ambient temperatures. For instance, if a 36 kV, three-core, 300 mm<sup>2</sup>, Cu conductor cable is to be laid in ambient air temperature of 35°C and the rating on the manufacturer's table is 630 A at 25 °C and the derating factor for 35 °C is given as 0,9, then the current rating in this application will be  $0,9 * 630 A = 567 A$ .

In case the cables are laid in a concrete trench the ambient air temperature in the trench is higher than that on the outside. In addition to this, the proximity to cables laid in the same trench will affect the ampacity of the cable. All derating factors are included in the manufacturer's literature.

Cables laid in direct outdoors should be protected from sunlight using appropriate sun shields. Metallic shields should not fully surround single-core cables due to their effects as a closed loop magnetic circuit to stray induced currents from the conductor.

#### 4.4 Cables laid in direct ground

Ampacity tables are generally based upon the thermal aspects of environmental data that follows:

Ground thermal resistivity,  $G = 1,0 \text{ Km/W}$  (Japan and Scandinavia)  $1,2 \text{ Km/W}$  (UK).

More accurate data can be collected from the site of a particular application. Values typically range between  $0,8$  to  $2,5 \text{ Km/W}$ . Derating factors in reference to the  $1,0 \text{ Km/W}$  standard value may be obtained from ERA report 69 – 30. A  $G$  value of  $2,5 \text{ °C m/W}$  would result in a derating factor of about 75 %.

Ground temperature  $t = 25 \text{ °C}$  (Japan),  $t = 15 \text{ °C}$  (Scandinavia)

Ground temperature variations from the standard are taken into account by derating factors with values deviating from the reference value by approximately 1% per °C.

Cable laying depth,  $d$  is typically 1 m. Depths vary according to the voltage level and the regulations in the concerned territory.

When cables are laid together in the same trench the proximity will make it necessary for derating factors to be used when determining the ampacity. In some cases, the use of special backfill can improve the ampacity by improving heat transfer.

Example:

Two three-phase circuits composed of single-core conductor,  $500 \text{ mm}^2$ , XLPE insulated, Al conductor cables are each laid in ground, in a trefoil formation in parallel at a nominal depth of  $0,7 \text{ m}$  and  $0,25 \text{ m}$  apart with their  $35 \text{ mm}$  copper screens bonded together at both ends. The  $90 \text{ °C}$  XLPE rating is  $655 \text{ A}$ . What is the rating of each circuit in this configuration?

$d = 0,7 \text{ m} \rightarrow$  derating factor =  $1,0$

$G = 1,5 \text{ °C m/W} \rightarrow$  derating factor,  $f_1 = 0,91$

$T = 25 \text{ °C} \rightarrow$  derating factor,  $f_2 = 0,93$

Proximity of parallel circuit (grouping) =  $0,25 \rightarrow$  derating factor,  $f_3 = 0,86$

$$I = I_o * f1 * f2 * f3 = 655 A * 0,93 * 0,91 * 0,86 = 477 A$$

It is important to follow agreed standards when installing cables and to maintain accurate records of their locations.

#### **4.5 Cables installed in ducts**

Cables can be installed in ducts with earth, sand, or concrete surround. The ducts are then buried in ground. It is good practise to install only one cable per duct and the diameter of the duct should be at least 35 mm wider than the diameter of the cable. Cable ratings for cables installed in ducts correspond to 80% of the direct burial in ground rating. To improve the thermal conditions from the cable to the surrounding ground and thus improve the derating factor, the ducts may be filled with a bentonite slurry after the cable pulling. Bentonite is a form of clay, that contains minerals that are formed from the breakdown of volcanic ash and has the characteristics of swelling when mixed with water. Bentonite also has a malleable nature that helps with sealing around cables at the duct ends. Filling the ducts has the added benefit of preventing thermomechanical movement, which can have damaging effects on the cable sheaths and joints.

#### **4.6 Joints and Terminations**

Key factors in the design of cable joints and terminations are as follows:

- Safe separation between phases and between phase and earth.
- Capacity to avoid electric breakdown at the interface under normal operating conditions and impulse surges.
- Adequate stress control measures to avoid high electromagnetic fields screen discontinuities and interfaces.

Great care needs to be taken to ensure dry and clean jointing conditions on-site. Soldered connections are not compatible with the 250 °C short circuit temperature rating of PEX-insulated cables, this also requires a trained professional jointer to avoid high resistance connections. Therefore, soldered connections are avoided. Instead, mechanical clamps can

be used to connect cable cores together. Metal inert gas welding is the preferred method for aluminium conductor cables. Usually, cable conductor connections are achieved using compression lugs and ferrules.

## **4.7 Earthing and bonding**

The conductor and sheath work like a transformer and causes induction of stray voltages. To prevent these stray voltages from being induced into uninsulated or lightly insulated metals in the event of a phase to earth fault the sheaths and armouring are bonded together and earthed at the terminations. A mechanically strong and sound connection is essential.

When cable sheaths are bonded together, the induced voltages are short-circuited. However, a current will flow in the closed loop and give rise to heat losses. Whether cables are bonded together or not there will be a circulating eddy current in the sheath due to the asymmetric flux distribution.

To summarize there are two types of heat losses occurring in the sheath:

- Sheath circuit loss (bonded sheaths only)
- Sheath eddy loss (usually small compared to the former) [6]

The metallic sheath currents can be reduced through different methods of bonding, this way the ampacity of the cable circuit can be increased. [15]

### **4.7.1 Three-core cables**

These cables are usually bonded so that the cable screen, sheath, and armour are connected to a grounding point at both ends. Each joint along the cable route is also bonded to earth. [6]

When a system is bonded at both ends it provides a path for circulating currents under normal conditions. This will cause losses at the screen, which reduces the ampacity of the system. These losses are smaller when cables are placed in a trefoil formation. [15]

Three-core cables carry all three phases so during normal operation the magnetic fields of each phase cancel out and no current is induced in the shields.

#### **4.7.2 Single-core cables**

These cables require special attention to be paid due to the voltages being induced in the metal sheath, these are proportional to the current and frequency in the conductor, and the induction of circulating sheath currents. They can be solidly bonded, which means that they are bonded at both ends, this is common practise up to 36 kV with trefoil configurations. When conductor sizes get larger, and the voltages get higher specially bonded systems will be more economic.

Single point bonding is used over short lengths (< 500m) to keep induced voltages between the screen-free ends within allowable limits. The sheath or screen insulated from ground at one end is often fitted with sheath voltage limiters. This method is sometimes referred to as endpoint earthing. This method provides no path for the currents to flow in the sheath.

Mid-point earthing is sometimes applied on routes that are too long for end-point earthing. The maximum route length for this to be effective is about 1 km. The cable is earthed at a joint in the middle of the cable route and fitted with voltage limiters at the terminations. Both single-point and mid-point earthed cables should be fitted with a separate earth continuity conductor for fault currents that would normally be carried by the sheath.

A method called cross-bonding or cyclic transposition is sometimes applied to reduce the effects of induced voltages. For cross bounding, the cable route is split into groups of three drum lengths and joints are fitted with insulating flanges. The cables that are laid in a flat formation are usually transposed at each joint position. The sheaths are connected and earthed at every third joint position. At the other joints, the sheaths occupying the same position in the trench are connected in series and to earth via sheath voltage limiters. [6]

## 5 Heat losses in electrical power cables

This chapter covers the physics behind heat development in power cables.

### 5.1 Heat development in conductors

In electrical conductors such as cables there is an electrical resistance,  $R$  that causes an active power development  $R * I^2$  that will only heat up the conductor. This is called active power loss,  $p_f$  that in symmetrical three phase systems can be calculated as follows:

$$p_f = 3 * R * I, R = R_e * I^2 \text{ or } p_f = R * \left(\frac{S}{U}\right)^2$$

Where:

$R$  = resistance per phase,  $I$  = Current per phase,  $S$  = apparent power in the system,  $U$  = Voltage level phase to phase.

The heat that is formed in a conductor at load current is partially stored while the rest is emitted to its environment. Heat is dissipated through radiation, conduction, and convection. The proportion between these types of heat loss varies depending on the insulation and the placement of the cables. For heating the following relationships apply:

$$dW_g = dW_d + dW_s \text{ (During the time } dt\text{)}$$

$$dW_g = P_f * dt = \text{Amount of heat generated during the time } dt$$

$$dW_d = \lambda * Y * \Theta * dt = \text{Amount of dissipated heat during the time } dt$$

$$dW_s = m * C * d\Theta = \text{Stored heat during the time } dt$$

$$P_l = R * I^2 \text{ (W)} = \text{Loss effect}$$

Where,

$\lambda$  = the thermal conductivity number  $\left(\frac{W}{m^2}\right)$  for the area of the conductor

$Y$  = the conductors cooling area ( $m^2$ )

$m$  = the mass of the conductor (kg)

$C$  = The specific heat for the material in  $\frac{J}{kgK}$

$\Theta$  = the temperature of the conductor in K

$\vartheta_f$  = final temperature in K

$\vartheta_i$  = Initial temperature in K

The heat dissipation for a body is increased when the difference in temperature,  $\Theta$ , between the body and the ambient environment. In time there will be a state of equilibrium, where the heat generation is equal to the heat dissipation. ( $dW_g = dW_d$ ). The final temperature is then reached:

$$P_l * dt = \lambda * Y * (\vartheta_i - \vartheta_f) * dt, \text{ gives}$$

$$\vartheta_i - \vartheta_f = \frac{P_l}{\lambda * Y} = \Theta, \text{ Final overtemperature.}$$

Gives:

$$\Theta = \frac{P_l}{\lambda * Y} * \left(1 - e^{-\frac{t}{T}}\right) = \Theta_f * \left(1 - e^{-\frac{t}{T}}\right), \quad \text{Where,}$$

$$T = \frac{m * C}{\lambda * Y}, \text{ is the thermal time constant.}$$

This solution requires that the power losses  $P_l$  are constant. [17]

## 5.2 Insulated conductors

For insulated conductors, the conditions are a bit different as the insulation reduces the heat dissipation from the conductor. Additionally, there will be heating caused by dielectric losses for alternating current operation. [17] This is because the insulation acts as a capacitor that stores and releases energy during each AC cycle. Most capacitors lose some of that energy during each AC period. The ratio of dissipated energy to stored energy is known as the dissipation factor,  $\tan\delta$ . This factor can be used to measure the efficiency of the insulation. [18] The dielectric losses per volume unit can be determined:

$$P_d = 2 * \pi * \varepsilon * \varepsilon_0 * f * E^2 * \tan\delta$$

Where,

$E$  = the electrical field strength (V/m)

$\tan\delta$  = dissipation factor of the insulation.

$\varepsilon$  = the permittivity of the insulation

$\varepsilon_0$  = the permittivity of vacuum

Therefore, the maximum allowable load current for insulated conductors at a certain area is decreased as the voltage rises. This happens because the electric field strength increases, and the insulation volume gets thicker. [17]

## 6 Ampacity

Ampacity is a shorter term for current carrying capacity first conceived by William Del Mar in the early 1950s. The term was first published in 1962. The term is defined as the maximum amount of current a cable can carry under prevailing operation conditions without sustaining immediate or progressive deterioration. These conditions include environmental and time considerations.

Cables are a source of heat whether they are only energized or carrying load current. This heat causes a temperature rise in the cable which must be kept within allowable limits. These limits have been established through years of experience. The various components can endure some maximum temperature on a sustained basis.

There are several heat sources in a cable such as dielectric loss in the insulation, losses due to current flow in the conductor, current in the sheaths, shielding, and armour. Sources external to the cable include adjacent cables, induced current in a surrounding conduit, etc. The sources of heat result in a temperature rise in the cable that must flow outward through the layers, that have varying resistances to the flow of heat. These resistances include cable insulation, shields, sheaths, jackets, air, conduits, concrete, surrounding soil, and finally ambient air.

To avoid damage to the cables, the temperature rise must not exceed the maximum temperatures the cables can endure. It is the careful balancing of temperature rise to

acceptable levels and the ability to dissipate that heat that determines the ampacity of cables.

There are two current levels that must be considered when designing a cable system. The maximum current under normal operation and the maximum fault current. The maximum fault current is much higher but only needs to be endured for a shorter period of time.

## 6.1 Soil thermal resistivity

The thermal resistivity of soil,  $\rho$  is the least known aspect of the thermal circuit but a very significant one. The distance for the heat to travel in soil is much greater than the dimensions of the cable or the duct bank. Another aspect of soil that must be considered is its stability during the long-term heating process. Heat tends to force moisture out of soils increasing their thermal resistivity substantially compared to the soil in its native undisturbed environment. This means that measuring the thermal resistivity prior to the cable loading may result in an optimistically lower value of  $\rho$  than will be the case during operation.

Factors that affect the drying rate of soils include the type of soil, grain size and distribution, compaction, depth of burial, duration of heat flow, moisture availability, and the amount of heat being released.

## 6.2 Ampacity calculations

The fundamental theory of heat transfer in steady state situations is similar to ohms law where the flow varies directly as temperature and inversely as resistance. [5]

The permissible current rating can be derived from the expression for current rise above ambient temperature:

$$\Delta\theta = \left( I^2 R + \frac{1}{2} * W_d \right) * T_1 + [I^2 R(1 + \lambda_1) + W_d] * nT_2 + [I^2 R(1 + \lambda_1 + \lambda_2) + W_d] * n * (T_3 + T_4)$$

The permissible current rating is obtained from the above formula as follows:

$$I = \left[ \frac{\Delta\theta - W_d[0,5 * T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR * (1 + \lambda_1) * T_2 + nR(1 + \lambda_1 + \lambda_2)(T_3 + T_4)} \right] \quad (6.1)$$

$I$  = current flow (A) that can be carried

$\Delta\theta$  = temperature rise of the conductor above the ambient temperature (K)

$R$  = Alternating current resistance per unit length of the conductor at maximum operating temperature ( $\Omega/m$ )

$W_d$  = The dielectric loss per unit length for the insulation surrounding the conductor (W/m)

$T_1$  = the thermal resistance per unit length between the conductor and the sheath (K.m/W)

$T_2$  = the thermal resistance per unit length of the bedding between sheath and armour (K.m/W)

$T_3$  = the thermal resistance per unit length of the external serving of the cable (K.m/W)

$T_4$  = the thermal resistance per unit length between the surface of the cable and the surrounding medium (K.m/W)

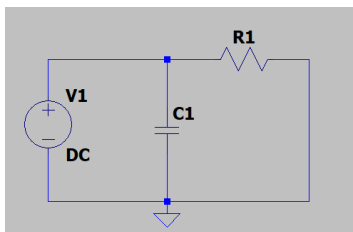
$n$  = the number of load-carrying conductors in the cable (conductors of equal size carrying the same load)

$\lambda_1$  = ratio of losses in the metal sheath to total losses in all conductors in the cable

$\lambda_2$  = the ratio of losses in the armouring to total losses in all conductors in the cable [10]

### 6.3 Heat transfer model

The cable materials store and conduct heat. Heat is generated when operation begins, this heat is stored in the components and conducted from regions of higher temperature to regions of lower temperature. A simplified thermal circuit for this is equivalent to an electrical RC - circuit.



Imagine there is a switch controlling the energy supply to the RC circuit. When time,  $t = 0$ , the switch is closed and essentially all of the energy is absorbed by the capacitor.

However, depending on the values of  $R$  and  $C$  as time progresses the capacitor will be fully charged, and all the current will flow through the resistor. Thus, for cables that are subject to large swings in load current for short periods of time, the thermal capacitance must be considered (AC). [5]

## 6.4 Load Factor

The ratio of average load to peak load is known as the load factor. This consideration is important as most loads on a utility system vary depending on external factors. The effect of cyclic load on ampacity depends on the amount of thermal capacitance involved. Cables in duct banks and cables directly buried in earth are surrounded by a substantial amount of thermal capacitance. The cable, surrounding ducts, concrete, and earth all take time to heat up (and cool down). Therefore, heat absorption takes place in those areas as the load increases. This permits a higher ampacity than if the load had been continuous. Naturally, cooling takes place during the dropping load portions of the load cycle.

The thermal lag is small for cables in air. The cables heat up relatively quickly, say 2 – 3 hours. For usual load cycles where the peak load exists for 2 hours or more, the load factor is generally not considered when determining ampacity. [5]

## 6.5 Loss Factor

The loss factor may be calculated from the following formula if the daily load factor is known:

$$LF = 0,3(lf) + 0,7(lf)^2$$

Where,

LF = Loss factor,

lf = daily load factor per unit

The loss factor becomes significant at a specified distance,  $D_x$  from the cable. This distance derived by Nehrer and McGrath is 211 mm. As the heat flows beyond this diameter, the effective soil thermal resistivity, rho, becomes lower hence the explanation of the loss factor in that area. [5]

## 6.6 Conductor losses

When an electric current is flowing through a material there is resistance to that flow. The measure of this inherent property of every material is known as resistivity. The reciprocal property of resistivity is conductivity. When selecting materials for electrical conductors it is desirable to use materials with as low resistivity as is consistent with the economics and mechanical properties of the material.

Copper and aluminium become the ideal choices for use in power cables. Regardless of the metal chosen, some resistance is always encountered. Therefore, it becomes necessary to determine the resistance of the conductor when calculating cable ampacity. Conductor losses are the most significant source of heat in a power cable. [5]

### 6.6.1 Direct current conductor resistance

The volume resistivity of annealed copper at 20 °C is:

$$\rho_{20} = 1,724 * 10^{-8} \Omega m$$

Aluminium:

$$\rho_{20} = 2,82 * 10^{-8} \Omega m$$

The conductivity of a conductor material is expressed as relative quantity, that is the percentage of a standard conductivity. IEC adopted a conductivity value known as the international annealed copper standard (IACS). The conductivity value for annealed copper is being 100% as it is used as reference. An aluminium conductor is typically 61,2 % as conductive as an annealed copper conductor. To adjust the values of conductor resistances at 20 °C to other temperatures the following formula applies:

$$R' = R_0[1 + \alpha_{20}(\theta - 20)] \quad (6.2)$$

Where,

$R'$  = DC resistance of conductor at maximum operating temperature

$R_0$  = The DC resistance of conductor at 20°C ( $\Omega/m$ )

$\theta$  = Maximum operating temperature of conductor in degrees Celsius.

$\alpha_{20}$  = The constant mass temperature coefficient at 20 °C per Kelvin

Temperature coefficients at 20 °C for copper and aluminium conductors can be found in table 1 in IEC60287-1-1.

## 6.6.2 Alternating current resistance of a conductor

The term AC conductor resistance is used to describe the DC resistance of that conductor plus an increment that reflects the increased apparent resistance caused by the skin effect inequality of current density.

The skin effect is a phenomenon that results in a decrease of current density towards the centre of the conductor. A longitudinal element of the conductor near the centre is surrounded by more magnetic field lines than an element near the rim. Therefore, the counter electromotive force (EMF) is greater in the centre of the conductor. The net driving EMF at the centre is reduced with a consequent reduction of current density. Methods for calculating this increase in resistance have been extensively treated in technical papers and bulletins. [5]

The AC resistance per unit length of the conductor at its maximum operating temperature is given by the following formula:

$$R = R'(1 + \gamma_s + \gamma_p) \quad (6.3)$$

Where,

$R$  = The current resistance of the conductor at maximum temperature ( $\Omega/m$ )

$R'$  = the DC resistance of the conductor at maximum temperature ( $\Omega/m$ )

$\gamma_s$  = the skin effect factor

$\gamma_p$  = the proximity effect factor

### 6.6.2.1 Skin effect factor

Skin effect is a phenomenon present in AC circuits, where the current tends to distribute itself near the conductor surface. This causes the current density at the surface of a conductor to be greater than in its core. A longitudinal element near the center of the

conductor axis is surrounded by more magnetic field lines than a conductor element at the rim. This causes an increase in inductance towards the center. The decreased conductivity results in an apparent increase in resistance. [7]

The skin effect factor  $\gamma_s$  is given by:

$$\text{For } 0 < x_s \leq 2,8 \quad \gamma_s = \frac{x_s^4}{192+0,8*x_s^4}$$

$$\text{For } 2,8 < x_s \leq 3,8 \quad \gamma_s = -0,136 - 0,017 * 7x_s + 0,056 * 3x_s^2 \quad (6.4)$$

$$\text{For } x_s > 3,8 \quad \gamma_s = 0,354 * x_s - 0,733$$

Where,

$$x_s = \frac{8\pi f}{R'} * 10^{-7} * k_s$$

f = supply frequency in hertz

Values for  $k_s$  are given in table 2 in IEC60287-1-1 [10]

Type of conductor	Type of Insulation system	$k_s$	$k_p$
Round, solid (Cu, Al)	All	1	1
Round, stranded (Al)	All	1	0,8
Round, stranded (Cu)	Extruded/mineral	1	1
Round Milliken (Al)	All	0,25	0,15
Round Milliken, insulated wires	Extruded	0,35	0,20
Round Milliken, bare uni-directional wires	Extruded	0,62	0,37
Round Milliken, bare bi-directional wires	Extruded	0,80	0,37

Table 2: Compacted version of IEC60287-1-1 table 2, only displaying the cables within the scope of this thesis. [10]

The amplitude of the skin effect factor depends on the system frequency, the voltage level, and the size and build of the conductor. [7]

## 6.7 Proximity effect

The linking of a conductor due to nearby current flow distorts the cross-sectional current flow in the conductor in the same way as the flux in the conductor itself. This phenomenon is called the proximity effect and is rarely separable from the skin effect. However, the combined effects are not directly cumulative. If the distance between conductors exceeds, 10 times the diameter of the conductors the extra  $I^2R$  loss is negligible. [5]

### 6.7.1 Proximity effect factor $Y_p$ for three-core cables and for three single-core cables

Circular conductor cables

The proximity effect factor is given by:

$$Y_p = \frac{x_p^4}{192+0,8*x_p^4} * \left(\frac{d_c}{s}\right)^2 * \left[ 0,312 \left(\frac{d_c}{s}\right)^2 + \frac{1,18}{\frac{x_p^4}{192+0,8*x_p^4}+0,27} \right] \quad (6.5)$$

Where,

$$x_p^2 = \frac{8\pi f}{R'} * 10^{-7} * k_p$$

$d_c$  = the diameter of the conductor (mm)

$s$  = the distance between conductor axes (mm)

Note: For cables in a flat formation,  $s$  is the spacing between adjacent phases. Where the spacing between adjacent phases is not equal;  $s = \sqrt{s_1 * s_2}$

Values for  $k_p$  can be found in table 2

The formula above is accurate given that  $x_p$  does not exceed 2.8, which applies to the majority of practical cases.

The spacing,  $s$  between the cables as can be seen from equation 5.5 have a significant effect on the proximity effect. The closer the cables are the more it's going to impact the AC resistance. The greater the spacing the less significant the proximity effect becomes. [10]

## 6.8 Hysteresis and eddy current effects

Hysteresis and eddy current losses in conductors and the adjacent metallic components of a cable add to the alternating current resistance. In order to supply these losses more power is drawn from the cable. These losses can be very significant in large ampacity conductors when a magnetic material is closely adjacent to the conductors. Currents greater than 200 A are considered large for these effects. [5]

According to IEC60287, these losses can be ignored for all other conductors except for Milliken-type conductors. [10] Milliken conductors are designed to keep the skin effect that usually occurs in large conductors ( $1200 \text{ mm}^2$  and above) within tolerable limits. This has the added benefit of reducing the proximity effect. The conductor is divided into several sector-shaped segments that are separated with insulating- or semiconducting tapes. [19]

### 6.8.1 Effect of Milliken conductors

Large Milliken conductors of insulated segmental design are subjected to a reduced proximity effect. Thus, the sheath loss factor  $\lambda_1''$  (eddy current loss) cannot be ignored. It is obtained by multiplying the value of  $\lambda_1''$  given in the section below by the factor  $F$  calculated from the following formula:

$$F = \frac{4 * M^2 * N^2 + (M + N)^2}{4 * (M^2 + 1)(N^2 + 1)} \quad (6.6)$$

Where,

$$M = N = \frac{R_s}{X} \text{ (Cables in trefoil formation)}$$

And

$$M = \frac{R_s}{X + X_m}$$

$$N = \frac{R_s}{X - \frac{X_m}{3}} \quad (\text{Cables in flat formation with equidistant spacing})$$

## 6.8.2 Single-core cables, with bonded sheaths at a single point or cross-bonded

### Eddy current losses

$$\lambda_1'' = \frac{R_s}{R} * \left[ g_s * \lambda_0 * (1 + \Delta_1 + \Delta_2) + \frac{(\beta_1 * t_s)^4}{12 * 10^{12}} \right] \quad (6.7)$$

Where,

$$g_s = 1 + \left( \frac{t_s}{D_s} \right)^{1,74} * (\beta_1 * D_s * 10^{-3} - 1,6)$$

$$\beta_1 = \sqrt{\frac{4\pi\omega}{10^7 * \rho_s}}$$

$\rho_s$  = the electrical resistivity of the sheath material at operating temperature (see table 1)  
( $\Omega\text{m}$ )

$D_s$  = The external diameter of the sheath (mm)

For corrugated sheaths the mean outside diameter is used:  $\frac{D_{oc} + D_{it}}{2} + t_s$

$t_s$  = the thickness of the sheath (mm):

$$\omega = 2\pi f$$

For lead sheathed cables,  $g_s$  can be taken as unity and  $\frac{(\beta_1 t_s)^4}{12 * 10^{12}}$  can be neglected.

For aluminium sheathed cables, both terms need to be evaluated when the sheath diameter is greater than 70 mm or the sheath is thicker than usual.

For cables with a wire screen and an equalizing tape, or foil screen over the wires, the eddy current losses are considered negligible.

Formulae for  $\lambda_0$ ,  $\Delta_1$  and  $\Delta_2$  follow:

$m = \frac{\omega}{R_s} * 10^{-7}$ , for,  $m \leq 0,1$ ,  $\Delta_1$  and  $\Delta_2$  can be neglected

Three single-core cables in trefoil formation

$$\lambda_0 = 3 \left( \frac{m^2}{1 + m^2} \right) \left( \frac{d}{2s} \right)^2$$

$$\Delta_1 = (1,14 * m^{2,45} + 0,33) \left( \frac{d}{2s} \right)^{(0,92*m+1,66)}$$

$$\Delta_2 = 0$$

Three single-core cables, flat formation

Centre cable

$$\lambda_0 = 6 \left( \frac{m^2}{1 + m^2} \right) \left( \frac{d}{2s} \right)^2$$

$$\Delta_1 = 0,86 * m^{3,08} \left( \frac{d}{2s} \right)^{(1,4*m+0,7)}$$

$$\Delta_2 = 0$$

Outer cable leading phase

$$\lambda_0 = 1,5 \left( \frac{m^2}{1 + m^2} \right) \left( \frac{d}{2s} \right)^2$$

$$\Delta_1 = 4,7 * m^{0,7} * \left( \frac{d}{2s} \right)^{(0,16*m+2)}$$

$$\Delta_2 = 21 * m^{3,3} \left( \frac{d}{2s} \right)^{(1,47*m+5,06)}$$

Outer cable lagging phase

$$\lambda_0 = 1,5 \left( \frac{m^2}{1 + m^2} \right) \left( \frac{d}{2s} \right)^2$$

$$\Delta_1 = - \frac{0,74 (m + 2) M^{0,5}}{2 + (m - 0,3)^2} * \left( \frac{d}{2s} \right)^{(m+1)}$$

$$\Delta_2 = 0,92 * m^{3,7} \left( \frac{d}{2s} \right)^{(m+2)} \quad [10]$$

## 6.9 Dielectric losses and calculations

Cables with the same insulation material, diameter, and similar construction from different manufacturers are going to have similar small dielectric losses which may be considered in the tender adjudication stage. The larger the diameter of the conductor the greater the dielectric loss for a given dielectric. XLPE cables have a lower dielectric loss compared to oil-filled paper insulated cables. Example losses for XLPE cable 240 – 800 mm<sup>2</sup>: 0,7 – 1,2 W/m<sup>2</sup>. [6]

Dielectric loss may have a significant effect on ampacity. The following formula applies for shielded single conductor cables, and multiconductor cables with shields over the individual conductors: [5]

$$W_d = \omega * C * U_0^2 * \tan \delta \quad \left( \frac{W}{m} \right) \quad (6.8)$$

Where,

$$\omega = 2\pi f$$

C = Capacitance per unit length (F/m)

$U_0$  = the voltage to earth (V)

Values of the loss factor  $\tan \delta$  of the insulation at power frequency and operating temperature are given in table 3.

The Capacitance for circular conductors is calculated:

$$C = \frac{\epsilon}{18 * \ln\left(\frac{D_i}{d_c}\right)} * 10^{-9} \quad \left(\frac{F}{m}\right)$$

Where,

$\epsilon$  = the relative permittivity of the insulation

$D_i$ = the external diameter of the insulation (excluding screen) (mm)

$d_c$ = the diameter of the conductor, including screen (mm) [10]

Type of Insulation	$\epsilon$	$\tan \delta^*$
XLPE up to 36 kV (unfilled)	2,5	0,004
XLPE greater than 36 kV (unfilled)	2,5	0,001
XLPE greater than 36 kV (filled)	3	0,005

Table 3: Permittivity values and loss factor values for XLPE insulation. [10]

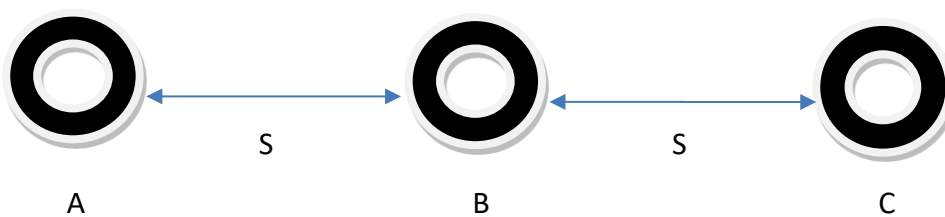
## 6.10 Metallic shield losses

There is a magnetic field associated with current flow in a conductor. When the current varies in magnitude with time as it does with 50 hertz AC, the field expands and contracts every AC period. If there is another conductor within the magnetic field of the AC conductor, a voltage will be induced into that conductor. If that conductor happens to be a part of a closed circuit, the induced voltage will result in a current flow in that conductor. This is a situation that occurs during the operation of conductors with metallic shields. The current flow in the phase conductors induces a voltage in the metallic shields of all power cables within reach of the magnetic field. If the shield has two or more grounded points or otherwise completes a circuit, current will flow in the metallic shield conductor.

These currents flowing in the metallic shields cause losses that appear as heat. The magnitude of these losses depends on the magnitude of the current caused by the induced voltage, and the resistance of the shield. These are called shield losses and in addition to

an economic loss, they also have a negative effect on ampacity and the voltage drop. The heat that is generated in the shield must be dissipated along with the phase conductor losses and dielectric losses. The amount of heat that can be dissipated for a given set of thermal conditions is fixed. The heat generated by the shield losses will thus reduce the amount of heat that can be assigned to the phase conductor. This means that the permissible phase conductor current is reduced.

In multiphase systems, the voltage induced in any shield is the result of the vectorial calculations of the fluxes linking the shield. The net current in a balanced three-phase system equals zero when all wires are equidistant to each other. When the distance between all the phase conductors,  $S$  is the same the net voltage is zero. However, this is usually not the case. In practical applications, there is always some net magnetic flux that will induce voltage into the shields. In a three-phase single conductor system of shielded cables, the cancellation of flux from other phases is reduced as the spacing,  $S$  is reduced. The shield of each cable then approaches the total flux linkage created by that cable.



Take phase A as an example: as the spacing,  $S$  between phases increases, so does the effects of phases B and C on phase A, and the metallic shield losses will almost only depend on the magnetic flux in phase A.

There are two general ways that shield losses can be minimized:

- Single point grounding (open circuit shield)
- Reduction of the amount of metal in the shield

The open circuit shield presents another problem. Voltage continues to be inducted into the shield and hence the voltage increases from zero at the grounding point to a maximum at the end furthest from the grounding point. The magnitude of this voltage is dependent on the magnitude of the current in the phase conductor. How much voltage can be tolerated depends on jacket design and safety considerations.

The other approach is to reduce the amount of metal used in the shield. The circuit acts as a one-to-one transformer, which means that an increase in the resistance in the shield will lead to a reduction in the amount of current that will be generated in the shield. The ampacity of power cables can be increased significantly this way.

To take shield losses into account when calculating ampacity, one must multiply all thermal resistances beyond the shield with one plus the ratio of shield loss to the conductor loss. The incremental thermal resistance reflects the effects of shield losses.

The calculation of shield losses in other configurations is complex, but very important. A method for closely approximating the voltages for single conductor cables in several common configurations was developed by Halperin and Miller. [5]

### 6.10.1 Screen or sheath losses

Sheath or screen losses are proportional to the current carried by the conductor. These losses are approximately the same for standard cables of the same size and type. If cables are to be installed on systems with high earth fault levels, the sheath will have to be increased so that it can withstand those levels. Future expansions that may lead to an increase in fault current during the lifetime of the cable installation should also be considered. Losses may be reduced by employing single-point bonding on short cable routes. For 3 single-core cables or three-core 240 - 800  $mm^2$  standard XLPE cables, the sheath or screen losses will range from 1,0 – 10 W/m. [6]

### 6.10.2 Loss factor calculation for sheath and screen

The loss of power in sheath or screen ( $\lambda_1$ ) consists of losses caused by circulating currents ( $\lambda'_1$ ) and eddy currents ( $\lambda''_1$ ), Thus,

$$\lambda_1 = \lambda'_1 + \lambda''_1 \quad (6.9)$$

The maximum operating temperature for the sheath or screen,  $\theta_{sc}$  is given by:

$$\theta_{sc} = \theta - (I^2R + 0,5W_d)T_1 \text{ (}^\circ\text{C)} \quad (6.10)$$

The resistance of the screen or sheath at its maximum operating temperature is given by the following formula:

$$R_s = R_{s0} [1 + \alpha_{20}(\theta_{sc} - 20)] \left( \frac{\Omega}{m} \right) \quad (6.11)$$

Where,

$R_{s0}$  = the resistance of the screen or sheath at 20 °C ( $\Omega/m$ )

#### **6.10.2.1 Two single-core cables, and three single-core cables (in trefoil formation), sheaths bonded at both ends of an electrical section**

$$\lambda'_1 = \frac{R_s}{R} * \frac{1}{1 + \left( \frac{R_s}{X} \right)^2}$$

$X$  = the reactance of screen or sheath per unit length of cable ( $\Omega/m$ )

$$= 2\omega * 10^{-7} * \ln \left( \frac{2s}{d} \right) \quad (\Omega/m)$$

$s$  = the distance between conductor axes in the electrical section considered (mm)

$d$  = the diameter of the sheath

$\lambda''_1 = 0$ , as eddy current losses are ignored except for cables with large Milliken conductors.

#### **6.10.2.2 Three single-core cables in flat formation, with regular transposition, sheaths bonded at both ends of an electrical section**

For three single-core cables in a flat formation, with the cable in the middle being equidistant to the outer cables, regular transposition with the cables bonded at every third transposition, the loss factor is given from:

$$\lambda'_1 = \frac{R_s}{R} * \frac{1}{1 + \left( \frac{R_s}{X_1} \right)^2}$$

Where,

$$X_1 = 2\omega 10^{-7} * \ln \left\{ 2\sqrt[3]{2} \left( \frac{S}{d} \right) \right\}$$

$$\lambda_1'' = 0 \quad [10]$$

Sheath losses are zero for three-core cables due to the magnetic fields of the 3 phases cancelling out one another. Circulating current losses (in the sheath) are calculated as  $\lambda_1'$ , replacing the sheath losses.

## 6.11 Armour losses

Armour losses are quite insignificant for multicore cables but become quite significant for single-core cables. The losses in the armour are similar to the losses in the sheath where the magnetic field causes eddy currents and circulating currents. Most commonly non-magnetic armour like bronze or aluminium is applied to single-core cables, which reduces the losses. However, they still need to be considered to get an accurate result. [20]

IEC60287 provides formulae for calculating the power loss occurring in metallic reinforcement or steel pipes (external to the cable).

The maximum operating temperature,  $\theta_{ar}$  is given by the following formula:

$$\theta_{ar} = \theta - \{(I^2 R + 0,5 * W_d) T_1 + [I^2 R(1 + \lambda_1) + W_d] n T_2\}$$

The resistance of the armour at its maximum temperature is given by:

$$R_A = R_{A_0} [1 + \alpha_{20}(\theta_{ar} - 20)] \quad (\Omega/m)$$

$$R_{A_0} = \text{resistance of armour at } 20 \text{ }^\circ\text{C}$$

### 6.11.1 Three-core cables – steel wire armour (round conductor)

$$\lambda_2 = 1,23 * \frac{R_A}{R} * \left( \frac{2c}{d_A} \right)^2 * \frac{1}{\left( \frac{2,77 * R_A * 10^6}{\omega} \right)^2 + 1}$$

Where,

$d_A$  = the mean diameter of armour (mm)

$c$  = the distance between the axis of one conductor and the cable centre (mm).

## 6.12 Typical Thermal Circuits

The flow of heat can be compared with the flow of electrical current. Heat flows from an area of higher temperature to an area of lower temperature. Different materials have different resistance to this heat flow. Thermal resistivity is defined as the difference in temperature between opposite sides of a cubic metre of material caused by the transfer of 1 watt of heat. Thus, the unit  $\text{K}\cdot\text{m}/\text{W}$ . [20]

Thermal circuits in increasing complexity will be shown below and the symbols used throughout will be:

$R$  = thermal resistance ( $\text{K}\cdot\text{m}/\text{W}$ )

$Q$  = Heat source ( $\text{W}/\text{m}$ )

$C$  = Thermal capacitance ( $\text{J}/\text{K}$ )

Subscripts throughout

$c$  = conductor

$I$  = insulator

$S$  = shield

$J$  = jacket

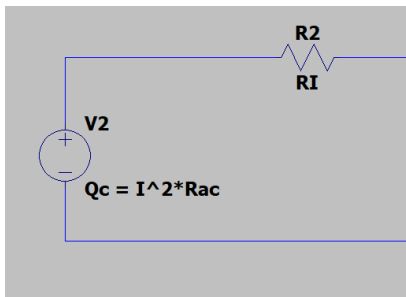
$D$  = duct

$SD$  = distance between cable and duct

$E$  = Earth [5]

### 6.13 Single layer of insulation, continuous load

In this simple thermal circuit, the conductor is the only internal heat source, and we only have one internal thermal resistance. This thermal resistance may be insulation, a covering, or a combination of both if the thermal resistance values of the two are similar enough. In this example, heat does not travel beyond the surface of the cable.

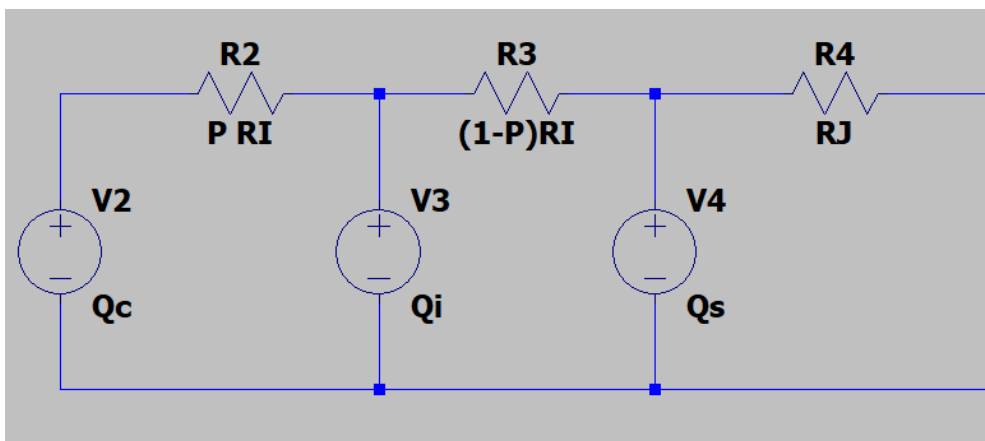


If the continuous load flows through two dissimilar materials, such as insulation and a jacket another thermal resistance is added in series with the first. The heat source is the electrical current flowing through the conductor that holds a certain resistance to that flow.

**Figure 3:** The figure shows a continuous load flowing through a single layer of insulation.

#### 6.13.1 Cable thermal circuit for primary cable with metallic shield and jacket, continuous load

Several heat sources and thermal resistances are introduced to this thermal circuit where  $P$  and  $(1-p)$  divide the thermal resistances to reflect  $Q_1$ .



**Figure 4:** Shielded cable with several heat sources ( $Q_i$  = dielectric losses,  $Q_s$  = shield losses)

Dielectric losses make the insulation itself a heat source, thus it is split into two thermal resistances.

### 6.13.2 Same cables as above, cyclic load

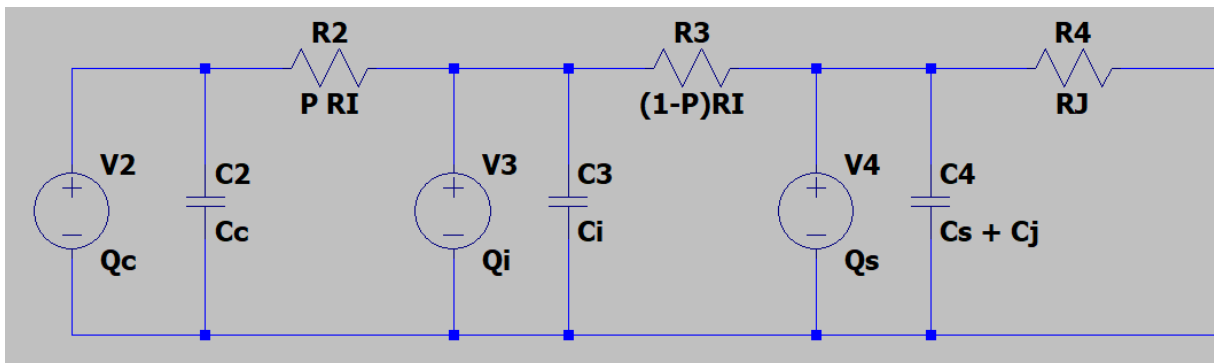


Figure 5: shielded cable with a jacket under cyclic load

Cyclic load (AC) is accounted for with capacitors in parallel to the heat sources representing the influence of thermal capacitance on the system. The thermal capacitance, thermal capacity, or thermal mass represents the slow response of a material to a change in temperature (heat energy). No energy is lost due to thermal capacitance. However, it represents a sort of inertia or delay in the heat flow. Objects store thermal energy and reject any sudden changes much like a capacitor. The further away an object is from the change, the longer it takes for it to respond, as all the closer objects must respond first. This phenomenon is displayed above using shunt capacitors. [21]

### 6.13.3 External thermal circuit, cable in duct, continuous load

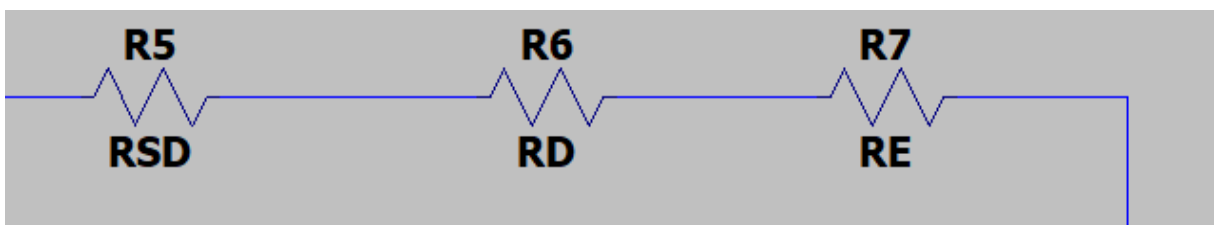


Figure 6: Shows only the thermal resistances external to the cable

Depending on the installation conditions the external thermal resistance will be different. In this case, duct installation means the thermal resistance between cable and duct +

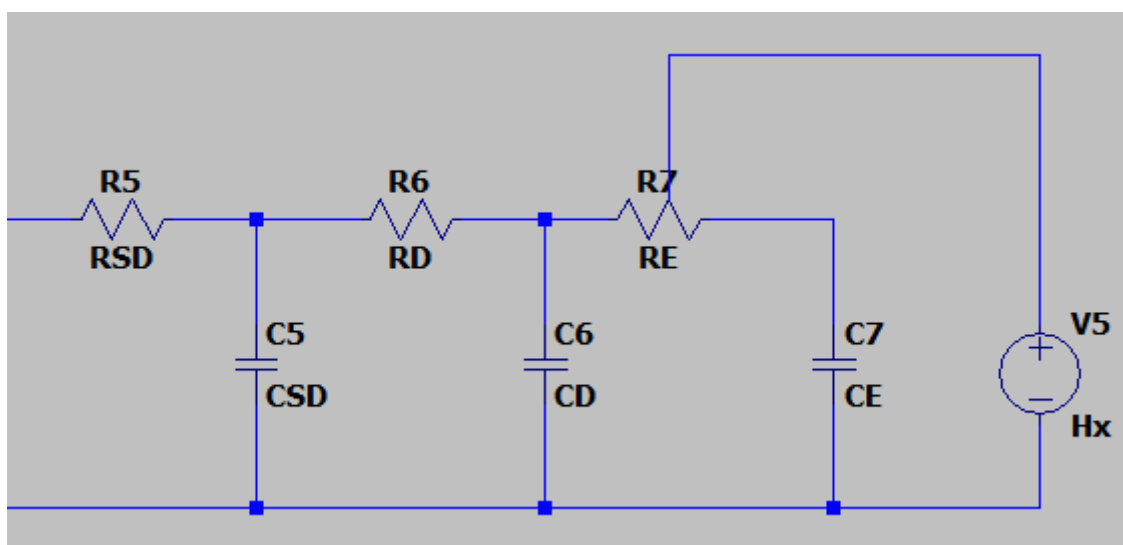
thermal resistance of duct + thermal resistance of the medium above the duct (most commonly earth). [5]

The external thermal resistance,  $T_4$  of cables in ducts is calculated as follows:

$$T_4 = T_4' + T_4'' + T_4'''$$

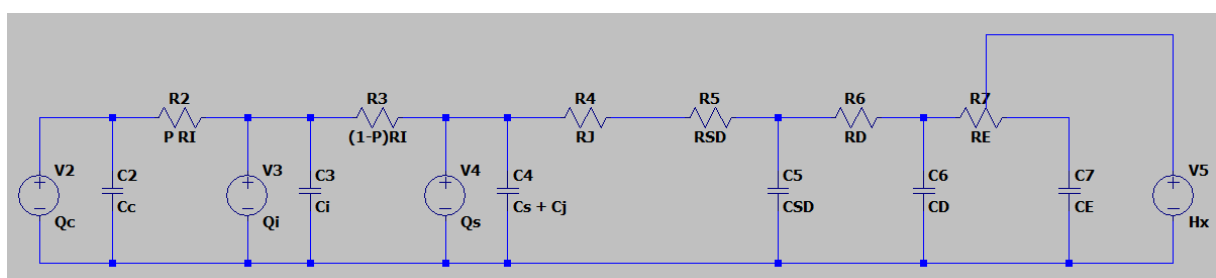
Each part is calculated separately and then added together. [22]

#### 6.13.4 External thermal circuit, cable in duct, time varying load, External heat source



Added external heat source,  $H_x$  to the external thermal circuit of a power cable with varying load laid in a duct. The external heat source is most commonly adjacent cables.

#### 6.14 Full thermal circuit of a single conductor shielded power cable in a multiphase system laid in duct.



This circuit represents a simplification of the thermal conditions of high and medium voltage AC substation cables. [5]

## 6.15 Calculation of thermal resistances

Calculations of the thermal resistances of the constituent parts of a cable,  $T_1$ ,  $T_2$  and  $T_3$ .

For Thermal calculations in cables where screening layers are present, metallic tapes are considered as part of the conductor or sheath while semi-conducting layers are considered a part of the insulation. The appropriate component dimensions shall be modified accordingly.

### 6.15.1 Thermal resistance between one conductor and sheath $T_1$

This is the thermal resistance of all cable layers between the conductor and the sheath of a cable. The insulation is the largest one and will therefore have the largest effect.

#### 6.15.1.1 Single-core cables

$$T_1 = \frac{\rho_T}{2\pi} \ln \left[ 1 + \frac{2t_1}{d_c} \right]$$

Where

$\rho_T$  = the thermal resistivity of the insulation

$d_c$  = the diameter of the conductor (mm)

$t_1$  = the thickness of the insulation (mm)

In the event that there are more layers between the conductor and sheath, their thermal resistance has to be calculated separately and added to  $T_1$ .

### 6.15.2 Thermal resistance between sheath and armour $T_2$

#### Single-core and three-core cables with a common metallic sheath

$$T_2 = \frac{1}{2\pi} \rho_T \ln \left[ 1 + \frac{2t_2}{D_s} \right]$$

Where

$t_2$  = thickness of the bedding (mm)

$D_s$  = the external diameter of the sheath (mm)

$\rho_T$  = Thermal resistance of the bedding

If there are more layers between sheath and armour, the thermal resistances need to be calculated separately and added to  $T_2$ . For unarmoured cables with metallic screens or sheaths  $T_2 = 0$ .

### 6.15.3 Thermal resistance of outer covering (serving) $T_3$

General case:

$$T_3 = \frac{1}{2\pi} \rho_T \ln \left( 1 + \frac{2t_3}{D'_a} \right)$$

Where,

$t_3$  = the thickness of the serving

$D'_a$  = the external diameter the armour

$\rho_T$  = Thermal resistance of the serving

If the cable is unarmoured then  $D'_a$  is taken as the external diameter of the layer directly beneath the serving (Sheath, bedding or screen). If there are any other layers between the sheath and serving the thermal resistance of those layers need to be calculated separately and added to  $T_3$ . [22]

### 6.15.4 External thermal resistance $T_4$

This is the thermal resistance external to the cable. Thus, it will mostly depend on the medium surrounding the cable.

#### 6.15.4.1 Single isolated buried cable

$$T_4 = \frac{1}{2\pi} \rho_T \ln \left( u + \sqrt{u^2 - 1} \right)$$

Where,

$\rho_T$  = Thermal resistivity of soil

$$u = \frac{2L}{D_e}$$

$L$  = the distance from the surface of the ground to the cable axis (mm)

$D_e$  = external diameter of the cable (mm)

When the value of  $u$  exceeds 10 a better approximation is found by:

$$T_4 = \frac{1}{2\pi} \rho_T \ln(2u)$$

#### 6.15.4.2 Three single-core cables, flat formation

##### Metallic sheathed cables

These are cables where it can be assumed there is a metallic layer that provides an isotherm at, or immediately under the outer sheath.

$$T_4 = \rho_T(0,475 \ln(2u) - 0,346) \quad \text{for } u \geq 5$$

##### Non-metallic sheathed cables

Cables where any metallic layer at or immediately under the outer sheath is not sufficient to provide an isotherm.

$$T_4 = \rho_T(0,475 \ln(2u) - 0,142) \quad \text{for } u \geq 5$$

#### 6.15.4.3 Three single-core cables, trefoil formation

For this configuration,  $L$  is measured from the centre of the trefoil configuration and  $D_e$  is the diameter of one cable.

##### Metallic sheathed cables

$$T_4 = \frac{1,5}{\pi} \rho_T [\ln(2u) - 0,630]$$

In this case the factor  $T_3$  (thermal resistance of the serving over the sheath and armour) shall be multiplied by 1,6.

##### Part metallic covered cables

$$T_4 = \frac{1,5}{\pi} \rho_T [\ln(2u) - 0,630]$$

In this case: factor  $T_1$  (thermal resistance of the insulation) shall be multiplied by 1,07 for cables up to 35 kV. Factor  $T_3$  shall be multiplied by 1,16 for cables up to 35 kV and 1,6 for cables up to 150 kV.

### **Non-metallic sheathed cables**

$$T_4 = \frac{1,5}{\pi} \rho_T [\ln(2u) - 2\ln(u)]$$

This formula is also used for the external thermal resistance of touching ducts. [22]

Note: A lot of the IEC60287 formulae used are left out as there are a lot of variations in cable types and installation conditions. Thus, it would take up a considerable amount of space to cover it all here.

## **6.16 Ampacity tables and computer programs**

### **6.16.1 Tables**

Standards: ex. IEC60287

Manufacturer catalogues cover the more common situations.

### **6.16.2 Computer programs**

Most large cable manufacturers and engineering firms have their own computer programs for determining ampacity. These programs are an excellent source of information when engineering a new cable system. These programs are usually not up for sale.

There are commercially available programs throughout North America. These are useful when determining the precise ampacity of a cable. The cost of these programs is about 5000 US dollars.

## **6.17 Ampacities under short circuit conditions**

Short circuit conditions generally involve large inrushes of current. The heating associated with these inrushes can be extremely hazardous and destructive. Calculations to determine the capacity of cables to withstand these conditions are generally handled by different calculation methods and assumptions. Some of these methods are published in IEC60949

– 9 “calculations of thermally permissible short circuit currents taking into account non-adiabatic heating effects” and other national standards.

### **6.18 Relationship between Ampacity and voltage drop calculations**

The same factors that impact ampacity also impact voltage drop calculations. For instance, when the temperature of the conductor rises the AC and DC resistance of said conductor increases which increases the voltage drop. Shield, sheath, and pipe losses have the same effect of increasing the apparent conductor resistance and impacting inductive reactance. [5]

## **7 Comparison of Calculation methods**

Various methods for determining underground cable ampacity have been developed in order to assist in designing electrical power systems. These methods include ampacity tables, derating factors, computer simulation programs, formulae based on the physics behind heat dissipation, and a method that considers the moisture migration through soil. Each of these methods results in different values of ampacity for the same installation. Regardless of which method is used, it is critical to use the correct value of soil thermal resistivity. Using the wrong value is likely to result in incorrectly sized cables. A few of these methods will be examined here to give some guidance on the implementation of each method.

A critical part of electrical power system design is to use accurate cable ampacities. Optimally sized cables result in high reliability with a minimum economical cost. Cable ampacities have been estimated using engineering assumptions and site conditions. Different parameters and assumptions are required depending on the cable configuration. For instance, cables placed under ground require information about the soil thermal resistivity, ambient earth temperature, the separation between adjacent cables, etc. In the event that these parameters are inaccurate, the resulting cable size will also be inaccurate. This leads to increased cost if oversized and overheating if undersized. The latter can result in deterioration of the insulating layer of the cable and eventually failure of the entire power system.

## **7.1 Ampacity calculations methods**

Methods compared here are IEEE cable ampacity tables, the Nehrer-McGrath Method, and a commercially available computer program. Each of these methods requires values that must be collected at the site of installation. These include soil thermal resistivity, “rho” and the highest expected ambient temperature (excluding heating from cables) at the depth of the power cable which carries the heaviest load. The thermal resistivity of soil is a parameter, that is not as available as the ambient temperature. The value is dependent on the moisture content of the soil. Measuring the soil thermal resistivity is not a difficult process. However, it is often overlooked resulting in incorrectly sized cables.

### **7.1.1 The black books**

The “black books” or AIEE-IPCEA power cable ampacities were tabulated using the Nehrer-McGrath method and published in 1962. This allowed an engineer to look up the value instead of using the Nehrer-McGrath calculations. The considerable amount of time it takes to calculate ampacities using the Neher-McGrath method made this the preferred method among Engineers and is still used by some as their primary method of sizing cables.

It is important to understand the assumptions that were made to create these tables. An example of an assumption is that the ambient temperature of the earth is 20 °C. This is not always the case as some locations experience temperatures above and below this value depending on latitude. Temperature values above this decrease the ampacity ratings below the tabulated values. It is also assumed depth of burial is 92 cm, and that the cable spacing is 19 cm. If the burial depth was only half the assumed value, it would increase the ampacity of the cable by about ten percent, and using double spacing distance would increase it by about six percent. Adjustment factors for these assumptions are not included in the tables. Therefore, the Nehrer-McGrath calculations must be performed if the conditions vary from the assumptions. Additionally, modern cables use different insulation materials and thicknesses. These tables also assume that cables are not equipped with jackets and that the sheaths are single point grounded. All these assumptions present difficulties for the modern user, as if differences are ignored the cable sizing will be incorrect.

### **7.1.2 IEEE 835 Cable Ampacity Tables**

A new set of ampacity tables were published by IEEE in 1994 in order to update the design and configuration changes that had been made since the original publication. All while maintaining the fundamental calculations made by Nehrer-McGrath. In addition to the updates in cable design, some of the original assumptions were adjusted. That includes an adjusted ambient ground temperature of 25 °C and the assumption that all shields are grounded at both ends for most cable sizes. Some step-by-step examples of the Nehrer-McGrath methods with updates to change the assumptions in the original method are also included in the standard. The steps given allow an engineer to develop a spreadsheet to calculate ampacity for any cable configuration eliminating the need for tables.

### **7.1.3 Computer modeling**

Computer software allows for an estimation of the cable ampacity by modeling the cable properties and configurations. The cable can be modeled according to the intended design and type. Software programs utilize constituent thermal resistivity as specified by IEEE 835 for each material, allowing the components and their thickness to be adjusted. Typically, programs are advertised using the Nehrer-McGrath method to determine Ampacity. This means that no other assumptions than those made by Nehrer and McGrath need to be made.

### **7.1.4 Nehrer-McGrath Adaption**

This method focuses on the thermal stability of the soil. All types of soil increase in resistivity as the moisture content decreases. This method addresses the issue of moisture migration by a simple procedure, that approximates the effective thermal resistance to ambient earth. The non-drying heat rate and the completely dried soil resistivity in addition to the in-situ soil resistivity are used to calculate a dried soil diameter which is then included in the Nehrer-McGrath method. The ampacity may be calculated by hand, using a computer program or spreadsheet as aid. Another perk of this method is that it does not assume that heat is only transferred from the cable through conduction to ambient air. Rather, it includes the heat transfer by the moisture moving through soil. [23]

## **7.2 Conclusions**

Ampacity calculation methods using assumptions differ depending on the climate conditions in the areas they were meant to be used for. They also use units that are standardized in the area.

The assumptions made in ampacity calculations like IEEE 835 and the black books result in an inaccurate result. Because IEEE tables assume a higher ambient earth temperature than the black books and that the shields are grounded at both ends, IEEE 835 results in a lower ampacity than black books. Using a software program based on the Nehrer-McGrath method or the method itself allows for calculating the ampacities of cables using various soil resistivities, ambient temperatures, and shield grounding configurations. This elimination of assumptions eliminates the errors in the calculations making this a more accurate method. The use of the calculations in standard IEC60287 allows for the same accuracy as input parameters can be adjusted. [23]

## **8 The Balance of current distribution in parallel cables**

Single-core cables may be connected in parallel to carry the current of the same phase. This is a common technique used to increase the ampacity of the system. The challenge here is that the current in an AC system does not distribute evenly between the cables. Some of the cables may be carrying a light load while others are overloaded in reference to the ampacity of each cable. This becomes a problem since the overloaded cables are heated to a point where the life expectancy of the insulation is reduced. Improper cable configuration leads to a highly unbalanced current distribution. In order to counteract this issue, studies have been made and a few different cable configurations have been proposed. The performance of different configurations is compared in terms of the largest cable current and total power losses of the system.

Some electrical standards specify the installation configuration requirements to avoid highly unbalanced current distribution in parallel cables. However, these guidelines and recommended configurations are not designed to obtain the most balanced current

distribution possible. Thus, they may not meet the required ampacity of the cable installation. The variety of configurations available for a practical cable installation is constricted by the available space and the type of cable tray used. An additional constraint for substation cables is the connection to medium voltage switchgear. Engineers have stated that no more than four parallel cables per phase can be used for connections to regular switchgear. Even though extensive studies have been conducted, there is yet no method of configuration that achieves perfect current sharing balance. However, some methods are superior to others.

The unequal current sharing between parallel cables connected in the same phase is caused by the electrical characteristics of alternating current. Mutual inductance which is a function of the distance between cables plays an important role when determining current sharing. The most economical and effective method for current distribution balancing is a properly designed configuration where the parallel cables are narrowly spaced. A solution will be presented based on some calculation results and the basic magnetic coupling theorem.

## 8.1 Electrical Characteristics associated with current distribution

It is well-known that the inter-cable distances and the phase angles in the nearby cables affect the current distribution of cables connected in parallel. The mutual inductance of the cables can be calculated when the position of each cable is specified so that the distance between any pair of cables can be obtained. The self-impedance of cable  $j$  and its mutual impedance with cable  $k$  for a group of parallel cables without a ground return path can be calculated as follows:

$$Z_{jj} = \left( R + j\omega \left( L + \frac{\mu_0}{2\pi} \left( \ln \frac{2s}{r} - 1 \right) \right) \right) \quad (8.1)$$

$$Z_{jk} = j\omega \left( \frac{\mu_0}{2\pi} \left( \ln \frac{2s}{D_{jk}} - 1 \right) \right) \quad (8.2)$$

Where,

$R$  = AC resistance of conductor ( $\Omega$ )

$L$  = internal inductance =  $\frac{\mu_0}{8\pi}$  (H/m)

$\mu_0 = 4\pi * 10^{-7}$  (H/m)

$r$  = radius of conductor (m)

$s$  = length of cable (m)

$D_{jk}$  = distance between cable  $j$  and  $k$

These equations do not include skin and proximity effects. A cable with a smaller cable radius is less affected by the effects of skin- and proximity effects on the conductor resistance than a cable with a larger one. The sum of all currents in the cables equals zero and the “ $s$ ” and “ $-1$ ” components can be left out from the equations above when they are used for calculating the voltage drop over the cables. The simplified equations follow:

$$Z_{jj} = \left( R + j\omega \left( L + \frac{\mu_0}{2\pi} \left( \ln \frac{1}{r} \right) \right) \right) \quad (8.3)$$

$$Z_{jk} = j\omega \left( \frac{\mu_0}{2\pi} \left( \ln \frac{1}{D_{jk}} \right) \right) \quad (8.4)$$

The voltage drop of every cable can be obtained through the summarization of self-impedance and the voltages induced by other cables:

$$\bar{E}_j = \sum_{k=1}^m \bar{Z}_{jk} * \bar{I}_k \quad (8.5)$$

Where,  $m$  = the number of cables in the system. The phase angle of  $\bar{I}_k$  is assumed to be the same as that of  $\bar{I}_j$ . The addition of  $\bar{Z}_{jk} * \bar{I}_k$  increases the voltage drop over cable  $j$ . However, because the voltage drops of the cables in the same phase are identical, the increase in mutual coupling induced voltage will decrease the self-impedance voltage drop and thus decrease the amplitude of  $\bar{I}_j$ . On the contrary when the phase angle of  $\bar{I}_k$  is opposite to

that of  $\bar{I}_j$ , the addition of  $\bar{Z}_{jk} * \bar{I}_k$  decreases the voltage drop of cable j. Therefore, the amplitude of  $\bar{I}_j$  is increased to keep all the voltage drops in the same phase identical. In equation 8.4 it is clear to see that the mutual inductance amplitude  $Z_{jk}$  has an inverse relationship with the distance between the cables  $D_{jk}$ . Hence the current in a nearby cable affects the voltage drop more than a farther away cable. This phenomenon explains why the currents in the cables that border between two phases are larger in amplitude than other cables. This is because the difference in phase angles between cables belonging to different phases is so large.

## 8.2 Calculation of current distribution

The impedance of a feeder cable is usually much smaller than that of the load. The impedance of the cables can therefore be neglected when calculating the amplitude and phase angles of the three-phase currents. These three phase currents are thereby independent of the cable configurations. Hence an impedance matrix of parallel cables can be established for a three-phase system modeled with three current sources. The matrix equation can be written as:

$$[\bar{E}] = [\bar{Z}][\bar{I}] \quad (8.6)$$

The total number of cables in the system is expressed as m, the dimensions of  $[\bar{E}]$  and  $[\bar{I}]$  are  $m * 1$ . The voltage drops of all parallel cables belonging to the same phase are identical.

$$\bar{E}_{A1} = \dots = \bar{E}_{An} = \bar{E}_A \quad (8.7)$$

Where E is the voltage drop, A is the name of the phase and n is the number of cables per phase. The same relationship is also true for phases B and C. For a system including only one three-phase system the relationship between m and n is  $m = 3 * n$ . The voltage drops are unknown, but the three-phase currents are known, that is the sum of the unbalanced parallel cable currents.

$$\bar{I}_A = \bar{I}_{A1} + \dots + \bar{I}_{An} \quad (8.8)$$

The same relationship is also true for phase B and C. Equations 8.6, 8.7 and 8.8 can be solved using iteration techniques or directly. The only direct method is introduced here [24]: For equation derivation we express equation (8.6) and (8.7) in matrix form these also containing the values of the other phases:

$$[\bar{E}] = [K][\bar{E}_{ABC}] \quad (8.9)$$

And

$$[\bar{I}_{ABC}] = [K]^T[\bar{I}] \quad (8.10)$$

Where,

$$[K]_{m \times 3} = \begin{array}{ccc} 1 & 0 & 0 \\ \dots & \dots & \dots \\ 1 & 0 & 0 \\ \hline 0 & 1 & 0 \\ \dots & \dots & \dots \\ 0 & 1 & 0 \\ \hline 0 & 0 & 1 \\ \dots & \dots & \dots \\ 0 & 0 & 1 \end{array}$$

And

$$[\bar{E}_{ABC}]_{3 \times 1} = \begin{bmatrix} \bar{E}_A \\ \bar{E}_B \\ \bar{E}_C \end{bmatrix}, \quad [\bar{I}_{ABC}]_{3 \times 1} = \begin{bmatrix} \bar{I}_A \\ \bar{I}_B \\ \bar{I}_C \end{bmatrix}$$

K is an incidence matrix that relates the cables to phases. By substituting equation (8.9) into (8.6) and then this new equation into (8.10) yields:

$$[\bar{E}_{ABC}] = ([K]^T[\bar{Z}]^{-1}[K])^{-1}[\bar{I}_{ABC}] \quad (8.11)$$

The impedance item in 8.11 is the three-phase impedance matrix of the parallel cable system with a dimension of 3x3. Finally applying equation (8.11) into (8.9) and the newfound equation into (8.6) the closed form solution for cable currents can be obtained as follows:

$$[\bar{E}_{ABC}] = [\bar{Z}]^{-1}[K] ([K]^T[\bar{Z}]^{-1}[K])^{-1}[\bar{I}_{ABC}] \quad (8.12)$$

Equation (8.12) can be used to solve the current distribution issue for a system with multiple distribution circuits when the three-phase load currents and cable positions are provided.

### 8.3 Processing techniques

#### Pattern generation for cable configurations

The number of possible configurations for a three-phase system with several cables per phase is very high, making it inefficient to calculate the current distribution of all possible configurations to determine the optimum configuration. Practically, the cables are configured in symmetrically arranged subgroups. A subgroup includes three cables for three-wire systems. Every cable in a subgroup belongs to different phases. This method of subgrouping is used here to limit the number of possible cable configurations.

### Performance indices and calculation procedure

In order to search for the top configurations having the most balanced current sharing among parallel cables, two performance indices are defined. Both of them are expressed in cable currents as:

$$\delta_T = \frac{\sum_p (\sum_{h=1}^n I_{ph}^2)}{\sum_p n \left(\frac{I_p}{n}\right)^2}, \quad \delta_M = \frac{\text{Max}(I_{ph})}{\text{Max}\left(\frac{I_p}{n}\right)} \quad (8.13)$$

Where  $p = A, B, C$ . Index  $\delta_T$  represents the power losses of all cables, while  $\delta_M$  is the largest cable current. These indexes are calculated based on the current distribution solved by (8.12). The denomination factors are based on the ideal uniform current distribution. For instance, a value of 1.14 for  $\delta_T$  indicates that the total cable losses are 14% higher than what it is when the current distribution is ideally uniform.

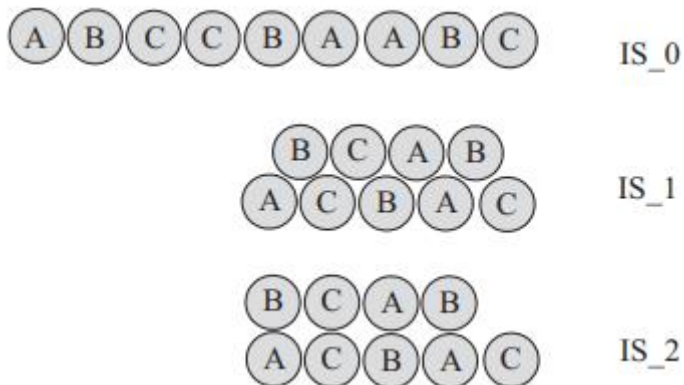
The whole calculation process described in this chapter can be summarized as a step-by-step process:

- 1) input cable installation structure parameters.
- 2) Input cable parameters and load currents.
- 3) create the binary sequence.
- 4) transform matrices of position numbers.
- 5) Calculate impedance matrices.
- 6) calculate cable currents
- 7) Calculate performance indices.
- 8) Sort performance indices.

The parameters of the cable installation structure are coordinates of the cable positions and are used to calculate the distances between cables. Aside from the input parameters, all other steps can easily be processed automatically using a software program.

The configuration with the best performance indices (closest to the ideal value of one) is the most efficient. In some cases, it might be a good idea to use a simpler configuration rather than the optimal one.

Configurations included can be seen below (the order of phases varies):



## 8.4 Results

The four best configurations in each category are tabulated below and the one that did best overall is written in bold and underlined. The last row shows the result of grouping all cables belonging to the same phase together.

No.	Configurations	$\delta_T$	Configurations	$\delta_M$
1	<b><u>ABCCBAABCCBA</u></b>	1,006	<b><u>ABCCBAABCCBA</u></b>	1,08
2	ACBBCAACBBCA	1,006	ACBBCAACBBCA	1,08
3	ACBBCABACCAB	1,019	ABCCBACABCAB	1,123
4	ABCCBACABBAC	1,019	ABCACBBACCAB	1,162
-	AAAABBBBCCCC	1,446	AAAABBBBCCCC	1,741

### Results for a 3 phase 3 wire 12-cable system with structure IS\_2

- 1) Putting all cables belonging to the same phase together will result in a highly unbalanced current distribution. With this type of configuration, more parallel cables will lead to a more unbalanced current distribution.

- 2) The fundamental rule for the configuration of parallel cables is to only include one cable per phase in a cable subgroup and to have them installed symmetrically.
- 3) A cable configuration with adjacent subgroups arranged in mirror symmetry (ABC/CBA/ABC) can obtain a very balanced current distribution.
- 4) For the installation structure IS\_2, where subgroups of cables are placed in two rows one on top of the other. The two cables in the same column can be treated as the same cable and the method described in 3 can be used to arrange cables in configurations to obtain the most balanced distribution of current. (See picture below)



- 5) The configurations with repeated cable subgroups such as ABC/ABC can in general obtain acceptable current distributions. This method is recommended for users who want a simple configuration.
- 6) The performance index and the installation structure can influence the solution of cable configuration patterns. The installation structure has a greater effect than the performance index so when the structures are different from the ones introduced here a computer simulation program may need to be used instead of the suggested rule in conclusion #2. [24]

Note: Engineers stated that for very short distances such as those within a substation the complexity of arranging cables optimally is rarely worth the effort. The purpose of the inclusion of this study was more to display the effects of a poor configuration of cables. It should be noted that in difficult cases a proper configuration can help solve the issue of large load currents.

## 9 Calculation tool development

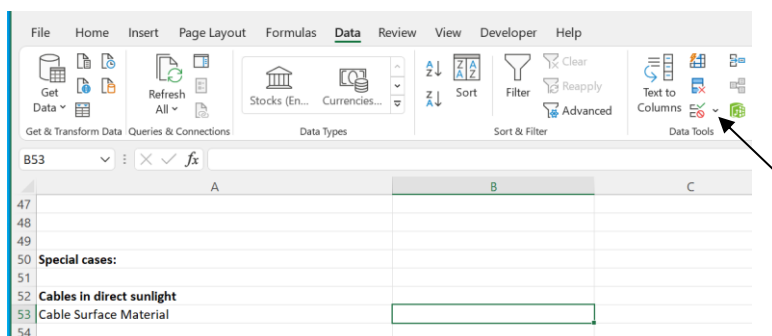
The calculation tool was developed using Microsoft Excel spreadsheets and the formulae found in IEC60287. This standard was written by the International Electrotechnical Commission and specifically concerns ampacity calculations. Similar formulae can also be found in standards written by other electrotechnical institutions such as ISO or IEEE.

### 9.1 Useful Excel Features and Functions

This section explains in short, the functions and work required to make an ampacity calculation tool using Microsoft Excel.

#### 9.1.1 Dropdown list – data validation

A dropdown list can make things easier for both computer and user. The list works as a sort of data validation where only allowable values are displayed. This makes it easier to find the correct value using Functions like XLOOKUP.



The dropdown list is created by selecting the cell in which the dropdown list is to be applied. The data tab is then selected where data validation can be found among the data tools at the top left corner of the picture above.

Material	$\sigma$
Bitumen/ jute serving	0,8
Polychloroprene	0,8
PVC	0,6
PE	0,4
Lead	0,6

Data Validation

Settings Input Message Error Alert

Validation criteria

Allow: List  Ignore blank

Data:  In-cell drop-down

between

Source: =Tables!\$F\$19:\$F\$23

Apply these changes to all other cells with the same settings

Clear All OK

Data validation is then configured by selecting “List” in the “Allow” field and a range in the workbook is selected as the source for the drop-down list. The values in the source table will be displayed in the dropdown list as the only allowed values for the selected cell.

### 9.1.2 XLOOKUP

This function is useful for finding a particular value from a table. This function will change the value in a cell depending on the value of another cell. When the lookup- and return values are tabulated side by side, XLOOKUP can be used to find the return value. This becomes even more useful when dealing with large tables.

PVC	=XLOOKUP(B53
	XLOOKUP(lookup_value; lookup_array; return_array; [if_not_found]; [match_mode]; [search_mode])

The value that the function is supposed to look for is selected first as the “lookup value”.

E	F	G	H	I
	Table 4 absorption of solar radiation for cable surfaces			
	Material	$\sigma$		
	Bitumen/ jute serving	0,8		
	Polychloroprene	0,8		
	PVC	0,6		
	PE	0,4		
	Lead	0,6		

The range in which the function is supposed to find the “lookup value” is selected as “lookup array”. Note that the input values need to be separated by a semicolon.

=XLOOKUP(Tables!;Tables!F19:F23;Tables!G19:G23

E	F	G	H	I
	<b>Table 4 absorption of solar radiation for cable surfaces</b>			
	Material	$\sigma$		
	Bitumen/ jute serving	XLOOKUP(lookup_value; lookup_array; return_array; [if		
		0,8		
	Polychloroprene	0,8		
	PVC	0,6		
	PE	0,4		
	Lead	0,6		

The next step is selecting the range containing the values needed in the cell containing the XLOOKUP function as “return value”. The function works so that it will match up the matching value from the lookup array with the value on the same row in the return array. This means that for the function to work the lookup and return arrays must match each other in terms of rows. However, it does not matter how many columns apart they are. This makes for quite versatile uses of the function.

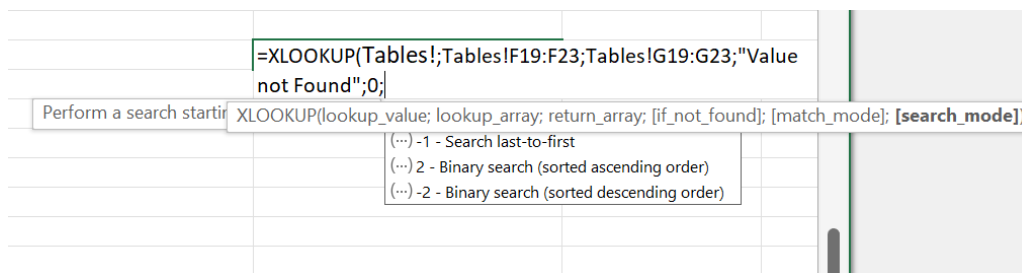
=XLOOKUP(Tables!;Tables!F19:F23;Tables!G19:G23;"Value not Found")
XLOOKUP(lookup_value; lookup_array; return_array; [if_not_found]; [match_mode]; [search_mode])

Next, a value can for what the function should do if no value is found can be selected. The value can equal a cell a number, a function, or a string containing text. It is good practice to have some kind of output that lets the user know that no value was found. If the data validation is done correctly, there should be no way that this can happen. Therefore, the content of this step is optional and can be left out.

PVC	=XLOOKUP(Tables!;Tables!F19:F23;Tables!G19:G23;"Value not Found")
Searches for an Exact match, if not found	XLOOKUP(lookup_value; lookup_array; return_array; [if_not_found]; [match_m
	(...)-1 - Exact match or next smaller item
	(...)-1 - Exact match or next larger item
	(...)-2 - Wildcard character match

The next step is match mode. Selecting, 0 will grant an exact match, -1 will grant an exact match or the next smaller item, while 1 will grant an exact match or the next larger item.

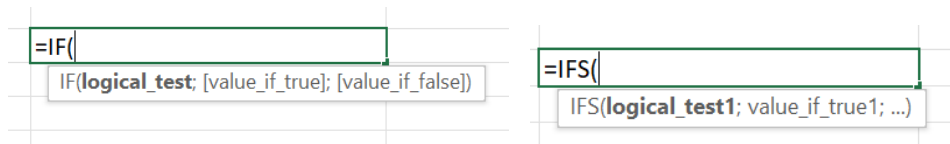
All 3 of these can be useful depending on the table and the application. However, selecting 2 will only result in a randomizer. Usually, 0 is the way to go.



Lastly, the function wants to know the search mode. Selecting 1, the function will begin searching at the top of the table, this is usually the way to go. Selecting – 1, it will begin searching from the bottom going up. 2 and – 2 are opposite types of binary searches. This is an efficient algorithm for finding a value from a sorted list of items that may save some RAM if the table is large. In this application, there was no use for it.

### 9.1.3 IF and IFS

Functions like IF allows for conditions to be set, under which a certain cell will enter a certain value or use a certain function. The standard IF function can be used to set a condition, one value for the condition being true and another value for if it is false. The IFS function is an evolved version that allows you to set multiple conditions and values if true. This avoids having to nestle a bunch of IF functions inside of If functions. [25]



## 9.2 Application of IEC60287 Formulae

Microsoft Excel allows for formulae to be written in cells using standard mathematical operators. By calculating different formulae in different cells and having some cells contain constants while others contain functions that find the suitable parameters based on the selected conditions, formulae found in IEC60287 can be applied to the spreadsheet. The same goes for the Nehrer-McGrath method or any other system of thermal and electrical

equations that results in an ampacity reading for the selected cable in the selected installation conditions.

## **10 Breakdown of Results**

A calculation tool using the IEC60287 standardized method for calculating the current carrying capacity of power cables was developed in Microsoft Excel. The workbook calculates the ampacity of three-core cables as well as single-core cables in trefoil- and flat formation. The workbook calculates the ampacity for cables in air, ground, and ducts. The conditions of installation can easily be adjusted, and the workbook will adjust the results accordingly. (See appendices)

### **10.1 Excel workbook for calculations**

The Excel workbook contains several sheaths used to calculate all necessary electrical and thermal parameters, losses, resistances etcetera. In accordance with the wishes of Hitachi Energy Finland Oy, there is a separate spreadsheet containing commonly used cables. This way a cable can be selected, and all of the dimensions and the electrical characteristics of the cable are automatically found and used as the basis for the calculations. The cables in the list can be replaced, their information can be changed, and new cables can be added without corrupting the calculation tool (see appendix 2).

### **10.2 Comparison of methods**

The engineers at Hitachi Energy requested a comparison because sometimes customers have been requesting that other methods should be used for calculating the ampacity. By comparing other methods to IEC60287 calculations the customers can be reassured that the same results will be reached regardless.

In order to get a comparison, a calculation had to be made the following results were reached assuming the following conditions: Single-core cables for 20 kV are installed in a flat formation with single point grounded sheaths. Soil thermal resistivity: 0,9 Km/W, ambient earth temperature: 25 °C, depth of burial: 0,9 m, spacing between phases: 200

mm, conductor temperature 90 °C. It is assumed that the soil does not dry out, thus the soil thermal resistivity remains at 0,9 Km/W. The amplitude of the current in the system is at 500A.

Method	Ampacity	Cable size
Nehrer-McGrath	541 A	400 mm <sup>2</sup>
Black books	534 A	400 mm <sup>2</sup>
IEEE 835 P.465	519 A	400 mm <sup>2</sup>
Computer program	549 A	400 mm <sup>2</sup>
IEC60287	547 A	400 mm <sup>2</sup>

All methods result in the same cable size, however slightly different ampacities were found, this can be contributed to the different assumptions made in each method. In conclusion, the methods used are all based upon similar thermal and electrical concepts and whichever method is used does not significantly affect the result. However, it must be stated that the methods that use more assumptions are inferior to those that use less. [23]

### **10.3 Balance of current distribution between adjacent cables**

The results have already been presented in 8.4.

In summary, a poor configuration of all cables belonging to the same phase packed together in one group will cause uneven current distribution. This leads to more power losses and a much larger current in one of the cables. If the maximum current ratings of the cables are very close to the balanced current that they need to carry this may lead to failure of the entire system.

## 11 Discussion

This thesis studied the broad area of electrical engineering which is the current carrying capacity of power cables. This subject is quite complex as it combines electrical engineering and thermodynamics. An installation that is electrically optimal so that minimum losses are achieved may be thermally improper so that the heat dissipation is poor leading to a lower current carrying capacity. It is often better to favour an installation that allows for optimum heat dissipation over low electrical losses if achieving a high ampacity is the goal. An engineer or researcher can devote his or her entire career to the study of this broad, complex, and interesting field. This thesis only covers a small part of all the information and research conducted in the area. The accuracy of the calculation tool will keep being improved in cooperation with the engineers at Hitachi Energy.

Achieving an accurate calculation tool for a wide variety of power cables and installation methods is a time-consuming and difficult process. It requires mathematical knowledge as well as a deep understanding of electrical and thermal concepts. The development of a calculation tool is however necessary as the performance of calculations for each individual case would not be efficient. IEC60287 requires knowledge about power cable dimensions. Most of which can be found in manufacturers' literature. Any dimensions that cannot be found there, can be estimated by a power cable expert, or found in electrical standards or other scientific literature covering the topic.

## 12 References

- [1] Hitachi , "www.hitachienergy.com," Hitachi, [Online]. Available: <https://www.hitachienergy.com/about-us/who-we-are/purpose>. [Accessed 21 03 2022].
- [2] K. A. Jacobsson, S. Lidström och C. Öhlén, Elkraftshandboken. Elkraftsystem 1, kapitel 8: Överföring med högspänd växelström, Stockholm: Liber Ab, 2016.

- [3] C. C. Landinger, *Electrical Power Cable Engineering Third Edition*, Chapter 2: Basic Dielectric Theory of a Cable, Boca Raton: CRC Press Taylor & Francis group, 2012.
- [4] Rugged monitoring, "www.ruggedmonitoring.com," Rugged monitoring, 28 02 2020. [Online]. Available: <https://www.ruggedmonitoring.com/blog/guidelines-to-perform-online-partial-discharge-measurements-in-underground-power-cable/5e58add9cde096000141a77e>. [Accessed 2022 03 17].
- [5] C. C. Landinger, *Electrical Power Cable Engineering Third edition*, Chapter 14: Ampacity of Cables, Boca Raton: CRC Press Taylor & Francis group, 2012.
- [6] C. Bayliss and B. Hardy, *Transmission and Distribution Electrical Engineering Fourth edition*, Chapter 12 Cables, Oxford: Elsevier Newebies, 2012.
- [7] L. J. Hiivala and C. C. Landinger, *Electrical Power Cable Engineering Third Edition*, Chapter 3: Conductors, Boca Raton: CRC Press Taylor & Francis group, 2012.
- [8] IEC, *IEC228 - Conductors of insulated cables*, Geneva: IEC, 2004.
- [9] W. A. Thue, *Electrical Power Cable Engineering*, Chapter 4: Cable Characteristics: Electrical, Boca Raton: CRC Press Taylor and Francis Group, 2012.
- [10] IEC, *IEC 60287-1-1: Electric cables – Calculation of current rating – Part 1-1 Current rating equations (100 % load factor) and calculation of losses – General*, Geneva: IEC, 2014.
- [11] K. A. Jacobsson, S. Lidström och C. Öhlén, *Elkraftshandboken, Elkraftsystem 2, kapitel 12 Formler och data*, Stockholm: Liber Ab, 2016.
- [12] IEC, *IEC60183 - Guidance for the selection of high-voltage A.C. cable systems*, Geneva: IEC, 2015.
- [13] IEC, *IEC60502-2 - Power cables with extruded insulation and their accessories for rated voltages from 1 kV ( $U_m = 1,2$  kV) up to 30 kV ( $U_m = 36$  kV) – Part 2: Cables for rated voltages from 6 kV ( $U_m = 7,2$  kV) up to 30 kV ( $U_m = 36$  kV)*, Geneva: IEC, 2014.
- [14] M. Suomi, *Insinööriyö - Kosketussuojan Poikkipinnan Vaikutus 60 - 400 kV Suurjännitekaapelien Kuormitettavuuteen*, Helsinki: Metropolia Ammattikorkeakoulu, 2010.
- [15] ABB, "XLPE Underground Cable Systems, User's Guide," ABB, Västerås, 2008.
- [16] ETC Cable Components Inc., "www.etscablecomponents.com," ETC Cable Components, 11 2013. [Online]. Available:

<https://www.etscablecomponents.com/blog/2013/11/single-core-cables-laid-trefoil-flat-formations-advantages-disadvantages/>. [Accessed 19 04 2022].

- [17] K. A. Jacobsson, S. Lindström och C. Öhlen, *Elkraftshandboken Elkraftsystem 2*, Kapitel 6 *Elkraftsberäkningar*, Stockholm: Liber Ab, 2016.
- [18] B. S. Bernstein, *Electrical Power Cable Engineering*, Third Edition, Chapter 6; *Electrical Properties of Cable Insulating Materials*, Boca Raton: CRC Press Taylor & Francis Group, 2012.
- [19] L. Heinhold, *Power Cables and their Application part 1*, Munich: Siemens AG, 1990.
- [20] BICC Cables Ltd, *Electric Cable Handbook*, Third Edition, Part 1: Theory Design and Principles Common to All Cable Types, Chapter 8: Current Carrying Capacity, Padstow, Cornwall: Blackwell Science Ltd, 1997.
- [21] M. Kutz, J. James E. Marthinuss and G. Hall, *Heat Transfer Calculations*, Chapter 15, *Thermal System Transient Response*, New York City: McGraw-Hill Professional, 2005.
- [22] IEC, *IEC60287-2-1 Electric cables – Calculation of the current rating – Part 2-1: Thermal resistance – Calculation of thermal resistance*, Geneva: IEC, 2015.
- [23] B. Carson, M. Keith and C. David, "Cable Ampacity Calculations: A Comparison of Methods," *IEEE Transactions on Industry Applications*, p. 7, 2015.
- [24] S.-Y. Lee, "A Cable Configuration Technique for Balancing of Current Distribution in Parallel Cables," *Journal of Marine Science and Technology*, vol. 18, no. 2, p. 8, 2010.
- [25] Microsoft, "support.microsoft.com," Microsoft, [Online]. Available: <https://support.microsoft.com/en-us/office/>. [Accessed 09 03 2022].

## Appendix 1: Selection of installation properties

Calculation of Ampacity			
Information is found in column A	Values That are to be inputed are found in column B	Comment	Standards
Parameter:	Input:		
Select a cable:	AHXLMK-W 1x500 110kV	Selects all dimensions and properties assigned to the cable	IEC60502 / IEC60228 etc.
System Frequency (Hz)	50		
Maximum conductor temperature °C	90	65 / 90 °C depends upon installation	IEC60287-1-1
Installation formation	Flat formation	Setup of the three-phase cable system	IEC60287-1-1
Apparent power in system (MVA)	95	Usually detemined by the power of the main transformer	
Distance between phases (mm)	200	Mean distance between the centre of one cable to the centre of another. Thus, the minimum length is one external dimeter of cable.	IEC60287-1-1
Type of bounding (Earthing)	Single point or cross-bounded	Impacts the amount of metallic sheath losses.	IEC60287-1-1
Ambient air temperature	20	Impacts installations in air.	IEC60287-1-1
<b>Cables in ground:</b>			
Thermal resistivity of soil	0,9	Important value that should be as exact as possible. Additional info in subsheet "External thermal resistance of cable"	IEC60287-2-1
Depth of burial (distance from cable axis to the surface of the ground) (mm)	910	The value of this is atomatically adjusted account for ducts	IEC60287-2-1
Ambient ground temperature °C	25	Standard values for different regions can be found in IEC60287-3-1	IEC60287-2-1
<b>Cables in ducts:</b>			
Type of duct/Installation	In fibre duct in air		IEC60287-2-1
Mean temperature of the medium filling the space between cable and duct. (A value may need to be assumed and the calculation repeted with a modified value if nessessary) °C	15		IEC60287-2-1
Material of duct/pipe	Fibre		IEC60287-2-1
Internal diameter of duct	200		IEC60287-2-1
External diameter of duct	210		IEC60287-2-1

## Appendix 2: Cable Selection

Cable Selection									
Cable (Prysmian)	Conductor material	Conductor diameter (mm)	Conductor screen thickness	Insulation thickness (mm)	Insulation screen thickness	External diameter of sheath	Thickness of sheath	Thickness of bedding	Thickness of Serving
AHXMLK-W 1x300 110kV	Aluminium	20,3	1,2	16	1,2	63	1,9	0,3	2,8
AHXMLK-W 1x500 110kV	Aluminium	26	1,2	15	1,2	69	2,1	0,3	3
AHXMLK-W 1x800 110kV	Aluminium	33,4	1,2	15	1,2	75	2,3	0,3	3,3
AHXMLK-W 1x1200 110kV	Aluminium	40,8	2	15	2	83	2,5	0,3	3,5
HXMLK-W 1x1600 110 kV	Copper	49	2	15	2	93	2,7	0,3	3,8
HXMLK-W 1x2000 110 kV	Copper	55,2	2	15	2	99	3,9	0,3	3,9
AHXCHBMK-W 1x300Al/35Cu 110 kV	Aluminium	20,3	1,2	16	1,2	61	3,2	0,3	3,1
AHXCHBMK-W 1x500Al/35Cu 110 kV	Aluminium	26	1,2	15	1,2	65	3,4	0,3	3,3

Cable property	Value	Unit
Conductor diameter (mm)	26	mm
	0	
Conductor screen thickness	1,2	mm
	0	
Insulation thickness (mm)	15	mm
Insulation screen thickness (mm)	1,2	mm
External diameter of sheath	69	mm

### Appendix 3: Calculation results

	Cables in air	Cables in ground	Cables in ducts
<b>Ampacity (A):</b>			
Trefoil	#SAKNAS!	#SAKNAS!	#SAKNAS!
Flat formation	895,407017	546,9485237	543,2131119
three core cable	#SAKNAS!	#SAKNAS!	#SAKNAS!
Conductor Temperature rise above ambient, $\Delta\theta$	70	65	75
<b>Losses:</b>			
AC resistance, R ( $\Omega/m$ )	0,00011	0,00011	0,00011
Conductor losses, Wc (W/m):	27,34848485	27,34848485	27,34848485
Dielectric loss, Wd (W/m)	2,2808E-07	2,2808E-07	2,2808E-07
Sheath losses in trefoil, $\lambda_1$	#SAKNAS!	#SAKNAS!	#SAKNAS!
Sheath losses flat, centre cable, $\lambda_1$	0,002489982	0,002489982	0,002489982
Sheath losses flat, outer cable, leading phase, $\lambda_1$	0,002595739	0,002595739	0,002595739
Sheath losses flat, outer cable, lagging phase, $\lambda_1$	0,002603674	0,002603674	0,002603674
Three core cable circulating current losses (Sheath), $\lambda_1$	#SAKNAS!	#SAKNAS!	#SAKNAS!
Armour loss:	0	0	0
<b>Thermal resistances:</b>			
T1 Between conductor and sheath	0,589175994	0,589175994	0,589175994
T2 Between Sheath and Armour	0,049607045	0,049607045	0,049607045
T3 Serving (Armour -> outside)	0,146292204	0,146292204	0,146292204
T4 (External Thermal Resistance)	0,008108185	1,186601055	1,521071977